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Spacecraft Engines and the Future of Transportation

Ryan He (author)[1]

[1]Pickering College, Aurora, Ontario, Canada

Abstract

Rocket propulsion has evolved from early theoretical work into a diverse toolkit of engines optimized for different missions. This paper traces key milestones from the Tsiolkovsky rocket equation and Goddard's first liquid fueled rockets to Cold War launch vehicles and the modern shift toward reusability. It then compares today's dominant chemical systems with electric propulsion, highlighting how each trades thrust for efficiency and mission flexibility. Finally, the paper surveys emerging approaches such as methane oxygen engines designed for reuse and in refueling, solar sails for propellant free deep space cruising, and nuclear thermal concepts that could reduce travel time for crewed missions beyond Earth orbit. Taken together, these developments suggest that the future of space transportation will rely on hybrid architectures rather than a single breakthrough engine, combining high thrust launch stages with high efficiency in space propulsion to maximize payload capability and long duration maneuvering.

Keywords: rocket propulsion, chemical rockets, electric propulsion, reusability, nuclear thermal propulsion

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Introduction

From the earliest theories of space travel to today's cutting-edge engines, the development of rocket propulsion has been a story of ambition, innovation, and persistence. Visionaries like Konstantin Tsiolkovsky and Robert Goddard laid the groundwork with fundamental theories and the first liquid-fueled rockets, while global conflicts and the Cold War rapidly advanced rocket technology for both military and space exploration purposes. What began as experimental concepts quickly grew into powerful machines capable of sending humans to the Moon, deploying satellites into orbit, and venturing deeper into space. Today, reusable rockets, electric propulsion, and advanced fuels reflect humanity's drive to make spaceflight more sustainable and accessible. As we look ahead, future propulsion technologies - ranging from advanced chemical systems to nuclear thermal rockets - will shape how far and how efficiently we can travel beyond Earth.

Background

The idea of rocket engines was first proposed by pioneers like Konstantin Tsiolkovsky and Robert Goddard. Konstantin developed the rocket equation, theorizing the possibility of rockets reaching outer space. He also theorized using liquid fuels offers higher efficiency compared to solid fuels. Robert Goddard designed and built the first liquid fueled rocket. His experiments with turbopumps, gyroscopic guidance, and staged combustion are still used in today's rockets.

By the 1940s, the military demanded accelerated progress in technology due to the Second World War. This is when rockets started to become military weapons, and transformed into missiles. The German V-2 rocket, which is the first large-scale liquid-fueled ballistic missile, capable of reaching a distance of up to 300 kilometers. Though the V-2 Rocket is designed for war, its engineering legacy directly translated to postwar space programs.

The cold war and the space race pushed the Russian/Soviet and United States in terms of technology advancement. The Soviet R-7 booster put the world's first artificial satellite, the Sputnik 1, into orbit. While the Soviets were sending satellites, the US developed the Saturn rockets, which allowed Apollo astronauts to reach the moon using the Saturn V.
In the space race, both cold war superpowers showed their technological prowess by launching rockets that would cost over a billion dollars (in today's money). Because it was so expensive, both the US and the Soviet Union began working on a more sustainable and reusable system.

The USA began working on the Space Shuttle in the 1970s as a partially reusable spacecraft. It was a revolutionary device that allowed cheaper trips to space. By attaching a shuttle redesigned to have features of an airplane onto two Solid Rocket Boosters (SRB), the SRB be able to provide enough thrust during lift-off. The SRB is the most powerful solid rocket motor ever built and the shuttle's RS-25 engines burn liquid hydrogen and oxygen, with some of the highest efficiency a chemical rocket can bring. However, the Space Shuttle's revolutionary reign fell short due to complex engineering and two tragic accidents. In the Soviet Union, they developed a different method. Using thirty smaller engines combined into a larger first stage, the N1 rocket was the Soviet's answer to the Saturn V. The N1 rocket was a failed experiment due to high complexity for 1960s technology. Later, Energia was produced, which was a super-heavy lift launch vehicle designed to carry the Buran Shuttle. It uses the most efficient kerosene and liquid oxygen engine, the four-chambered RD-170.

Electric propulsion was also becoming more prominent. The long theorized ion engines had much higher fuel efficiency compared to traditional chemical engines in exchange for lowered thrust. Although very useful for satellites like Nasa's Deep Space 1, it does not have enough thrust to launch the rocket into orbit, but it does enable the engine to produce thrust for months while barely bringing any fuel.

In the 2000s, a new era of spacecraft engineering appeared. SpaceX, founded in 2002, led the industry by being the first private space craft engineering company. The Falcon 9 rocket also led the industry by being the most successful reusable rocket with its kerosene-oxygen engines.

Present

One of the most defining parts of the present era of rocket engineering is reusability. For most of our history, boosters and different rocket stages are abandoned either in space or in the ocean. This made going to space extremely expensive, since no one can recycle their previous rockets and boosters.

SpaceX started creating self-landing first-stage boosters to aid in developing reusable rocket technology. The Falcon 9, after finishing its job as a booster, saves some fuel and comes back down to the surface safely. It is the first of its kind, and currently, has over 440 reflights done. It uses the Merlin series engine developed by SpaceX, which has two variants. The normal Merlin engine is used for the first stage and is designed to be recovered and reused. The Merlin Vacuum engine is designed to maximize efficiency in a vacuum. Both engines use LOX/RP-1 (Kerosene). They have also created the ambitious Starship, which is able to descend and connect itself onto its launchsite, which gets rid of the hassle of finding the rocket and sending cargo ships to retrieve it. The Raptor engines that power the Starship also have two variants, the normal and the vacuum version. The Super Heavy (Starship's first stage) contains thirty-three Raptor engines.

The choice in propellant has also become mission dependent (some may lean towards one type for better efficiency, one may lean towards another for higher thrust). Hydrolox (Liquid hydrogen and liquid oxygen) are the efficient standard for later stages and for vacuum engines while kerosene (like RP-1) are widely used in spacecraft carrying lots of load due to their high thrust and dense fuel. Electric propulsion is also on the rise with hall-effect thrusters. It has proven itself worthy by being on many commercial satellites.

Specific Impulse

Specific impulse (Isp) measures how effectively a rocket uses propellant. It is expressed in seconds and defined as thrust produced per unit weight flow rate of propellant. A higher Isp means more thrust is generated per kilogram of propellant. Specific impulse is the amount of time one kilogram of fuel can produce one kilogram of thrust. For example, a specific impulse of 300s means the engine will produce 1kg of thrust using 1kg of propellant for 300 seconds.

Future of Rocket Engines

Although fuel, shape, and size may matter a lot for the flight performance of a rocket, the engine and powersource will always matter the most. It is the thing that drives the rocket into space.

Advanced Chemical Rockets

Soon, Mars will be as close to us as the place one station away by train, but to get to Mars, we need a good enough train. Currently, our rockets are not efficient enough and the fuel we use is not available on Mars. One solution is to use methalox fuel (Methane and liquid oxygen). Although methane has less specific impulse (fuel efficiency), it is easier to store due to higher density and higher boiling point. It also leaves less residue in the engine compared to kerosene, which increases reusability. Methalox is also chosen as the propellant mixture in NASA's Mars Design Reference Mission 5.0. Methane was also expected to be able to be created on Mars due to the Sabatier reaction and methane is able to be stored much easier.

We are already making a step towards having this happen by applying our knowledge onto the SpaceX's Starship. Due to Methane's availability on Mars and Elon Musk's goal of reaching Mars, it is clear why SpaceX would choose Methalox over Hydrolox and Kerosene. This method is already possible but just requires some more time and research to make it better and allow us to reach other planets. There is one downside where it will not be necessary in the far future, as better alternatives (compared to chemical rockets) will have been developed.

Solar Sailing

Although it may sound preposterous, it is possible. Solar sails harness the power of the sun by simply using the photons as wind. Since photons are extremely fast and there are a lot of them, the sails could pick up a lot of speed using them. Unfortunately, if we want to carry a lot of load, it will either require a sail too large or so much time to accelerate that it will be not necessary.

It is useful for carrying small loads at high speeds, and it is able to go long distances since it does not require fuel. This technology was also proven to be effective, as proven by JAXA's IKAROS. This technology will not be able to carry much load, but may be effective towards interstellar exploration.

Electric Propulsion

Electric engines do not rely on traditional fuel sources, which means it does not need bulky chemical fuel cells. It uses electrostatic or electromagnetic fields to accelerate mass to generate thrust. Electric thrusters operate at a much higher efficiency (uses less propellant) because they have a higher exhaust speed than chemical rockets.

First demonstrated in the 1960s, it is now widely spread on many American and Russian satellites. Electric thrusters can achieve high exhaust velocities, which in turn allow spacecraft to accumulate large delta-v values over time. For example, ion engines enable missions with total velocity changes exceeding tens of km/s. With an external power source (like transmitting power through photovoltaic panels via laser), it is theoretically possible for interstellar flight. There are two main types of electric thrusters: ion and plasma drives and non-ion drives.

Ion and Plasma Drives

These types of rocket-like reaction engines use electric energy to obtain thrust from the propellant. Ion and plasma drives may be grouped into three types.

Electrostatic

When the acceleration is caused by the Coulomb force (application of a static electric field in the direction of the acceleration), it is considered to be electrostatic. There are multiple different types of electrostatic thrusters.

1: The gridded ion thruster injects the propellant atoms into the discharge chamber and ionizes it. The ionized gas turns into a plasma and gets accelerated to produce thrust. There are several ways to ionize the gas: electron bombardment, radio frequency oscillation of an electric field, or microwave heating. It has a range of 3000-10000 s of specific impulse (one of the highest for ion thrusters) and the ions can be accelerated up to 100 km/s.

2: The hall effect thruster, as the name suggests, uses the hall effect to accelerate the propellant. The thruster has an annular ceramic channel with an anode at the base that inject neutral gas and a cathode outside the channel that releases electrons. Electrons spiral in the magnetic field induced by magnets and form a hall current, which increases collisions with xenon atoms, which ionizes the gas. An electric field then accelerates the ions outward at 10 to 20 kilometers per second, creating thrust. It has a specific impulse of 1600 seconds. These are the two main types of electrostatic thrusters used, the rest are either theoretical or not common.

Electrothermal

Electrothermal thrusters use electromagnetic fields to generate a plasma to increase the temperature of the propellant. The thermal energy of the propellant gas is turned into kinetic energy by either a solid or magnetic field nozzle. It has a specific impulse of 500 to 1000 seconds.

The Resistojet rocket is one of the most effective electrothermal thrusters. Heating is achieved by passing electricity through a resistor consisting of a hot incandescent filament, with the expanded gas (due to heat) expelled through a nozzle.

Electromagnetic

Electromagnetic thrusters operate by accelerating ions using the Lorentz force or by the effect of electromagnetic fields where the electric field is not in the direction of the acceleration. It is not commonly used.

Non-ion drives are not commonly used mainly due to their ineffectiveness. For these electric thrusters, it is also possible that we use a nuclear reactor to generate electricity which powers ion thrusters.

Nuclear Thermal Rocket

A nuclear thermal rocket is a type of thermal rocket where nuclear reaction replaces the chemical energy of chemical rockets. In this rocket, a working fluid (usually liquid hydrogen), is heated to high temperature in a nuclear reactor and then expands through the nozzle creating thrust. Using the external nuclear heat source, allows the theoretical effective exhaust velocity to be much higher compared to chemical rockets.

While early application for nuclear thermal rockets uses a fission reaction, recent developments and research in the 2010s has been aimed towards fusion approaches. The Direct Fusion Drive project at Princeton Plasma Physics Laboratory is one of these approaches for interplanetary spacecraft. Currently theoretical, it is projected to be able to produce 5 to 10 Newtons of thrust for each megawatts of fusion power. Approximately 35%

of fusion power goes through thrust, 30% to electricity, 25% lost to heat, and 10% is recirculated for radio-frequency heating.

Demonstration Rocket for Agile Cislunar Operation (DRACO) is another project under the joint cooperation of DARPA, NASA, Lockheed Martin, and BWX Technologies, aiming to achieve a successful demonstration of Nuclear Thermal Rockets by 2027. Using Uranium as the heat source, its theoretical reusability and performance were to be much better than current chemical rockets. This project, however, was canceled due to financial issues and complexity.

There are several types of Nuclear Thermal Rockets which use different types of fuels and reactions. The first type is a solid core of Uranium undergoing a controlled fission to heat up liquid hydrogen. The reactor produces a specific impulse of 850 to 1000 seconds, which is twice of liquid hydrogen-oxygen engines. With the 7:1 thrust to weight ratio, it is far less effective compared to the chemical rockets with a thrust to weight ratio 70:1. The second type is a liquid core, which is fueled by components that are fissionable in liquid state. It is extremely difficult for us to build with our current technology.

Nuclear Thermal Rocket is an extremely promising realm that may allow for efficient interstellar exploration using nuclear materials such as uranium (fission reactors) or hydrogen isotopes (mined from the surface of the planet due to solar winds).

Comparison

Each different rocket has their advantages and disadvantages, and are each good at something different. Solar sailing, although very fast, is hard to control and can only carry a small amount of load. Advanced chemical rockets are not fuel efficient, but can produce a lot of thrust. Electric thrusters don't produce a lot of thrust but are very fuel efficient. Nuclear Thermal Rockets are very hard to build for our current technologies but once built, are able to produce a lot of thrust while being very fuel efficient.

We can also see that instead of using just one type of booster, we can combine them. Using chemical rockets to escape Earth's gravity and electric boosters to maintain fuel efficiency and long distance travel in space. Using a combination of different boosters and thrusters may result in much better overall performance.

Conclusion

The story of rocket engines is not just about machines; it is about human ingenuity and the determination to expand our reach beyond Earth. Each generation of propulsion technology, from chemical to electric to nuclear concepts, has built upon the achievements and lessons of the past. Reusability has already transformed space travel economics, while experimental systems like solar sails and nuclear thermal rockets hint at possibilities far beyond our current limitations. Ultimately, the future of space exploration will not rely on a single type of engine, but on a combination of technologies working together to balance thrust, efficiency, and sustainability. Rockets remain the driving force behind our journey to the stars, and the engines of tomorrow will decide how far that journey can take us.

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