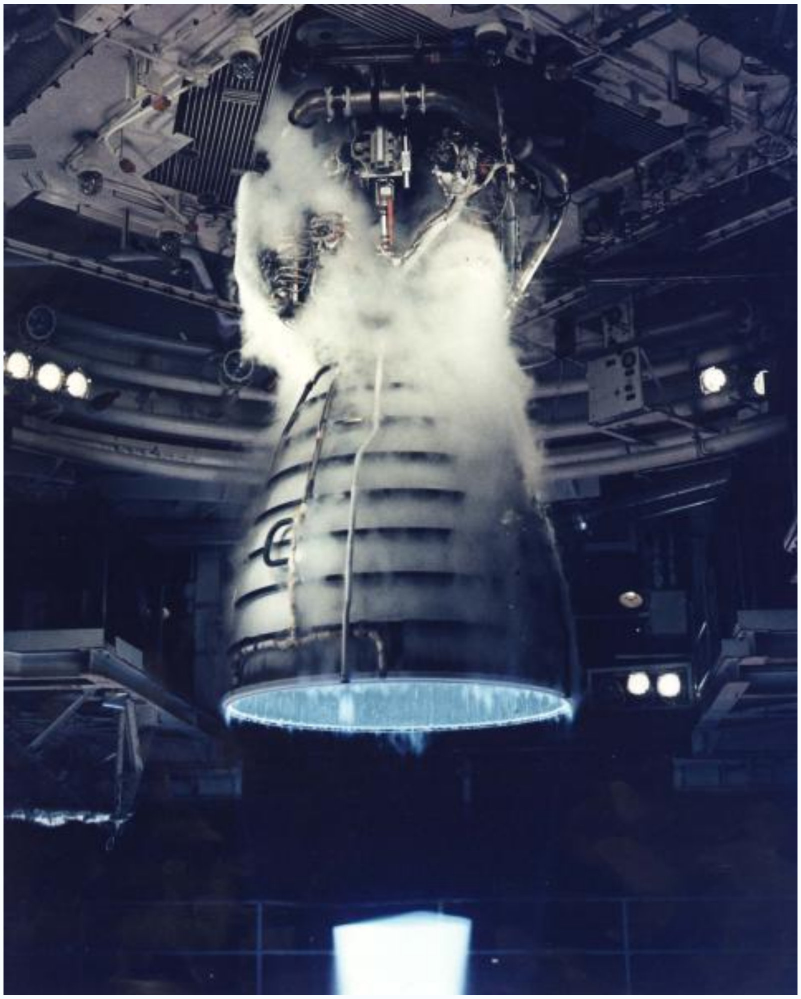
Spacecraft propulsion



A remote camera captures a close-up view of a Space Shuttle Main Engine during a test firing at the John C. Stennis Space Center in Hancock County, Mississippi

Spacecraft propulsion is used to change the velocity of spacecraft and artificial satellites, or in short, to provide delta-v. There are many different methods. Each method has drawbacks and advantages, and spacecraft propulsion is an active area of research. Most spacecraft today are propelled by heating the reaction mass and allowing it to flow out the back of the vehicle. This sort of engine is called a **rocket engine**.

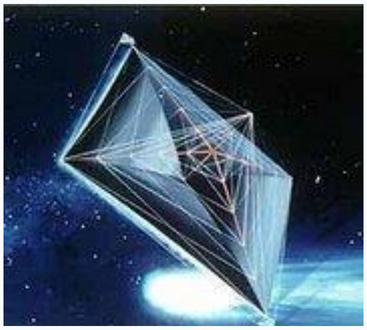
All current spacecraft use chemical rocket (bipropellant or solid-fuel) for launch, though some (such as the Pegasus rocket and SpaceShipOne) have used air-breathing engines on their first stage. Most satellites have simple reliable chemical rockets (often monopropellant rockets) or resistojet rockets to keep their station, although some use momentum wheels for attitude control. Newer geo-orbiting spacecraft are starting to use electric propulsion for north-south stationkeeping. Interplanetary vehicles mostly use chemical rockets as well, although a few have experimentally used ion thrusters with some success (a form of electric propulsion).

The necessity for propulsion systems

Artificial satellites must be launched into orbit, and once there they must accelerate to circularize their orbit. Once in the desired orbit, they often need some form of attitude control so that they are correctly pointed with respect to the Earth, the Sun, and possibly some astronomical object of interest. They are also subject to drag from the thin atmosphere, so that to stay in orbit for a long period of time some form of propulsion is occasionally necessary to make small corrections (orbital stationkeeping). Many satellites need to be moved from one orbit to another from time to time, and this also requires propulsion. When a satellite has exhausted its ability to adjust its orbit, its useful life is over.

Spacecraft designed to travel further also need propulsion methods. They need to be launched out of the Earth's atmosphere just as satellites do. Once there, they need to leave orbit and move around.

For interplanetary travel, a spacecraft must use its engines to leave Earth orbit. Once it has done so, it must somehow make its way to its destination. Current interplanetary spacecraft do this with a series of short-term orbital adjustments. In between these adjustments, the spacecraft simply falls freely along its orbit. The simplest fuel-efficient means to move from one circular orbit to another is with a Hohmann transfer orbit: the spacecraft begins in a roughly circular orbit around the Sun. A short period of thrust in the direction of motion accelerates or decelerates the spacecraft into an elliptical orbit around the Sun which is tangential to its previous orbit and also to the orbit of its destination. The spacecraft falls freely along this elliptical orbit until it reaches its destination, where another short period of thrust accelerates or decelerates it to match the orbit of its destination. Special methods such as aerobraking are sometimes used for this final orbital adjustment.


Artist's conception of a solar sail

Some spacecraft propulsion methods such as solar sails provide very low but inexhaustible thrust; an interplanetary vehicle using one of these methods would follow a rather different trajectory, either constantly thrusting against its direction of motion in order to decrease its distance from the Sun or constantly thrusting along its direction of motion to increase its distance from the Sun.

Spacecraft for interstellar travel also need propulsion methods. No such spacecraft has yet been built, but many designs have been discussed. Since interstellar distances are very great, a tremendous velocity is needed to get a spacecraft to its destination in a reasonable amount of time. Acquiring such a velocity on launch and getting rid of it on arrival will be a formidable challenge for spacecraft designers.

Effectiveness of propulsion systems

When in space, the purpose of a propulsion system is to change the velocity v of a spacecraft. Since this is more difficult for more massive spacecraft, designers generally discuss momentum, mv. The amount of change in momentum is called impulse. So the goal of a propulsion method in space is to create an impulse.

When launching a spacecraft from the Earth, a propulsion method must overcome the Earth's gravitational pull in addition to providing acceleration.

The rate of change of velocity is called acceleration, and the rate of change of momentum is called force. To reach a given velocity, one can apply a small acceleration over a long period of time, or one can apply a large acceleration over a short time. Similarly, one can achieve a given impulse with a large force over a short time or a small force over a long time. This means that for maneuvering in space, a propulsion method that produces tiny accelerations but runs for a long time can produce the same impulse as a propulsion method that produces large accelerations for a short time. When launching from a planet, tiny accelerations cannot overcome the planet's gravitational pull and so cannot be used.

The law of conservation of momentum means that in order for a propulsion method to change the momentum of a space craft it must change the momentum of something else as well. A few designs take advantage of things like magnetic fields or light pressure in order to change the spacecraft's momentum, but in free space the rocket must bring along some mass to accelerate away in order to push itself forward. Such mass is called reaction mass.


An ion engine test

In order for a rocket to work, it needs two things: reaction mass and energy. The impulse provided by launching a particle of reaction mass having mass m at velocity v is mv. But this particle has kinetic energy $mv^2/2$, which must come from somewhere. In a conventional solid fuel rocket, the fuel is burned, providing the energy, and the reaction products are allowed to flow out the back, providing the reaction mass. In an ion thruster, electricity is used to accelerate ions out the back. Here some other source must provide the electrical energy (perhaps a solar panel or a nuclear reactor) while the ions provide the reaction mass.

When discussing the efficiency of a propulsion system, designers often focus on the reaction mass. After all, energy can in principle be produced without much difficulty, but the reaction mass must be carried along with the rocket and irretrievably consumed when used. A way of measuring the amount of impulse that can be obtained from a fixed amount of reaction mass is the specific impulse. This is the impulse per unit mass in newton seconds per kilogram (N·s/kg). This corresponds to metres per second (m/s), and is the effective exhaust velocity v_e.

A rocket with a high exhaust velocity can achieve the same impulse with less reaction mass. However, the kinetic energy is proportional to the square of the exhaust velocity, so that more efficient engines (in the sense of having a large specific impulse) require more energy to run.

A second problem is that if the engine is to provide a large amount of thrust, that is, a large amount of impulse per second, it must also provide a large amount of energy per second. So highly efficient engines require enormous amounts of energy per second to produce high thrusts. As a result, most high-efficiency engine designs also provide very low thrust.

Calculations

Burning the entire usable propellant of a spacecraft through the engines in a straight line in free space would produce a net velocity change to the vehicle- this number is termed 'delta-v'.

The total Δ*v* of a vehicle can be calculated using the rocket equation, where M is the mass of fuel, P is the mass of the payload (including the rocket structure), and I_{sp} is the specific impulse of the rocket. This is known as the Tsiolkovsky rocket equation:

$$\Delta V = -I_{sp} \ln\left(\frac{P}{M+P}\right)$$

For a long voyage, the majority of the spacecraft's mass may be reaction mass. Since a rocket must carry all its reaction mass with it, most of the first reaction mass goes towards accelerating reaction mass rather than payload. If we have a payload of mass *P*, the spacecraft needs to change its velocity by Δv, and the rocket engine has exhaust velocity v_e, then the mass *M* of reaction mass which is needed can be calculated using the rocket equation and the formula for I_{sp}

$$M = P\left(e^{\Delta v / v_e} - 1\right)$$

For Δv much smaller than v_e, this equation is roughly linear, and little reaction mass is needed. If Δv is comparable to v_e, then there needs to be about twice as much fuel as combined payload and structure (which includes engines, fuel tanks, and so on). Beyond this, the growth is exponential; speeds much higher than the exhaust velocity require very high ratios of fuel mass to payload and structural mass.

In order to achieve this, some amount of energy must go into accelerating the reaction mass. Every engine will waste some energy, but even assuming 100% efficiency, the engine will need energy amounting to

$$\tfrac{1}{2} M v_e^2$$

This formula reflects the fact that even with 100% engine efficiency, certainly not all energy supplied ends up in the vehicle - some of it, indeed usually most of it, ends up as kinetic energy of the exhaust.

For a mission, for example, when launching from or landing on a planet, the effects of gravitational attraction and any atmospheric drag must be overcome by using fuel. It is typical to combine the effects of these and other effects into an effective mission delta-v. For example a launch mission to low Earth orbit requires about 9.3-10 km/s delta-v. These mission delta-vs are typically numerically integrated on a computer.

Suppose we want to send a 10,000 kg space probe to Mars. The required Δ*v* from LEO is approximately 3000 m/s, using a Hohmann transfer orbit. (A manned probe would need to take a faster route and use more fuel). For the sake of argument, let us say that the following thrusters may be used:

Engine	Effective Exhaust Velocity (m/s)	Specific impulse (s)	Fuel mass (kg)	Energy required (GJ)	Energy per kg
Solid rocket	1,000	100	190,000	95	500 kJ
Bipropellant rocket	5,000	500	8,200	103	12.6 MJ
Ion thruster	50,000	5,000	620	775	1.25 GJ
VASIMR	300,000	30,000	100	4,500	45 GJ

Observe that the more fuel-efficient engines can use far less fuel; its mass is almost negligible (relative to the mass of the payload and the engine itself) for some of the engines. However, note also that these require a large total amount of energy. At one gravity, the total acceleration takes about 300 s, or about five minutes. So, for it to be possible for one of the high-efficiency engines to generate a gravity of thrust, they would have to be supplied with 2.5 or 15 GW of power - equivalent to a major metropolitan generating station. This would need to be included in the 10,000 kg of payload and structural weight, which is clearly impractical.

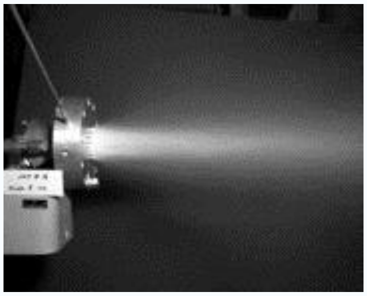
Instead, a much smaller, less powerful generator may be included which will take much longer to generate the total energy needed. This lower power is only sufficient to accelerate a tiny amount of fuel per second, but over long periods the velocity will be finally achieved. For example. it took the Smart 1 more than a year to reach the Moon, while with a chemical rocket it takes a few days. Because the ion drive's needs much less fuel, the total launched mass is usually lower, which typically results in lower overall cost.

Interestingly, for a mission delta-v, there is a fixed I_{sp} that minimises the overall energy used by the rocket. This comes to an exhaust velocity of about 2/3 of the delta-v (see also the energy computed from the rocket equation). Drives such as VASIMR, and to a lesser extent other Ion thrusters have exhaust velocities that can be enormously higher than this ideal, and thus end up powersource limited and give very low thrust. If the vehicle performance is limited by available power, e.g. if solar power is used, then in the case of a large v_e the maximum acceleration is inversely proportional to it, hence the time to reach a required delta-v is inversely proportional to v_e. Thus the latter should not be too large.

Propulsion methods

Propulsion methods can be classified based on their means of accelerating the reaction mass. There are also some special methods for launches, planetary arrivals, and landings.

Rockets


A "cold" (un-ignited) rocket engine test at NASA

A rocket engine accelerates its reaction mass by heating it, producing hot high-pressure gas or plasma. The reaction mass is then allowed to escape from the rear of the vehicle by passing through a nozzle, which dramatically accelerates the reaction mass, converting thermal energy into kinetic energy. It is this nozzle which gives a rocket engine its characteristic shape.

Hot fluid is required because it maximises the speed at the throat of the nozzle. The expansion part of the rocket nozzle then accelerates by a further factor, typically between 1.5 and 4 times. The speed ratio of a rocket nozzle is mostly determined by its area expansion ratio—the ratio of the area of the throat to the area at the exit. The larger this is, the more heat energy the nozzle is able to extract from the combustion gases, and the faster, colder and lower pressure the exhaust becomes. However, larger nozzles are heavier.

A significant complication arises when launching a vehicle from the Earth's surface as the ambient atmospheric pressure changes with altitude. For maximum performance it turns out that the pressure of the gas leaving a rocket nozzle should be the same as ambient pressure; if lower the vehicle will be slowed by the difference in pressure between the top of the engine and the exit, if higher then this represents pressure that the bell has not turned into thrust. To achieve this ideal, the diameter of the nozzle would need to increase with altitude, which is difficult to arrange. A compromise nozzle is generally used and some percentage reduction in performance occurs. To improve on this, various exotic nozzle designs such as the plug nozzle, stepped nozzles, the expanding nozzle and the aerospike have been proposed, each having some way to adapt to changing ambient air pressure and each allowing the gas to expand further against the nozzle giving extra thrust at higher altitude.

The reaction mass's combustion temperature is often far higher than the melting point of the nozzle and combustion chamber materials. Nevertheless, materials technology mostly does not place an upper limit on the exhaust temperature of chemical rockets. Rockets can use ablative materials that erode in a controlled fashion, or very high temperature materials, such as graphite, ceramics or certain exotic metals. Alternatively, rockets may employ cooling systems to prevent the nozzle material itself becoming too hot. Regenerative cooling, where the propellant is passed through tubes around the combustion chamber or nozzle, and other techniques such as curtain cooling or film cooling, may also be employed to give essentially unlimited nozzle life.

Rockets emitting plasma can potentially carry out reactions inside a magnetic bottle and release the plasma via a magnetic nozzle, so that no solid matter need come in contact with the plasma. Of course, the machinery to do this is complex, but research into nuclear fusion has developed methods, some of which have been used in speculative propulsion systems.


H-1 rocket engine


Linear aerospike XRS-2200 engine

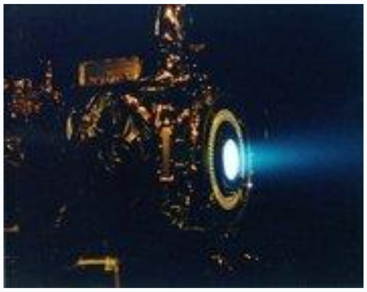
Rocket engines that could be used in space (all emit gases unless otherwise noted):

- Solid rocket (chemical energy)
- Hybrid rocket (chemical energy)
- Monopropellant rocket (chemical energy)
- Bipropellant rocket (chemical energy)
- Tripropellant rocket (chemical energy)
- Dual mode propulsion rocket (chemical energy)
- Resistojet rocket (electric heating)
- Arcjet rocket (chemical burning aided by electrical discharge)
- Pulsed plasma thruster (electric arc heating; emits plasma)
- Magnetoplasmadynamic thruster (acceleration by electromagnetic forces; emits plasma)
- Variable specific impulse magnetoplasma rocket (electromagnetic heating; emits plasma)
- Solar thermal rocket (solar energy)
- Nuclear thermal rocket (nuclear fission energy)
- Radioisotope rocket/Poodle thruster (radioactive decay energy)
- Antimatter catalyzed nuclear pulse propulsion (fission and/or fusion energy)
- Gas core reactor rocket (nuclear fission energy)
- Fission-fragment rocket (nuclear fission energy)
- Fission sail (nuclear fission energy)
- Nuclear salt-water rocket (nuclear fission energy)
- Nuclear pulse propulsion (exploding fission/fusion bombs)
- Fusion rocket (nuclear fusion energy)
- Antimatter rocket (annihilation energy)

On the other hand, engines have been proposed that take advantage of the air in some way (as do jet engines and other air-breathing engines):

- ramjets
- Air-augmented rocket
- Liquid air cycle engine
- SABRE
- Scramjets

Electromagnetic acceleration of reaction mass


This test engine accelerates ions using electrostatic forces

Rather than relying on high temperature and fluid dynamics to accelerate the reaction mass to high speeds, there are a variety of methods that use electrostatic or electromagnetic forces to accelerate the reaction mass directly. Usually the reaction mass is a stream of ions. Such an engine requires electric power to run, and high exhaust velocities require large amounts of energy.

It turns out that to a reasonable approximation, for these drives, that fuel use, energetic efficiency and thrust are all inversely proportional to exhaust velocity. Their very high exhaust velocity means they require huge amounts of energy and provide low thrust, but use hardly any fuel.

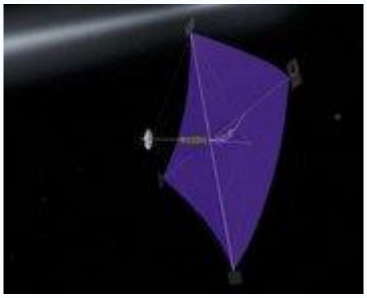
For some missions, solar energy may be sufficient, but for others nuclear energy will be necessary; engines drawing their power from a nuclear source are called nuclear electric rockets. With any current source of power, the maximum amount of power that can be generated limits the maximum amount of thrust that can be produced to a very small value. Power generation also often adds significant mass to the spacecraft. The dissipation of waste heat from the powerplant may make any propulsion system requiring a separate power source infeasible for interstellar travel.

Some electromagnetic methods:

- Ion thruster
  - Electrostatic ion thruster
  - Hall effect thruster
  - Field Emission Electric Propulsion
  - Pulsed inductive thruster
- Magnetoplasmadynamic thruster
- Variable specific impulse magnetoplasma rocket
- Mass drivers (for propulsion)

The Biefeld-Brown effect is a somewhat exotic electrical effect. In air, a voltage applied across a particular kind of capacitor produces a thrust. There have been claims that this also happens in a vacuum due to some sort of coupling between the electromagnetic field and gravity, but recent experiments show no evidence of this hypothesis.

Systems without reaction mass



NASA study of a solar sail. The sail would be half a kilometer wide.

The law of conservation of momentum states that any engine which uses no reaction mass cannot move the center of mass of a spaceship (changing orientation, on the other hand, is possible). But space is not empty, especially space inside the Solar Systems; there is a magnetic field and a solar wind. Various propulsion methods try to take advantage of this; since all these things are very diffuse, propulsion structures need to be large.

Space drives that need no (or little) reaction mass:

- Tether propulsion
- Solar sails
- Magnetic sails
- Mini-magnetospheric plasma propulsion

For changing the orientation of a satellite or other space vehicle, conservation of angular momentum does not pose a similar constraint. Thus many satellites use momentum wheels to control their orientations. These cannot be the only system for controlling satellite orientation, as frictional losses eventually require the momentum to be "bled off" using a secondary system.

Launch mechanisms

An artist's conception of an electromagnetic catapult on the Moon

High thrust is of vital importance for launch, the thrust per unit mass has to be well above g, see also gravity drag. Many of the propulsion methods above do not provide that much thrust, especially if solar power is used. For a solar-powered launch, at the very least the mass of the solar panel would have to be less than 20 grams per kilowatt of power, and even less if the specific impulse is higher or lower than the optimum value, which would be in the order of magnitude of 10 km/s; also the engine would have to be very light and energy-efficient.

Exhaust toxicity or other side effects can also have detrimental effects on the environment the spacecraft is launching from, ruling out other propulsion methods.

Therefore, all current spacecraft use chemical rocket engines (bipropellant or solid-fuel) for launch.

One advantage that spacecraft have in launch is the availability of infrastructure on the ground to assist them. Proposed ground-assisted launch mechanisms include:

- Space elevator
- Orbital airship
- Space fountain
- Hypersonic skyhook
- Electromagnetic catapult (railgun, coilgun)
- Ballistic acceleration (Project HARP, ram accelerator)
- Laser propulsion (Lightcraft)

Planetary arrival and landing

A test version of the MARS Pathfinder airbag system

When a vehicle is to enter orbit around its destination planet, or when it is to land, it must adjust its velocity. This can be done using all the methods listed above (provided they can generate a high enough thrust), but there are a few methods that can take advantage of planetary atmospheres.

- aerobraking brings a probe into orbit
- parachutes can land a probe on a planet with an atmosphere
- airbags can soften the final landing

Gravitational slingshots can also be used to carry a probe onward to other destinations.

Methods requiring new principles of physics

Artist's conception of a warp drive design

In addition, a variety of hypothetical propulsion techniques have been considered that would require entirely new principles of physics to realize. To date, such methods are highly speculative:

- Diametric drive
- Pitch drive
- Bias drive
- Disjunction drive
- Alcubierre drive (Warp drive)
- Differential sail
- Wormholes
- Time machines

Table of methods and their specific impulse

Below is a summary of some of the more popular, proven technologies, followed by increasingly speculative methods.

Three numbers are shown. The first is the effective exhaust velocity: the equivalent speed that the propellant leaves the vehicle. This is not necessarily the most important characteristic of the propulsion method, thrust and power consumption and other factors can be, however:

- if the delta-v is much more than the exhaust velocity, then exorbitant amounts of fuel are necessary (see the section on calculations, above)
- if it is much more than the delta-v, then, proportionally more energy is needed; if the power is limited, as with solar energy, this means that the journey takes a proportionally longer time

The second and third are the typical amounts of thrust and the typical burn times of the method. Outside a gravitational potential small amounts of thrust applied over a long period will give the same effect as large amounts of thrust over a short period. (This result does not apply when the object is significantly influenced by gravity.)

Propulsion methods

Method	Effective Exhaust Velocity (m/s)	Thrust (N)	Duration
Propulsion methods in current use			
Solid rocket	1,000 - 4,000	10^3 - 10^7	minutes
Hybrid rocket	1,500 - 4,200		minutes
Monopropellant rocket	1,000 - 3,000	0.1 - 100	milliseconds - minutes
Momentum wheel (attitude control only)	N/A	N/A	indefinite
Bipropellant rocket	1,000 - 4,700	0.1 - 10^7	minutes
Tripropellant rocket	2,500 - 4,500		minutes
Resistojet rocket	2,000 - 6,000	10^{-2} - 10	minutes
Arcjet rocket	4,000 - 12,000	10^{-2} - 10	minutes
Hall effect thruster (HET)	8,000 - 50,000	10^{-3} - 10	months
Electrostatic ion thruster	15,000 - 80,000	10^{-3} - 10	months
Field Emission Electric Propulsion (FEEP)	100,000 - 130,000	10^{-6} - 10^{-3}	weeks
Magnetoplasmadynamic thruster (MPD)	20,000 - 100,000	100	weeks
Pulsed plasma thruster (PPT)			
Pulsed inductive thruster (PIT)	50,000	20	months
Nuclear electric rocket	As electric propulsion method used		
Tether propulsion	N/A	1 - 10^{12}	minutes
Currently feasible propulsion methods			
Solar sails	N/A	9 per km^2 (at 1 AU)	Indefinite
Mass drivers (for propulsion)	30,000 - ?	10^4 - 10^8	months
Orion Project (Near term nuclear pulse propulsion)	20,000 - 100,000	10^9 - 10^{12}	several days
Variable specific impulse magnetoplasma rocket (VASIMR)	10,000 - 300,000	40 - 1,200	days - months
Nuclear thermal rocket	9,000	10^5	minutes
Solar thermal rocket	7,000 - 12,000	1 - 100	weeks
Radioisotope rocket	7,000-8,000		months
Air-augmented rocket	5,000 - 6,000		seconds-minutes
Liquid air cycle engine	4,500		seconds-minutes
SABRE	30,000/4,500		minutes
Dual mode propulsion rocket			
Technologies requiring further research			
Magnetic sails	N/A	Indefinite	Indefinite
Mini-magnetospheric plasma propulsion	200,000	~1 N/kW	months
Nuclear pulse propulsion (Orion drive)	20,000 - 1,000,000	10^9 - 10^{12}	half hour

Gas core reactor rocket	10,000 - 20,000	10^3 - 10^6	
Antimatter catalyzed nuclear pulse propulsion	20,000 - 400,000		days-weeks
Nuclear salt-water rocket	100,000	10^3 - 10^7	half hour
Beam-powered propulsion	As propulsion method powered by beam		
Fission sail			
Fission-fragment rocket	10,000,000		
Nuclear photonic rocket	300,000,000	10^{-5} - 1	years-decades
Significantly beyond current engineering			
Fusion rocket			
Bussard ramjet			
Antimatter rocket			
Redshift rocket			

See also

- interplanetary travel
- interstellar travel
- specific impulse
- rocket
- Tsiolkovsky rocket equation
- satellite