

A Comprehensive Introduction to Spacecraft Propulsion

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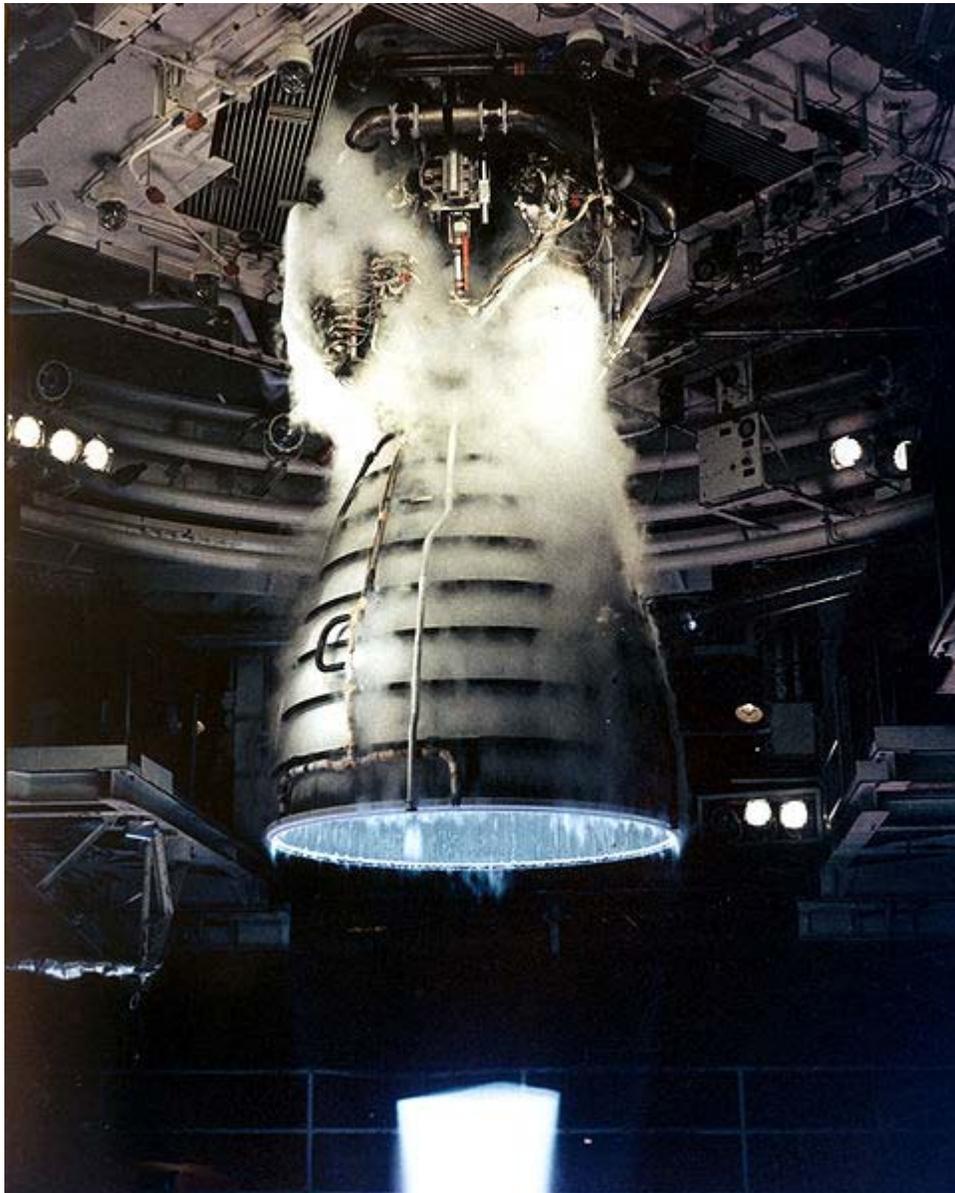
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Chapter- 1

Introduction to 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 any method used to accelerate spacecraft and artificial satellites. There are many different methods. Each method has drawbacks and advantages, and spacecraft propulsion is an active area of research. However, most spacecraft today are propelled by forcing a gas from the back/rear of the vehicle at very high speed through a supersonic de Laval nozzle. This sort of engine is called a rocket engine.

All current spacecraft use chemical rockets (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 thrusters (often monopropellant rockets) or resistojet rockets for orbital station-keeping and some use momentum wheels for attitude control. Soviet bloc satellites have used electric propulsion for decades, and newer Western geo-orbiting spacecraft are starting to use them for north-south stationkeeping. Interplanetary vehicles mostly use chemical rockets as well, although a few have used ion thrusters and Hall effect thrusters (two different types of electric propulsion) to great success.

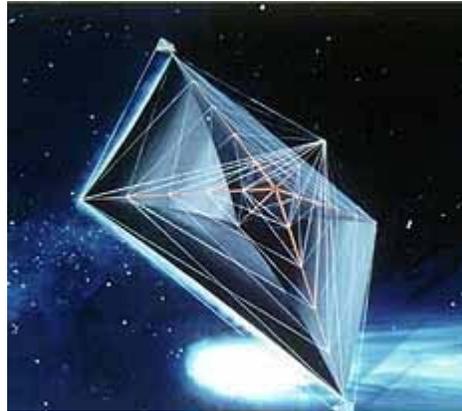
Need

Artificial satellites must be launched into orbit, and once there they must be placed in their nominal 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. A satellite's useful life is over once it has exhausted its ability to adjust its orbit.

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 trajectory adjustments. In between these adjustments, the spacecraft simply falls freely along its trajectory. The most 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 concept 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. The concept has been successfully tested by the Japanese IKAROS solar sail spacecraft.

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

When in space, the purpose of a propulsion system is to change the velocity, or 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 a higher gravitational pull to provide a positive net acceleration. In orbit, any additional impulse, even very tiny, will result in a change in the orbit path.

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 Earth's surface is situated fairly deep in a gravity well. The escape velocity required to get out of it is 11.2 kilometers/second. As human beings evolved in a gravitational field of $1g$ (9.8 m/s^2), an ideal propulsion system would be one that provides a continuous acceleration of $1g$ (though human bodies can tolerate much larger accelerations over short periods). The occupants of a rocket or spaceship having such a propulsion system would be free from all the ill effects of free fall, such as nausea, muscular weakness, reduced sense of taste, or leaching of calcium from their bones.

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.

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, liquid, or hybrid 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 effectively using the reaction mass. Reaction mass must be carried along with the rocket and is irretrievably consumed when used. One way of measuring the amount of impulse that can be obtained from a fixed amount of reaction mass is the specific impulse, the impulse per unit weight-on-Earth (typically designated by I_{sp}). The unit for this value is seconds. Since the weight on Earth of the reaction mass is often unimportant when discussing vehicles in space, specific impulse can also be discussed in terms of impulse per unit mass. This alternate form of specific impulse uses the same units as velocity (e.g. m/s), and in fact it is equal to the effective exhaust velocity of the engine (typically designated v_e). Confusingly, both values are sometimes called specific impulse. The two values differ by a factor of g_n , the standard acceleration due to gravity 9.80665 m/s^2 ($I_{sp}g_n = v_e$).

A rocket with a high exhaust velocity can achieve the same impulse with less reaction mass. However, the energy required for that impulse is proportional to the exhaust velocity, so that more mass-efficient engines require much more energy, and are typically less energy efficient. This is a problem if the engine is to provide a large amount of

thrust. To generate a large amount of impulse per second, it must use a large amount of energy per second. So high-mass-efficient engines require enormous amounts of energy per second to produce high thrusts. As a result, most high-mass-efficient engine designs also provide lower thrust due to the unavailability of high amounts of energy.

Methods

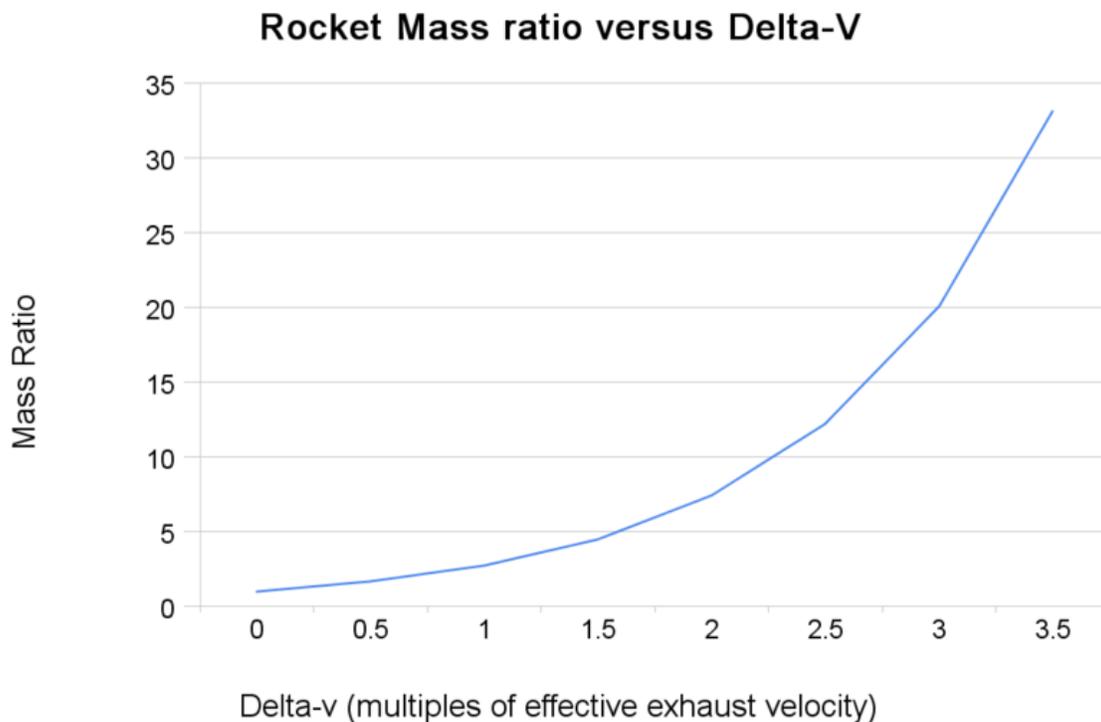
Propulsion methods can be classified based on their means of accelerating the reaction mass. There are also some special methods for launches, planetary arrivals, and landings.

Reaction engines

A **reaction engine** is an engine which provides propulsion by expelling reaction mass, in accordance with Newton's third law of motion. This law of motion is most commonly paraphrased as: "For every action force there is an equal, but opposite, reaction force".

Examples include both duct engines and rocket engines, and more uncommon variations such as Hall effect thrusters, ion drives and mass drivers. Duct engines are obviously not used for space propulsion due to the lack of air; however some proposed spacecraft have these kinds of engines to assist takeoff and landing.

Delta-v and propellant



Rocket mass ratios versus final velocity, as calculated from the rocket equation

Exhausting 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' (Δv).

If the exhaust velocity is constant then the total Δv of a vehicle can be calculated using the rocket equation, where M is the mass of propellant, P is the mass of the payload (including the rocket structure), and v_e is the velocity of the rocket exhaust. This is known as the Tsiolkovsky rocket equation:

$$\Delta v = v_e \ln \left(\frac{M + P}{P} \right).$$

For historical reasons, as discussed above, v_e is sometimes written as

$$v_e = I_{sp} g_o$$

where I_{sp} is the specific impulse of the rocket, measured in seconds, and g_o is the gravitational acceleration at sea level.

For a high delta-v mission, the majority of the spacecraft's mass needs to be reaction mass. Since a rocket must carry all of its reaction mass, most of the initially-expended reaction mass goes towards accelerating reaction mass rather than payload. If the rocket has 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.

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.

Some effects such as Oberth effect can only be significantly utilised by high thrust engines such as rockets, i.e. engines that can produce a high g-force (thrust per unit mass, equal to delta-v per unit time).

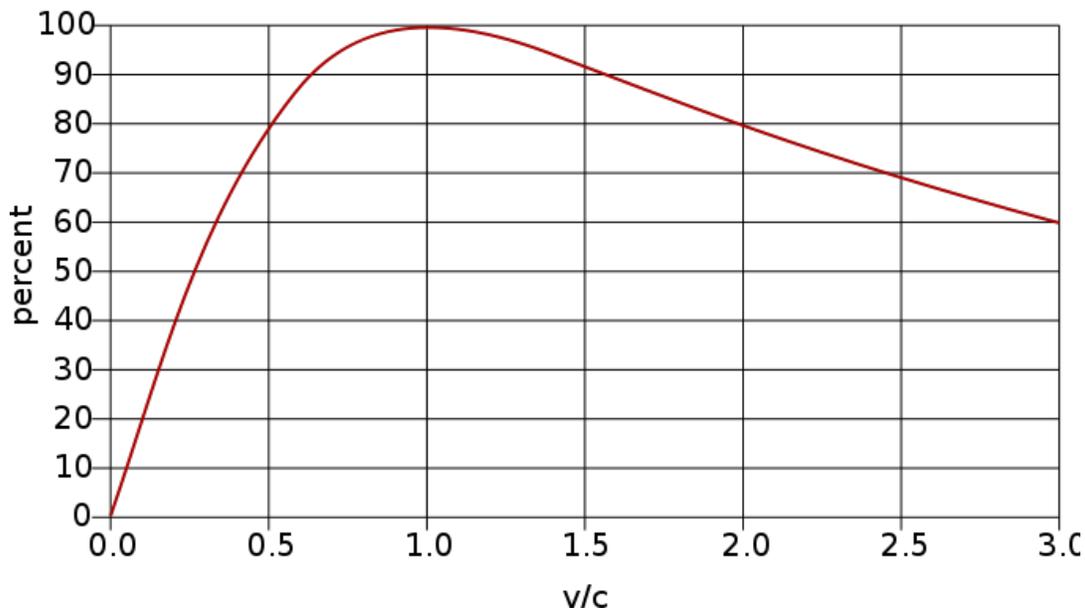
Power use and propulsive efficiency

For all reaction engines (such as rockets and ion drives) some energy must go into accelerating the reaction mass. Every engine will waste some energy, but even assuming 100% efficiency, to accelerate an exhaust the engine will need energy amounting to

$$\frac{1}{2} \dot{m} v_e^2$$

This energy is not necessarily lost- some of it usually ends up as kinetic energy of the vehicle, and the rest is wasted in residual motion of the exhaust.

Propulsive efficiency



Due to energy carried away in the exhaust the energy efficiency of a reaction engine varies with the speed of the exhaust relative to the speed of the vehicle, this is called propulsive efficiency

Comparing the rocket equation (which shows how much energy ends up in the final vehicle) and the above equation (which shows the total energy required) shows 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.

The exact amount depends on the design of the vehicle, and the mission. However there are some useful fixed points:

- if the I_{sp} is fixed, for a mission delta-v, there is a particular I_{sp} that minimises the overall energy used by the rocket. This comes to an exhaust velocity of about $\frac{2}{3}$ of the mission delta-v. Drives with a specific impulse that is both high and fixed such as Ion thrusters have exhaust velocities that can be enormously higher than this ideal for many missions.

- if the exhaust velocity can be made to vary so that at each instant it is equal and opposite to the vehicle velocity then the absolute minimum energy usage is achieved. When this is achieved, the exhaust stops in space and has no kinetic energy; and the propulsive efficiency is 100%- all the energy ends up in the vehicle (in principle such a drive would be 100% efficient, in practice there would be thermal losses from within the drive system and residual heat in the exhaust). However in most cases this uses an impractical quantity of propellant, but is a useful theoretical consideration. Anyway the vehicle has to move before the method can be applied.

Some drives (such as VASIMR or Electrodeless plasma thruster) actually can significantly vary their exhaust velocity. This can help reduce propellant usage or improve acceleration at different stages of the flight. However the best energetic performance and acceleration is still obtained when the exhaust velocity is close to the vehicle speed. Proposed ion and plasma drives usually have exhaust velocities enormously higher than that ideal (in the case of VASIMR the lowest quoted speed is around 15000 m/s compared to a mission delta-v from high Earth orbit to Mars of about 4000m/s).

It might be thought that adding power generation capacity is helpful, and while initially this can improve performance, this inevitably increases the weight of the power source, and eventually the mass of the power source and the associated engines and propellant dominates the weight of the vehicle, and then adding more power gives no significant improvement.

For, although solar power and nuclear power are virtually unlimited sources of *energy*, the maximum *power* they can supply is substantially proportional to the mass of the powerplant (i.e. specific power takes a largely constant value which is dependent on the particular powerplant technology). For any given specific power, with a large v_e which is desirable to save propellant mass, it turns out that the maximum acceleration is inversely proportional to v_e . Hence the time to reach a required delta-v is proportional to v_e . Thus the latter should not be too large.

Power to thrust ratio

The power to thrust ratio is simply:

$$\frac{P}{F} = \frac{\frac{1}{2}\dot{m}v^2}{\dot{m}v} = \frac{1}{2}v$$

Thus for any vehicle power P, the thrust that may be provided is:

$$\frac{P}{\frac{1}{2}v} = \frac{2P}{v}$$

Example

Suppose we want to send a 10,000 kg space probe to Mars. The required Δv from LEO is approximately 3000 m/s, using a Hohmann transfer orbit. (A manned craft 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 (km/s)	Specific impulse (s)	Fuel mass (kg)	Energy required (GJ)	Energy per kg of propellant	minimum power/thrust	Power generat or mass/th rust*
Solid rocket	1	100	190,000	95	500 kJ	0.5 kW/N	N/A
Bipropellant rocket	5	500	8,200	103	12.6 MJ	2.5 kW/N	N/A
Ion thruster	50	5,000	620	775	1.25 GJ	25 kW/N	25 kg/N
Advance electrically powered drive	1,000	100,000	30	15,000	500 GJ	500 kW/N	500 kg/N

* - assumes a specific power of 1kW/kg

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. For Earth launch, engines require a thrust to weight ratio of more than one. To do this with the ion or more theoretical electrical drives, the engine would have to be supplied with one to several gigawatts of power — equivalent to a major metropolitan generating station. From the table it can be seen that this is clearly impractical with current power sources.

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, and would be insufficient for launching from the Earth. However, over long periods in orbit where there is no friction, 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 needs much less fuel, the total launched mass is usually lower, which typically results in a lower overall cost, but takes longer.

Mission planning therefore frequently involves adjusting and choosing the propulsion system so as to minimise the total cost of the project, and can involve trading off launch costs and mission duration against payload fraction.

Rocket engines



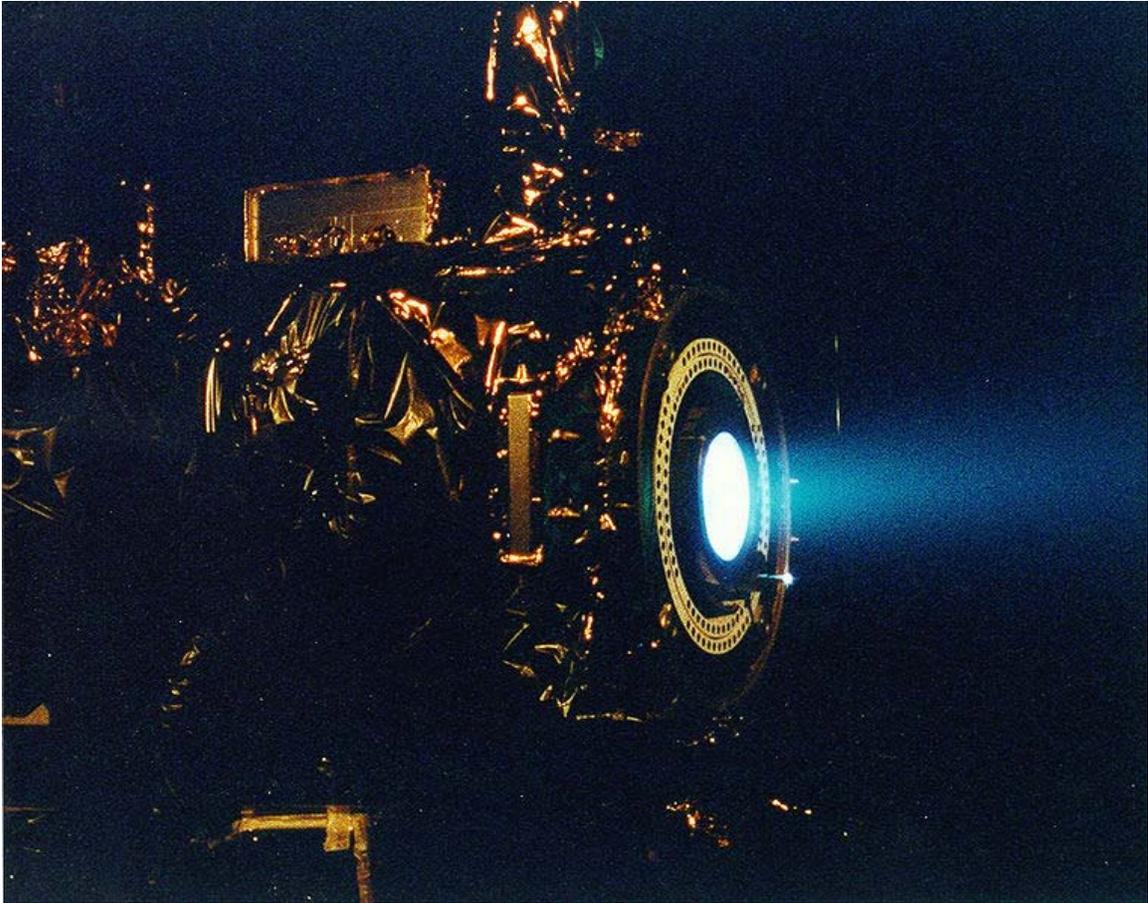
SpaceX's Kestrel engine is tested

Most rocket engines are internal combustion heat engines (although non combusting forms exist). Rocket engines generally produce a high temperature reaction mass, as a hot gas. This is achieved by combusting a solid, liquid or gaseous fuel with an oxidiser within a combustion chamber. The extremely hot gas is then allowed to escape through a high-expansion ratio nozzle. This bell-shaped nozzle is what gives a rocket engine its characteristic shape. The effect of the nozzle is to dramatically accelerate the mass, converting most of the thermal energy into kinetic energy. Exhaust speed reaching as high as 10 times the speed of sound at sea level are common.

Rocket engines provide essentially the highest specific powers and high specific thrusts of any engine used for spacecraft propulsion.

Ion propulsion rockets can heat a plasma or charged gas inside a magnetic bottle and release it 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 proposed to be used in propulsion systems, and some have been tested in a lab.

Electromagnetic propulsion



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 typically uses electric power, first to ionize atoms, and then to create a voltage gradient to accelerate the ions to high exhaust velocities.

The idea of electric propulsion dates back to 1906, when Robert Goddard considered the possibility in his personal notebook. Konstantin Tsiolkovsky published the idea in 1911.

For these drives, at the highest exhaust speeds, energetic efficiency and thrust are all inversely proportional to exhaust velocity. Their very high exhaust velocity means they require huge amounts of energy and thus with practical power sources provide low thrust, but use hardly any fuel.

For some missions, particularly reasonably close to the Sun, solar energy may be sufficient, and has very often been used, but for others further out or at higher power, nuclear energy is necessary; engines drawing their power from a nuclear source are called nuclear electric rockets.

With any current source of electrical power, chemical, nuclear or solar, the maximum amount of power that can be generated limits the amount of thrust that can be produced to a small value. Power generation adds significant mass to the spacecraft, and ultimately the weight of the power source limits the performance of the vehicle.

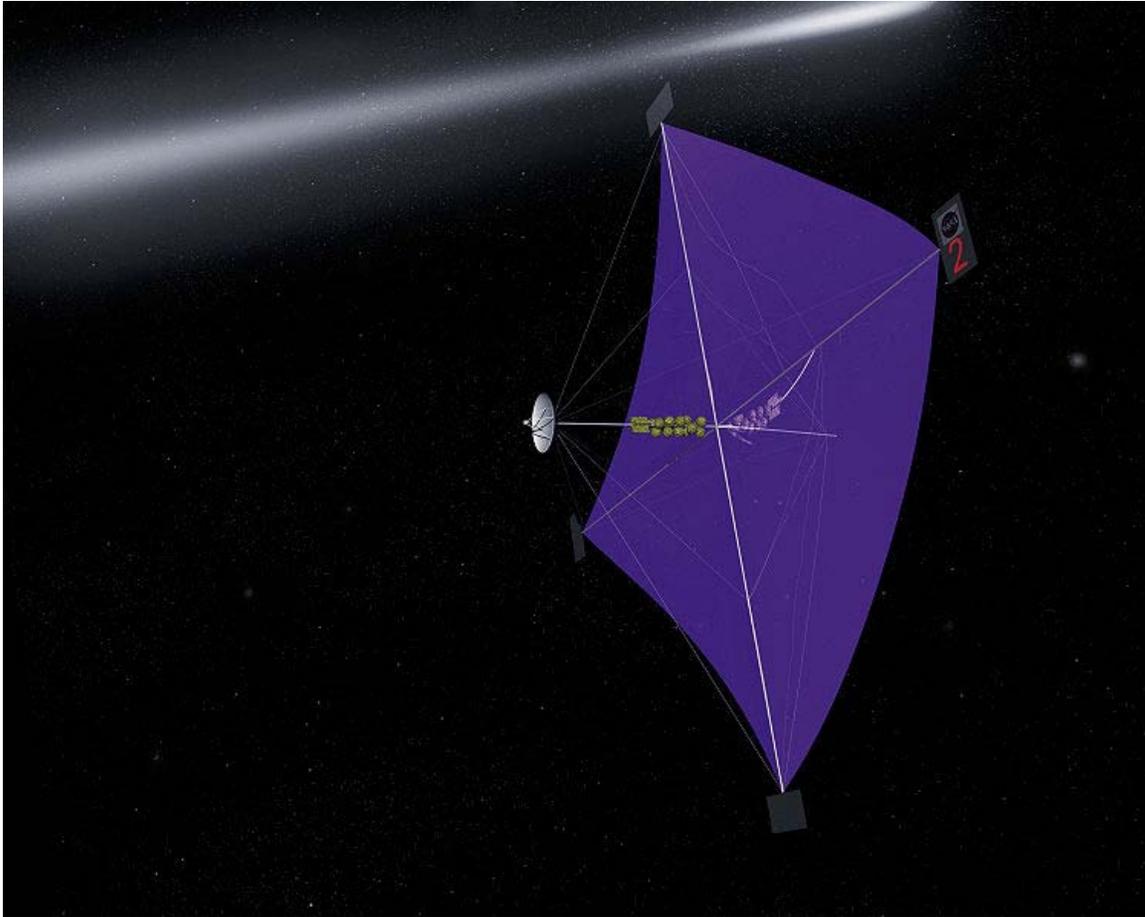
Current nuclear power generators are approximately half the weight of solar panels per watt of energy supplied, at terrestrial distances from the Sun. Chemical power generators are not used due to the far lower total available energy. Beamed power to the spacecraft shows some potential. However, the dissipation of waste heat from any power plant may make any propulsion system requiring a separate power source infeasible for interstellar travel.

Some electromagnetic methods:

- Ion thrusters (accelerate ions first and later neutralize the ion beam with an electron stream emitted from a cathode called a neutralizer)
 - Electrostatic ion thruster
 - Field Emission Electric Propulsion
 - Hall effect thruster
 - Colloid thruster
- Electrothermal thrusters (electromagnetic fields are used to generate a plasma to increase the heat of the bulk propellant, the thermal energy imparted to the propellant gas is then converted into kinetic energy by a nozzle of either physical material construction or by magnetic means)
 - DC arcjet
 - microwave arcjet
 - Pulsed plasma thruster
 - Helicon Double Layer Thruster
- Electromagnetic thrusters (ions are accelerated either by the Lorentz Force or by the effect of electromagnetic fields where the electric field is not in the direction of the acceleration)
 - Magnetoplasmadynamic thruster
 - Electrodeless plasma thruster
 - Pulsed inductive thruster
 - Variable specific impulse magnetoplasma rocket (VASIMR)
- Mass drivers (for propulsion)

In electrothermal and electromagnetic thrusters, both ions and electrons are accelerated simultaneously, no neutralizer is required.

Without internal 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 accelerate 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 System; there are gravitation fields, magnetic fields, solar wind and solar radiation. Various propulsion methods try to take advantage of these. However, since these phenomena are diffuse in nature, corresponding propulsion structures need to be proportionately large.

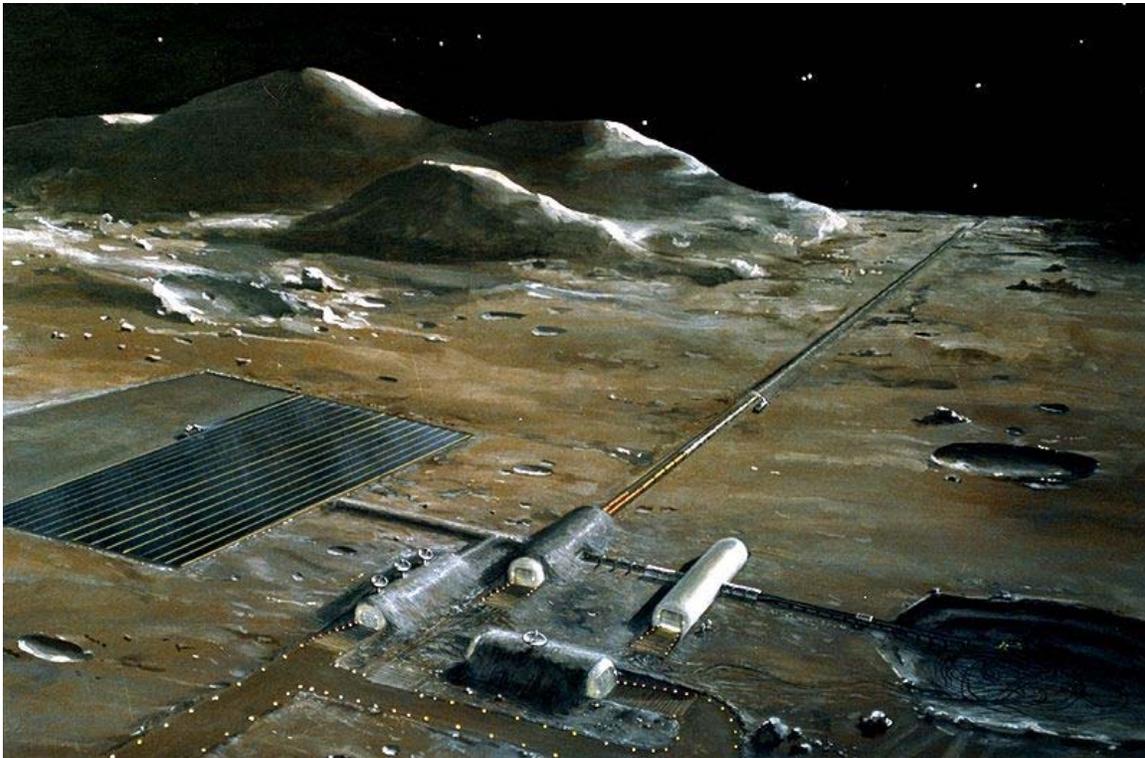
There are several different space drives that need little or no reaction mass to function. A tether propulsion system employs a long cable with a high tensile strength to change a spacecraft's orbit, such as by interaction with a planet's magnetic field or through momentum exchange with another object. Solar sails rely on radiation pressure from electromagnetic energy, but they require a large collection surface to function effectively. The magnetic sail deflects charged particles from the solar wind with a magnetic field, thereby imparting momentum to the spacecraft. A variant is the mini-magnetospheric plasma propulsion system, which uses a small cloud of plasma held in a magnetic field to deflect the Sun's charged particles.

A satellite or other space vehicle is subject to the law of conservation of angular momentum, which constrains a body from a net change in angular velocity. Thus, for a vehicle to change its relative orientation without expending reaction mass, another part of the vehicle may rotate in the opposite direction. Non-conservative external forces, primarily gravitational and atmospheric, can contribute up to several degrees per day to angular momentum, so secondary systems are designed to "bleed off" undesired rotational energies built up over time. Accordingly, many spacecraft utilize reaction wheels or control moment gyroscopes to control orientation in space.

A gravitational slingshot can carry a space probe onward to other destinations without the expense of reaction mass. By harnessing the gravitational energy of other celestial objects, the spacecraft can pick up kinetic energy. However, even more energy can be obtained from the gravity assist if rockets are used.

Planetary and atmospheric propulsion

Launch mechanisms



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

High thrust is of vital importance for Earth launch, thrust has to be greater than weight. Many of the propulsion methods above give a thrust/weight ratio of much less than 1, and so cannot be used for launch.

All current spacecraft use chemical rocket engines (bipropellant or solid-fuel) for launch. Other power sources such as nuclear have been proposed and tested, but safety, environmental and political considerations have so far curtailed their use.

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

- Space elevator (a geostationary tether to orbit)
- Launch loop (a very fast enclosed rotating loop about 80 km tall)
- Space fountain (a very tall building held up by a stream of masses fired from base)
- Orbital ring (a ring around the Earth with spokes hanging down off bearings)
- Hypersonic skyhook (a fast spinning orbital tether)
- Electromagnetic catapult (railgun, coilgun) (an electric gun)
- Rocket sled launch
- Space gun (Project HARP, ram accelerator) (a chemically powered gun)
- Beam-powered propulsion rockets and jets powered from ground via a beam
- High Altitude Platforms to assist initial stage

Airbreathing engines

Studies generally show that conventional air-breathing engines, such as ramjets or turbojets are basically too heavy (have too low a thrust/weight ratio) to give any significant performance improvement when installed on a launch vehicle itself. However, launch vehicles can be air launched from separate lift vehicles (e.g. B-29, Pegasus Rocket and White Knight) which do use such propulsion systems. Jet engines mounted on a launch rail could also be so used.

On the other hand, very lightweight or very high speed engines have been proposed that take advantage of the air during ascent:

- SABRE - a lightweight hydrogen fuelled turbojet with precooler
- ATREX - a lightweight hydrogen fuelled turbojet with precooler
- Liquid air cycle engine - a hydrogen fuelled jet engine that liquifies the air before burning it in a rocket engine
- Scramjet - jet engines that use supersonic combustion

Normal rocket launch vehicles fly almost vertically before rolling over at an altitude of some tens of kilometers before burning sideways for orbit; this initial vertical climb wastes propellant but is optimal as it greatly reduces air drag. Airbreathing engines burn propellant much more efficiently and this would permit a far flatter launch trajectory, the vehicles would typically fly approximately tangentially to the earth surface until leaving the atmosphere then perform a rocket burn to bridge the final delta-v to orbital velocity.

Planetary arrival and landing



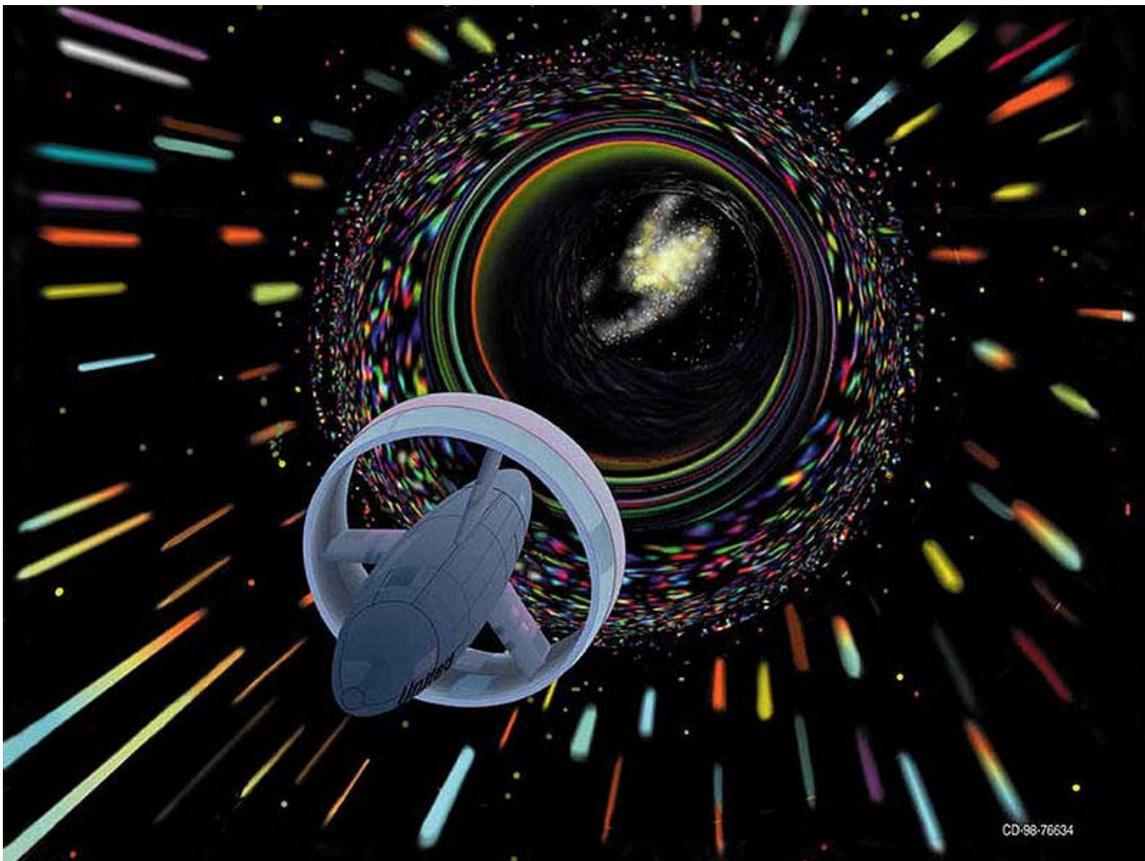
A test version of the MARS Pathfinder airbag system

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 and/or surfaces.

- Aerobraking allows a spacecraft to reduce the high point of an elliptical orbit by repeated brushes with the atmosphere at the low point of the orbit. This can save a considerable amount of fuel since it takes much less delta-V to enter an elliptical orbit compared to a low circular orbit. Since the braking is done over the course of many orbits, heating is comparatively minor, and a heat shield is not required. This has been done on several Mars missions such as Mars Global Surveyor, Mars Odyssey and Mars Reconnaissance Orbiter, and at least one Venus mission, Magellan.
- Aerocapture is a much more aggressive manoeuvre, converting an incoming hyperbolic orbit to an elliptical orbit in one pass. This requires a heat shield and much trickier navigation, since it must be completed in one pass through the atmosphere, and unlike aerobraking no preview of the atmosphere is possible. If the intent is to remain in orbit, then at least one more propulsive maneuver is required after aerocapture—otherwise the low point of the resulting orbit will remain in the atmosphere, resulting in eventual re-entry. Aerocapture has not yet been tried on a planetary mission, but the re-entry skip by Zond 6 and Zond 7 upon lunar return were aerocapture maneuvers, since they turned a hyperbolic orbit into an elliptical orbit. On these missions, since there was no attempt to raise

- the perigee after the aerocapture, the resulting orbit still intersected the atmosphere, and re-entry occurred at the next perigee.
- a Ballute is an inflatable drag device
 - Parachutes can land a probe on a planet with an atmosphere, usually after the atmosphere has scrubbed off most of the velocity, using a heat shield.
 - Airbags can soften the final landing.
 - Lithobraking, or stopping by simply smashing into the target, is usually done by accident. However, it may be done deliberately with the probe expected to survive (see, for example, Deep Space 2), in which case very sturdy probes and low approach velocities are required.

Hypothetical methods



Artist's conception of a warp drive design

A variety of hypothetical propulsion techniques have been considered that would require entirely new principles of physics to realize and that may not actually be possible. To date, such methods are highly speculative and include:

- Diametric drive
- Pitch drive

- Bias drive
- Disjunction drive
- Alcubierre drive (a form of Warp drive)
- Differential sail
- Wormholes - theoretically possible, but unachievable in practice with current technology
- Reactionless drives - breaks the law of conservation of momentum; theoretically impossible
- EmDrive - tries to circumvent the law of conservation of momentum; may be theoretically impossible
- A "hyperspace" drive based upon Heim theory

A NASA assessment is found at Marc G Millis *Assessing potential propulsion breakthroughs* (2005)

Chapter- 2

Launch Mechanisms



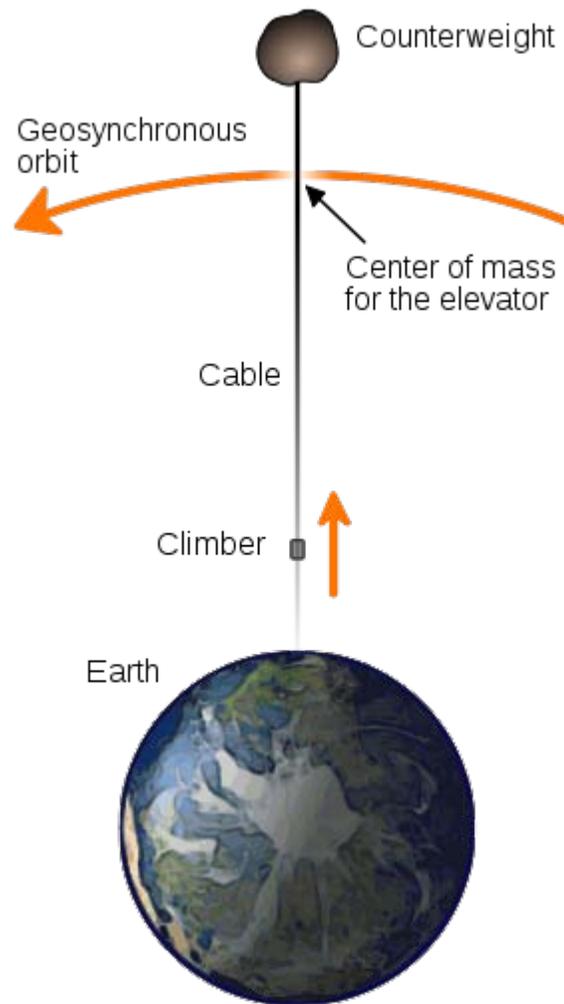
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Space elevator



A space elevator for Earth would consist of a cable anchored to the Earth's surface, reaching into space. By attaching a counterweight at the end (or by further extending the cable for the same purpose), inertia ensures that the cable remains stretched taut, countering the gravitational pull on the lower sections, thus allowing the elevator to remain in geostationary orbit. Once beyond the gravitational midpoint, carriages would be accelerated further by the planet's rotation. (Diagram is not to scale.)

A **space elevator** is a proposed non-rocket spacelaunch structure (a structure designed to transport material from a celestial body's surface into space). Many elevator variants have been suggested, all of which involve travelling along a fixed structure instead of using rocket powered space launch. The concept most often refers to a cable that reaches from

the surface of the Earth on or near the Equator to geostationary orbit (GSO) and a counter-mass outside of the atmosphere.

The concept of a space elevator dates back to 1895 when Konstantin Tsiolkovsky proposed a free-standing "Tsiolkovsky" tower reaching from the surface of Earth to geostationary orbit. Most recent discussions focus on tensile structures (specifically, tethers) reaching from geostationary orbit to the ground. This structure would be held in tension between Earth and the counterweight in space like a guitar string held taut. Space elevators have also sometimes been referred to as *beanstalks*, *space bridges*, *space lifts*, *space ladders*, *skyhooks*, *orbital towers*, or *orbital elevators*.

While some variants of the space elevator concept are technologically feasible, current technology is not capable of manufacturing practical engineering materials that are sufficiently strong and light to build an Earth-based space elevator of the geostationary orbital tether type. Recent conceptualizations for a space elevator are notable in their plans to use carbon nanotube or boron nitride nanotube based materials as the tensile element in the tether design, since the measured strength of microscopic carbon nanotubes appears great enough to make this possible. Technology as of 1978 could produce elevators for locations in the solar system with weaker gravitational fields, such as the Moon or Mars.

A further issue is that for human riders on an Earth-based elevator, space radiation due to the Van Allen belts would, if unshielded, give a dose well above permitted levels. This would not be an issue for non-living cargo, however.

Geostationary orbital tethers

This concept, also called an **orbital space elevator**, **geostationary orbital tether**, or a **beanstalk**, is a subset of the skyhook concept, and is what people normally think of when the phrase 'space elevator' is used (although there are variants).

Construction would be a large project: the minimum length of an Earth-based space elevator is well over 38,000 km (24,000 mi) long. The tether would have to be built of a material that could endure tremendous stress while also being light-weight, cost-effective, and manufacturable in great quantities. Materials currently available do not meet these requirements, although carbon nanotube technology shows great promise. As with all leading-edge engineering projects, other novel engineering problems would also have to be solved to make a space elevator practical, and there are problems regarding feasibility that have yet to be addressed. Nevertheless, the LiftPort Group stated in 2002 that by developing the technology, the first space elevator could be operational by 2014.

History



Konstantin Tsiolkovsky

Early concepts

The key concept of the space elevator appeared in 1895 when Russian scientist Konstantin Tsiolkovsky was inspired by the Eiffel Tower in Paris to consider a tower that reached all the way into space, built from the ground up to an altitude of 35,790 kilometers (22,238 mi) above sea level (geostationary orbit). He noted that a "celestial castle" at the top of such a spindle-shaped cable would have the "castle" orbiting Earth in a geostationary orbit (i.e. the castle would remain over the same spot on Earth's surface).

Tsiolkovsky's tower would be able to launch objects into orbit without a rocket. Since the elevator would attain orbital velocity as it rode up the cable, an object released at the tower's top would also have the orbital velocity necessary to remain in geostationary orbit. Unlike more recent concepts for space elevators, Tsiolkovsky's (conceptual) tower was a compression structure, rather than a tension (or "tether") structure.

Twentieth century

Building a compression structure from the ground up proved an unrealistic task as there was no material in existence with enough compressive strength to support its own weight under such conditions. In 1959 another Russian scientist, Yuri N. Artsutanov, suggested a more feasible proposal. Artsutanov suggested using a geostationary satellite as the base from which to deploy the structure downward. By using a counterweight, a cable would be lowered from geostationary orbit to the surface of Earth, while the counterweight was extended from the satellite away from Earth, keeping the center of gravity of the cable motionless relative to Earth. Artsutanov's idea was introduced to the Russian-speaking public in an interview published in the Sunday supplement of *Komsomolskaya Pravda* in 1960, but was not available in English until much later. He also proposed tapering the

cable thickness so that the tension in the cable was constant—this gives a thin cable at ground level, thickening up towards GSO.

Both the tower and cable ideas were proposed in the quasi-humorous *Ariadne* column in *New Scientist*, 24 December 1964.

Making a cable over 35,000 kilometers (22,000 miles) long is a difficult task. In 1966, Isaacs, Vine, Bradner and Bachus, four American engineers, reinvented the concept, naming it a "Sky-Hook," and published their analysis in the journal *Science*. They decided to determine what type of material would be required to build a space elevator, assuming it would be a straight cable with no variations in its cross section, and found that the strength required would be twice that of any existing material including graphite, quartz, and diamond.

In 1975 an American scientist, Jerome Pearson, reinvented the concept yet again, publishing his analysis in the journal *Acta Astronautica*. He designed a tapered cross section that would be better suited to building the elevator. The completed cable would be thickest at the geostationary orbit, where the tension was greatest, and would be narrowest at the tips to reduce the amount of weight per unit area of cross section that any point on the cable would have to bear. He suggested using a counterweight that would be slowly extended out to 144,000 kilometers (90,000 miles, almost half the distance to the Moon) as the lower section of the elevator was built. Without a large counterweight, the upper portion of the cable would have to be longer than the lower due to the way gravitational and centrifugal forces change with distance from Earth. His analysis included disturbances such as the gravitation of the Moon, wind and moving payloads up and down the cable. The weight of the material needed to build the elevator would have required thousands of Space Shuttle trips, although part of the material could be transported up the elevator when a minimum strength strand reached the ground or be manufactured in space from asteroidal or lunar ore.

In 1977, Hans Moravec published an article called "A Non-Synchronous Orbital Skyhook", in which he proposed an alternative space elevator concept, using a rotating cable, in which the rotation speed exactly matches the orbital speed in such a way that the instantaneous velocity at the point where the cable was at the closest point to the Earth was zero. This concept is an early version of a space tether transportation system.

In 1979, space elevators were introduced to a broader audience with the simultaneous publication of Arthur C. Clarke's novel, *The Fountains of Paradise*, in which engineers construct a space elevator on top of a mountain peak in the fictional island country of *Taprobane* (loosely based on Sri Lanka, albeit moved south to the Equator), and Charles Sheffield's first novel, *The Web Between the Worlds*, also featuring the building of a space elevator. Three years later, in Robert A. Heinlein's 1982 novel *Friday* the principal character makes use of the "Nairobi Beanstalk" in the course of her travels. In Kim Stanley Robinson's 1993 novel *Red Mars*, colonists build a space elevator on Mars that allows both for more colonists to arrive on Mars and also for natural resources mined on Mars to be able to leave Mars for Earth.

21st century

After the development of carbon nanotubes in the 1990s, engineer David Smitherman of NASA/Marshall's Advanced Projects Office realized that the high strength of these materials might make the concept of an orbital skyhook feasible, and put together a workshop at the Marshall Space Flight Center, inviting many scientists and engineers to discuss concepts and compile plans for an elevator to turn the concept into a reality. The publication he edited, compiling information from the workshop, "Space Elevators: An Advanced Earth-Space Infrastructure for the New Millennium", provides an introduction to the state of the technology at the time, and summarizes the findings.

Another American scientist, Bradley C. Edwards, suggested creating a 100,000 km (62,000 mi) long paper-thin ribbon using a carbon nanotube composite material. He chose a ribbon type structure rather than a cable because that structure might stand a greater chance of surviving impacts by meteoroids. Supported by the NASA Institute for Advanced Concepts, the work of Edwards was expanded to cover the deployment scenario, climber design, power delivery system, orbital debris avoidance, anchor system, surviving atomic oxygen, avoiding lightning and hurricanes by locating the anchor in the western equatorial Pacific, construction costs, construction schedule, and environmental hazards. The largest holdup to Edwards' proposed design is the technological limit of the tether material. His calculations call for a fiber composed of epoxy-bonded carbon nanotubes with a minimal tensile strength of 130 GPa (19 million psi) (including a safety factor of 2); however, tests in 2000 of individual single-walled carbon nanotubes (SWCNTs), which should be notably stronger than an epoxy-bonded rope, indicated the strongest measured as 52 GPa (7.5 million psi). Multi-walled carbon nanotubes have been measured with tensile strengths up to 63 GPa (9 million psi).

To speed space elevator development, proponents are planning several competitions, similar to the Ansari X Prize, for relevant technologies. Among them are Elevator:2010, which will organize annual competitions for climbers, ribbons and power-beaming systems, the Robolympics Space Elevator Ribbon Climbing competition, as well as NASA's Centennial Challenges program, which, in March 2005, announced a partnership with the Spaceward Foundation (the operator of Elevator:2010), raising the total value of prizes to US\$400,000.

In 2005, "the LiftPort Group of space elevator companies announced that it will be building a carbon nanotube manufacturing plant in Millville, New Jersey, to supply various glass, plastic and metal companies with these strong materials. Although LiftPort hopes to eventually use carbon nanotubes in the construction of a 100,000 km (62,000 mile) space elevator, this move will allow it to make money in the short term and conduct research and development into new production methods. The space elevator is proposed to launch in 2010." On February 13, 2006 the LiftPort Group announced that, earlier the same month, they had tested a mile of "space-elevator tether" made of carbon-fiber composite strings and fiberglass tape measuring 5 cm (2 in) wide and 1 mm (approx. 6 sheets of paper) thick, lifted with balloons.

In 2007, Elevator:2010 held the 2007 Space Elevator games, which featured US\$500,000 awards for each of the two competitions, (US\$1,000,000 total) as well as an additional US\$4,000,000 to be awarded over the next five years for space elevator related technologies. No teams won the competition, but a team from MIT entered the first 2-gram (0.07 oz), 100% carbon nanotube entry into the competition. Japan held an international conference in November 2008 to draw up a timetable for building the elevator.

In 2008 the book "Leaving the Planet by Space Elevator", by Dr. Brad Edwards and Philip Ragan, was published in Japanese and entered the Japanese best seller list. This has led to a Japanese announcement of intent to build a Space Elevator at a projected price tag of £5 billion. In a report by Leo Lewis, Tokyo correspondent of The Times newspaper in England, plans by Shuichi Ono, chairman of the Japan Space Elevator Association, are unveiled. Lewis says: "Japan is increasingly confident that its sprawling academic and industrial base can solve those [construction] issues, and has even put the astonishingly low price tag of a trillion yen (£5 billion/ \$8 billion) on building the elevator. Japan is renowned as a global leader in the precision engineering and high-quality material production without which the idea could never be possible."

Structure



One concept for the space elevator has it tethered to a mobile seagoing platform.

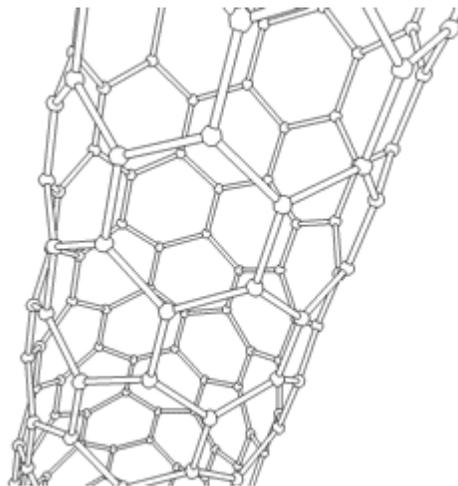
The centrifugal force of earth's rotation is the main principle behind the elevator. As the earth rotates, the centrifugal force tends to align the nanotube in a stretched manner. There are a variety of tether designs. Almost every design includes a base station, a cable, climbers, and a counterweight.

Base station

The base station designs typically fall into two categories—mobile and stationary. Mobile stations are typically large oceangoing vessels. Stationary platforms would generally be located in high-altitude locations, such as on top of mountains, or even potentially on high towers.

Mobile platforms have the advantage of being able to maneuver to avoid high winds, storms, and space debris. While stationary platforms don't have these advantages, they typically would have access to cheaper and more reliable power sources, and require a shorter cable. While the decrease in cable length may seem minimal (no more than a few kilometers), the cable thickness could be reduced over its entire length, significantly reducing the total weight.

Cable



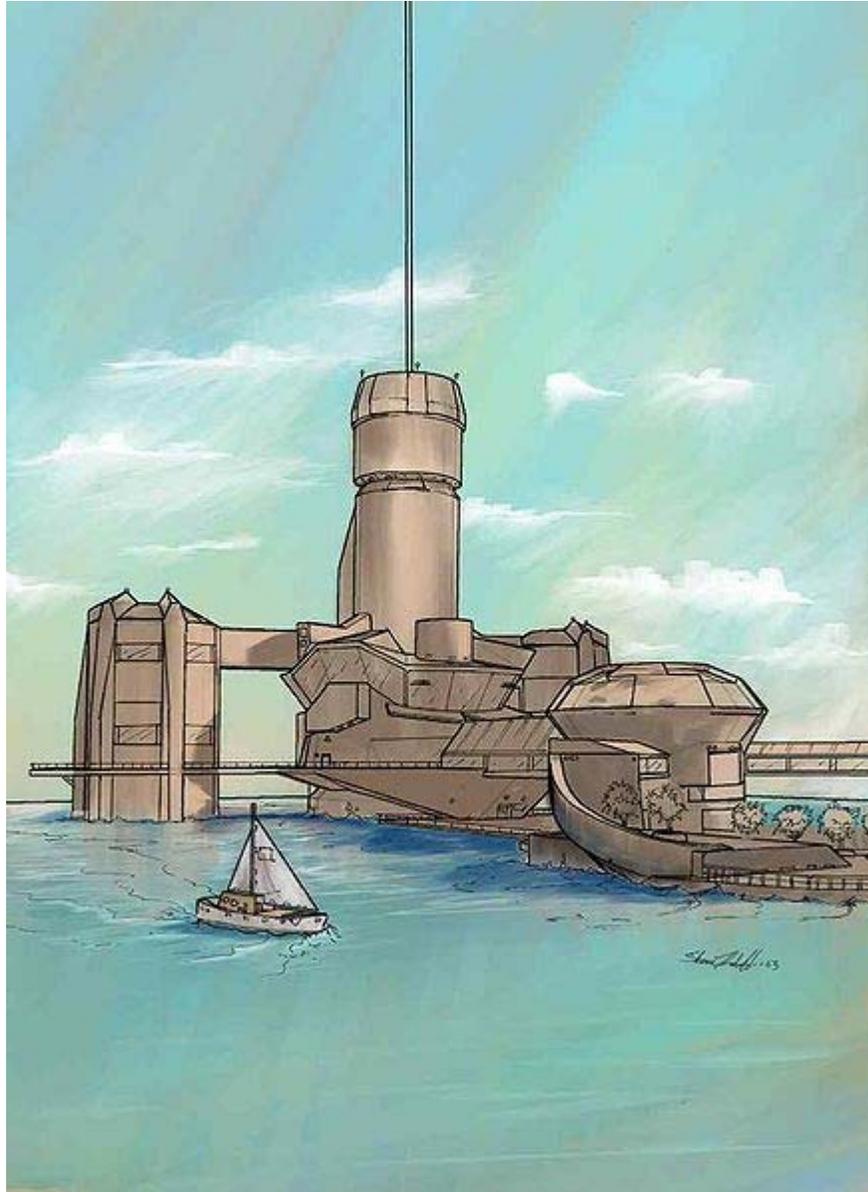
Carbon nanotubes are one of the candidates for a cable material

A space elevator cable must carry its own weight as well as the (smaller) weight of climbers. The required strength of the cable will vary along its length, since at various points it has to carry the weight of the cable below, or provide a centripetal force to retain the cable and counterweight above. In a 1998 report, NASA researchers noted that "maximum stress [*sic*] [on a space elevator cable] is at geosynchronous altitude so the cable must be thickest there and taper exponentially as it approaches Earth. Any potential material may be characterized by the taper factor – the ratio between the cable's radius at geosynchronous altitude and at the Earth's surface."

The cable must be made of a material with a large tensile strength/mass ratio. For example, the Edwards space elevator design assumes a cable material with a specific strength of at least 100,000 kN/(kg/m). This value takes into consideration the entire weight of the space elevator. A space elevator would need a material capable of sustaining 4,960 kilometers (3082 mi) of its own weight *at sea level* to reach a geostationary altitude of 36,000 km (22,300 mi) without tapering. This is at least necessary value, and about 50,000 kN/(kg/m) if it shows by specific strength. Therefore, a material with very high strength and lightness is needed.

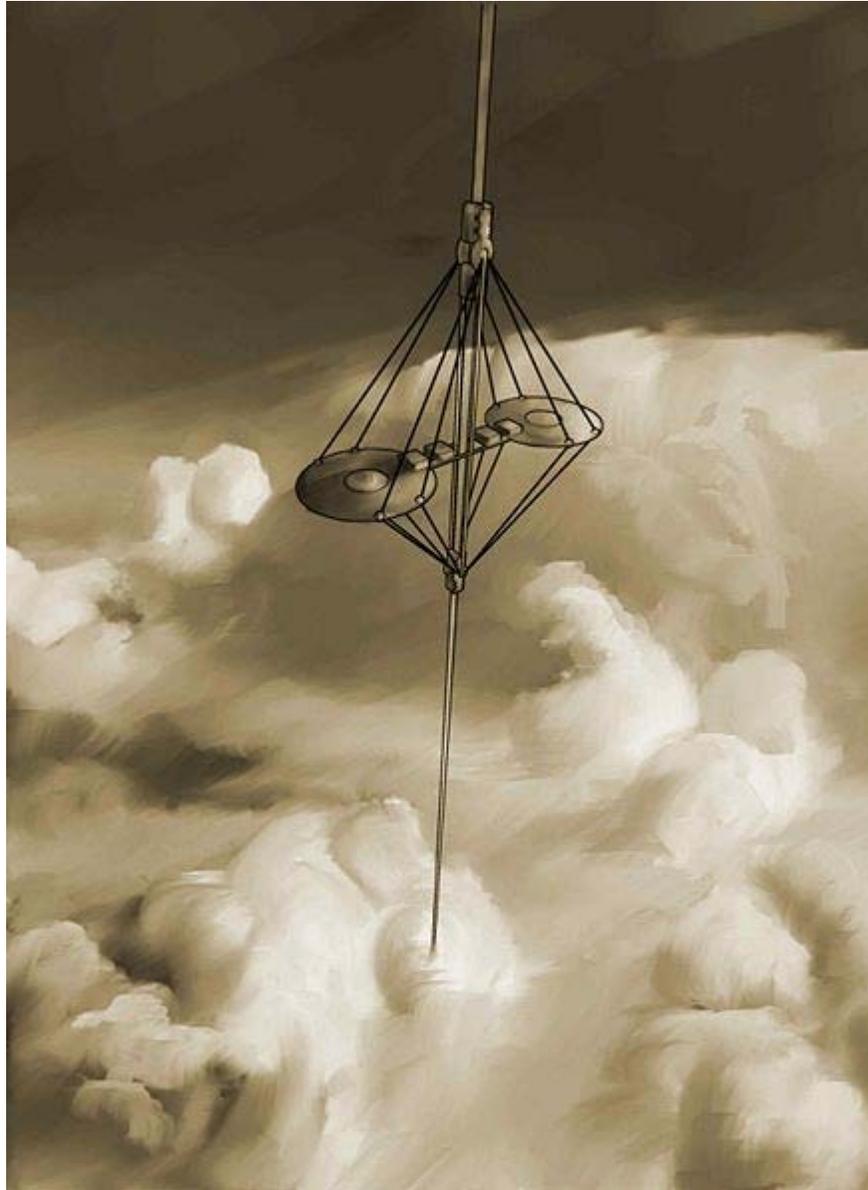
Carbon nanotubes' theoretical tensile strength has been estimated between 140 and 177 GPa (20.3-25.6 million psi) depending on their geometry and its measured tensile strength varies in the range 11–150 GPa (1.6-21.7 million psi), however only on a microscopic scale. The current (2009) technology allows growing tubes up to a few tens of centimeters. This limit can be mitigated by spinning nanotubes into a yarn, but at the price of lowering the cable strength.

The density of carbon nanotubes depends greatly on their packing and can be estimated as 1.3 g/cm³ (0.75 oz/cubic in). Therefore, necessary tensile strength is 65–130 GPa (9.4-18.5 million psi) in density. By comparison, most steel has a tensile strength of under 2 GPa (290,000 psi), and the strongest steel resists no more than 5.5 GPa (798,000 psi). The much lighter material Kevlar has a tensile strength of 2.6–4.1 GPa (377,000-595,000 psi), while quartz fibers can reach 20 GPa (2.9 million psi). Quartz fibers have an advantage that they can be drawn to a length of hundreds of kilometers (270 km—168 mi) even with the present-day technology.



A seagoing anchor station would incidentally act as a deep-water seaport.

Climbers



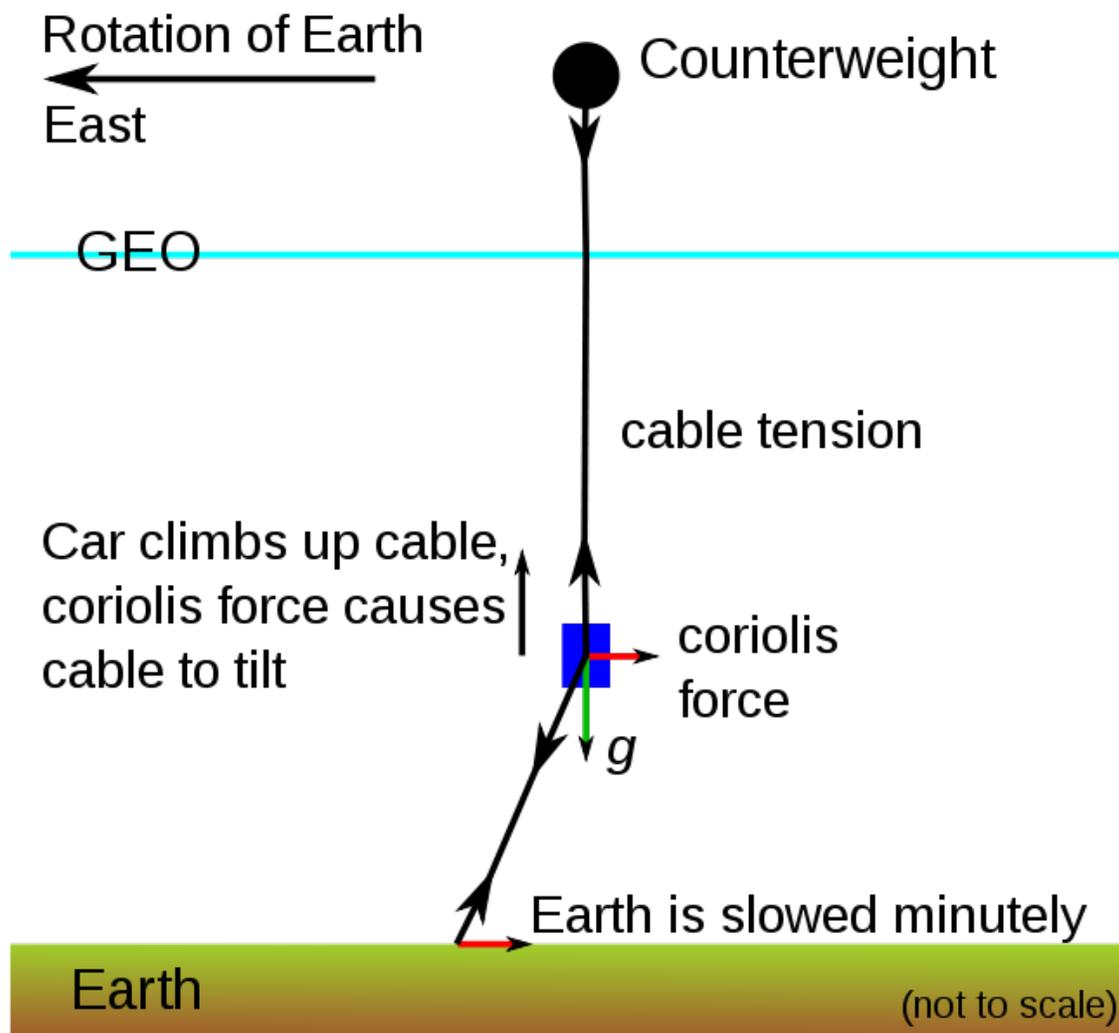
A conceptual drawing of a space elevator climbing through the clouds.

A space elevator cannot be an elevator in the typical sense (with moving cables) due to the need for the cable to be significantly wider at the center than the tips. While various designs employing moving cables have been proposed, most cable designs call for the "elevator" to climb up a stationary cable.

Climbers cover a wide range of designs. On elevator designs whose cables are planar ribbons, most propose to use pairs of rollers to hold the cable with friction.

Climbers must be paced at optimal timings so as to minimize cable stress and oscillations and to maximize throughput. Lighter climbers can be sent up more often, with several

going up at the same time. This increases throughput somewhat, but lowers the mass of each individual payload.



As the car climbs, the elevator takes on a 1 degree lean, due to the top of the elevator traveling faster than the bottom around the Earth (Coriolis force). This diagram is not to scale.

The horizontal speed of each part of the cable increases with altitude, proportional to distance from the center of the Earth, reaching orbital velocity at geostationary orbit. Therefore as a payload is lifted up a space elevator, it needs to gain not only altitude but angular momentum (horizontal speed) as well. This angular momentum is taken from the Earth's own rotation. As the climber ascends it is initially moving slightly more slowly than the cable that it moves onto (Coriolis force) and thus the climber "drags" on the cable.

The overall effect of the centrifugal force acting on the cable causes it to constantly try to return to the energetically favourable vertical orientation, so after an object has been

lifted on the cable the counterweight will swing back towards the vertical like an inverted pendulum . Provided that the space elevator is designed so that the center of weight always stays above geostationary orbit for the maximum climb speed of the climbers, the elevator cannot fall over. Lift and descent operations must be carefully planned so as to keep the pendulum-like motion of the counterweight around the tether point under control.

By the time the payload has reached GEO the angular momentum (horizontal speed) is enough that the payload is in orbit.

The opposite process would occur for payloads descending the elevator, tilting the cable eastwards and insignificantly increasing Earth's rotation speed.

It has also been proposed to use a second cable attached to a platform to lift payload up the main cable, since the lifting device would not have to deal with its own weight against Earth's gravity. Out of the many proposed theories, powering any lifting device also continues to present a challenge.

Another design constraint will be the ascending speed of the climber. As geosynchronous orbit is at 35,786 km (22,236 mi). Assuming the climber can reach the speed of a very fast car or train of 300 km/h (180 mph) it will take 5 days to climb to geosynchronous orbit.

Powering climbers

Both power and energy are significant issues for climbers—the climbers need to gain a large amount of potential energy as quickly as possible to clear the cable for the next payload.

All proposals to get that energy to the climber fall into 3 categories:

- transfer the energy to the climber through wireless energy transfer while it is climbing
- transfer the energy to the climber through some material structure while it is climbing
- store the energy in the climber before it starts—this requires an extremely high specific energy.

Nuclear energy and solar power have been proposed, but generating enough energy to reach the top of the elevator in any reasonable time without weighing too much is not feasible.

The proposed method is laser power beaming, using megawatt powered free electron or solid state lasers in combination with adaptive mirrors approximately 10 m (33 ft) wide and a photovoltaic array on the climber tuned to the laser frequency for efficiency. A

major obstacle for any climber design is the dissipation of the substantial amount of waste heat generated due to the less than perfect efficiency of any of the power methods.

Yoshio Aoki, a professor of precision machinery engineering at Nihon University and director of the Japan Space Elevator Association, suggested including a second cable and using the conductivity of carbon nanotubes to provide power.

Various mechanical means of applying power have also been proposed; such as moving, looped or vibrating cables.

Counterweight

Several solutions have been proposed to act as a counterweight:

1. a heavy, captured asteroid;
2. a space dock, space station or spaceport positioned past geostationary orbit; or
3. an extension of the cable itself far beyond geostationary orbit.

The third idea has gained more support in recent years due to the relative simplicity of the task and the fact that a payload that went to the end of the counterweight-cable would acquire considerable velocity relative to the Earth, allowing it to be launched into interplanetary space.

Additionally, Brad Edwards has proposed that initially elevators would be up-only, and that the elevator cars that are used to thicken the cable could simply be parked at the top of the cable and act as a counterweight.

Alternative concepts

Many different types of structures for accessing space have been suggested. As of 2004, concepts using geostationary tethers seem to be the only space elevator concept that is the subject of active research and commercial interest in space.

The original concept envisioned by Tsiolkovsky was a compression structure, a concept similar to an aerial mast. While such structures might reach the agreed altitude for space (100 km—62 mi), they are unlikely to reach geostationary orbit (35,786 km—22,236 mi). The concept of a Tsiolkovsky tower combined with a classic space elevator cable has been suggested. Other alternatives to a space elevator include an orbital ring, a pneumatic space tower, a space fountain, a launch loop, a Skyhook, a space tether, and a space hoist.

Launching into deep space

The velocities that might be attained at the end of Pearson's 144,000 km (90,000 mi) cable can be determined. The tangential velocity is 10.93 kilometers per second

(6.79 mi/s), which is more than enough to escape Earth's gravitational field and send probes at least as far out as Jupiter. Once at Jupiter a gravitational assist maneuver permits solar escape velocity to be reached.

Extraterrestrial elevators

A space elevator could also be constructed on other planets, asteroids and moons.

A Martian tether could be much shorter than one on Earth. Mars' surface gravity is 38% of Earth's, while it rotates around its axis in about the same time as Earth. Because of this, Martian areostationary orbit is much closer to the surface, and hence the elevator would be much shorter. Current materials are already sufficiently strong to construct such an elevator. However, building a Martian elevator would be a unique challenge because the Martian moon Phobos is in a low orbit, and intersects the Equator regularly (twice every orbital period of 11 h 6 min).

A lunar space elevator can possibly be built with currently available technology about 50,000 kilometers (31,000 miles) long extending through the Earth-Moon L1 point from an anchor point near the center of the visible part of Earth's moon.

On the far side of the moon, a lunar space elevator would need to be very long (more than twice the length of an Earth elevator) but due to the low gravity of the Moon, can be made of existing engineering materials.

Rapidly spinning asteroids or moons could use cables to eject materials to convenient points, such as Earth orbits; or conversely, to eject materials to send the bulk of the mass of the asteroid or moon to Earth orbit or a Lagrangian point. Freeman Dyson, a physicist and mathematician, has suggested using such smaller systems as power generators at points distant from the Sun where solar power is uneconomical. For the purpose of mass ejection, it is not necessary to rely on the asteroid or moon to be rapidly spinning. Instead of attaching the tether to the equator of a rotating body, it can be attached to a rotating hub on the surface. This was suggested in 1980 as a "Rotary Rocket" by Pearson and described very succinctly on the Island One website as a "Tapered Sling".

Construction

The construction of a space elevator would be a vast project requiring advances in engineering, manufacturing, and physical technology.

Safety issues and construction challenges

Radiation exposure to passengers traveling through the Van Allen radiation belts, if unshielded, would give a total exposure above levels considered safe. Adequate shielding would be required for manned transits.

A space elevator would present a navigational hazard, both to aircraft and spacecraft. Aircraft could be diverted by air-traffic control restrictions. All objects in stable orbits that have perigee below the maximum altitude of the cable that are not synchronous with the cable will impact the cable eventually, unless avoiding action is taken. For spacecraft one potential solution proposed by Edwards is to use a movable anchor (a sea anchor) to allow the tether to "dodge" any space debris large enough to track.

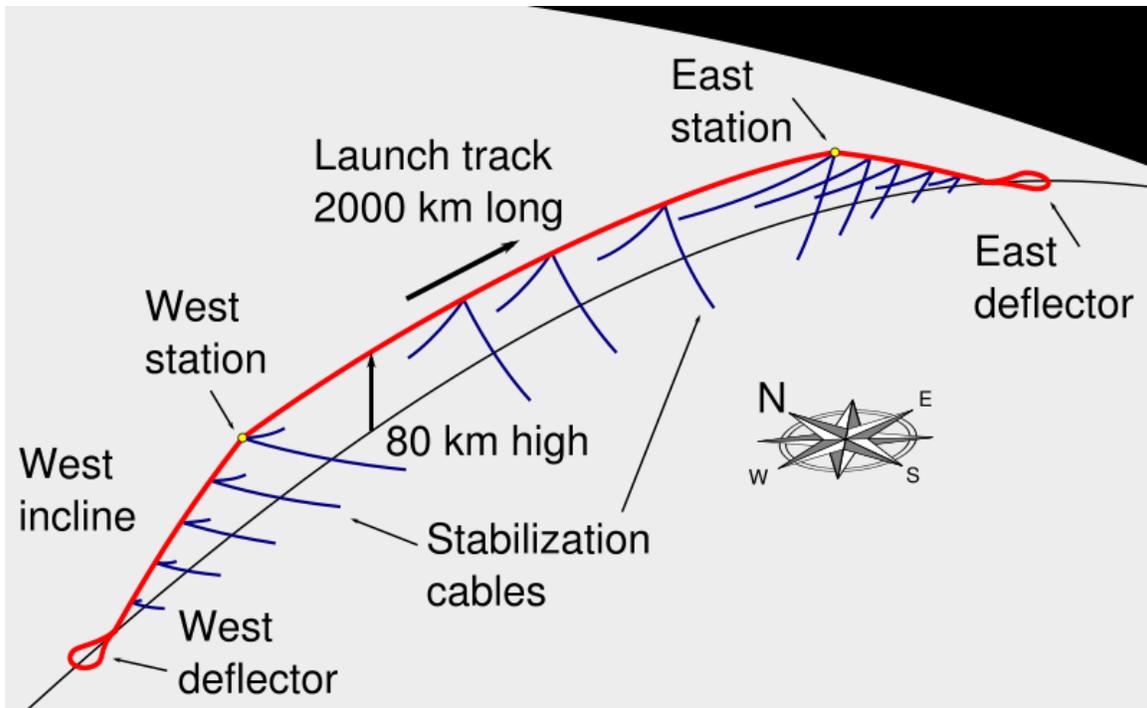
Impacts by space objects such as meteoroids, micrometeorites and orbiting man-made debris, pose a more difficult problem, because the potential of a strand break to cause a failure cascade is, according to Tom Nugent, the Research Director of LiftPort Inc., "A potential show-stopper for construction of the space elevator [that] has not yet been adequately addressed." .

Economics

With a space elevator, materials might be sent into orbit at a fraction of the current cost. As of 2000, conventional rocket designs cost about \$11,000 per pound (\$25,000 per kilogram) for transfer to geostationary orbit. Current proposals envision payload prices starting as low as \$100 per pound (\$220 per kilogram), similar to the \$5–\$300/kg estimates of the Launch loop, although nowhere near the \$310/ton to 500 km orbit quoted to Dr. Jerry Pournelle for an orbital airship system.

Philip Ragan, co-author of the book "Leaving the Planet by Space Elevator", states that "The first country to deploy a space elevator will have a 95 percent cost advantage and could potentially control all space activities."

Launch loop



Launch loop. (Not to scale). The red marked line is the moving loop itself, blue lines are stationary cables.

A **launch loop** or **Lofstrom loop** is a published design for an active structure maglev cable transport system intended for orbital launch that would be around 2,000 km (1,240 mi) long and maintained at an altitude of up to 80 km (50 mi). A launch loop would be held up at this altitude by momentum of the belt as it circulates around the structure. This circulation, in effect, transfers the weight of the structure onto a pair of magnetic bearings, one at each end, which support it.

Launch loops are intended to achieve non-rocket spacelaunch of vehicles weighing 5 metric tons by electromagnetically accelerating them so that they are projected into Earth orbit or even beyond. This would be achieved by the flat part of the cable which forms an acceleration track above the atmosphere.

The published cost estimates for a working launch loop are significantly lower than a space elevator and additionally the proposed system has a greater launch capacity, lower payload costs and similar or greater payload masses. Unlike the space elevator, no new materials need to be developed.

The system is designed to be suitable for launching humans for space tourism, space exploration and space colonization, and provides a relatively low 3g acceleration.

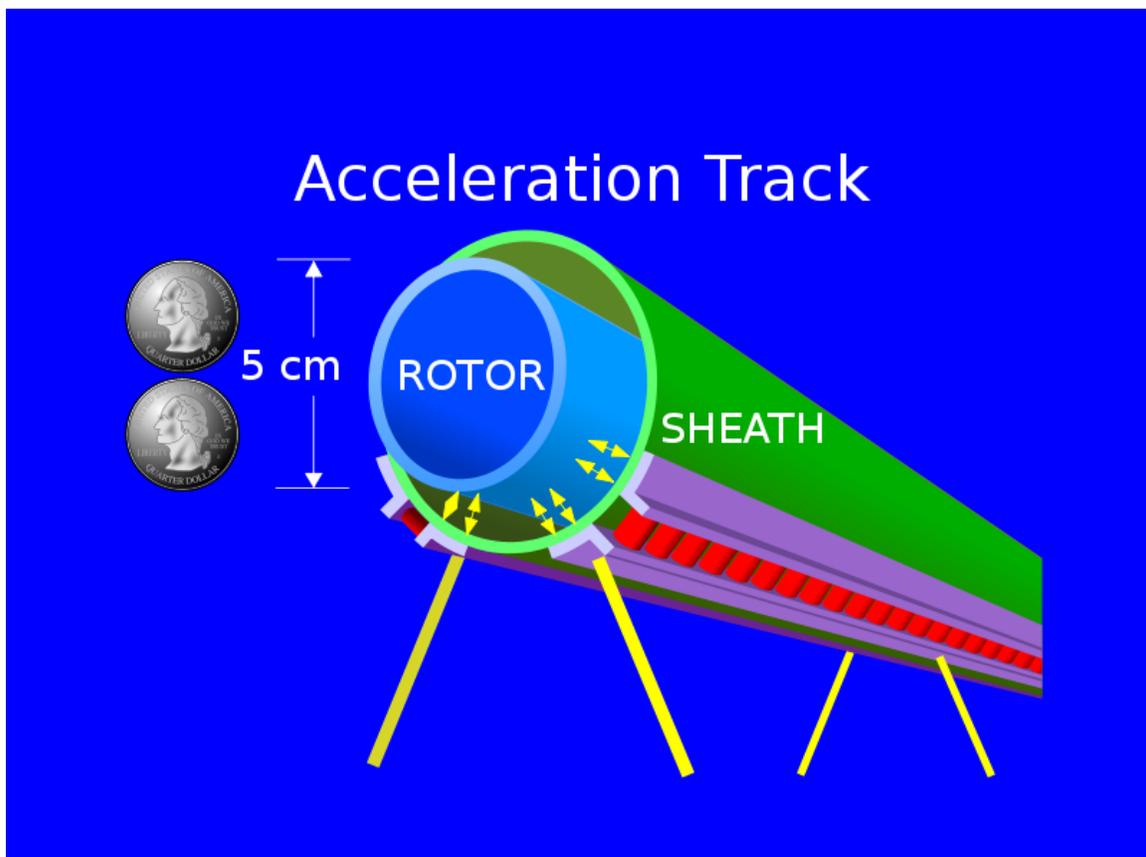
History

Launch loops were described by Keith Lofstrom in November 1981 Reader's Forum of the American Astronautical Society News Letter, and in the August 1982 L5 News.

In 1982 Paul Birch published a series of papers in *Journal of the British Interplanetary Society* which described orbital rings and described a form which he called Partial Orbital Ring System (PORS).

The launch loop idea was worked on in more detail around 1983–1985 by Lofstrom. It is a fleshed-out version of PORS specifically arranged to form a mag-lev acceleration track suitable for launching humans into space; but whereas the orbital ring used superconducting magnetic levitation, launch loops use Electromagnetic suspension (EMS).

Description



Launch loop accelerator section (return cable not shown)

A launch loop is proposed to be a structure around 2,000 km long and 80 km high. The loop runs along at 80 km above the earth for 2000 km then descends to earth before looping back on itself rising back to 80 km above the earth to follow the reverse path then looping back to the starting point. The loop would be in the form of a tube, known as the **sheath**. Floating within the sheath is another continuous tube, known as the **rotor** which

is a sort of belt or chain. The rotor is an iron tube approximately 5 cm (2 inches) in diameter, moving around the loop at 14 km/s (31 000 miles per hour).

Although the overall loop is very long, at around 4,000 km circumference, the rotor itself would be thin, around 5 cm diameter and the sheath is not much bigger.

Ability to stay aloft

When at rest, the loop is at ground level. The rotor is then accelerated up to speed. As the rotor speed increases, it curves to form an arc. The sheath forces it to follow a curve steeper than the rotor's natural ballistic curve, which, in turn, exerts a reactive centrifugal force on the sheath, holding it aloft. The loop would be anchored to the ground to remain at a fixed height.

Once raised, the structure requires continuous power to overcome the energy dissipated. Additional energy would be needed to power any vehicles that are launched.

Launching payloads

To launch, vehicles are raised up on an 'elevator' cable that hangs down from the West station loading dock at 80 km, and placed on the track. The payload applies a magnetic field which generates eddy currents in the fast-moving rotor. This both lifts the payload away from the cable, as well as pulls the payload along with 3g (30 m/s²) acceleration. The payload then rides the rotor until it reaches the required orbital velocity, and leaves the track.

If a stable or circular orbit is needed, once the payload reaches the highest part of its trajectory then an on-board rocket engine ("kick motor") or other means is needed to circularize the trajectory to the appropriate Earth orbit.

The eddy current technique is compact, lightweight and powerful, but inefficient. With each launch the rotor temperature increases by 80 kelvins due to power dissipation. If launches are spaced too close together, the rotor temperature can approach 770 °C (1043 K), at which point the iron rotor loses its ferromagnetic properties and rotor containment is lost.

Capacity and capabilities

Closed orbits with a perigee of 80 km quite quickly decay and re-enter, but in addition to such orbits, a launch loop by itself would also be capable of directly injecting payloads into escape orbits, gravity assist trajectories past the Moon, and other non closed orbits such as close to the Trojan points.

To access circular orbits using a launch loop a relatively small 'kick motor' would need to be launched with the payload which would fire at apogee and would circularise the orbit. For GEO insertion this would need to provide a delta-v of about 1.6 km/s, for LEO to

circularise at 500 km would require a delta-v of just 120 m/s. Conventional rockets require delta-vs of roughly 10 and 14 km/s to reach LEO and GEO respectively.

Launch loops in Lofstrom's design are placed close to the equator and can only directly access equatorial orbits. However other orbital planes might be reached via high altitude plane changes, lunar perturbations or aerodynamic techniques.

Launch rate capacity of a launch loop is ultimately limited by the temperature and cooling rate of the rotor to 80 per hour, but that would require a 17 GW power station; a more modest 500 MW power station is sufficient for 35 launches per day.

Economics

For a launch loop to be economically viable it would require customers with sufficiently large payload launch requirements.

Lofstrom estimates that an initial loop costing roughly \$10 billion with a one-year payback could launch 40,000 metric tons per year, and cut launch costs to \$300/kg, or for \$30 billion, with a larger power generation capacity, the loop would be capable of launching 6 million metric tons per year, and given a five-year payback period, the costs for accessing space with a launch loop could be as low as \$3/kg.

Comparisons

Advantages of launch loops

Lofstrom's launch loops are expected to launch at high rates (many launches per hour, independent of weather), and are not inherently polluting. Rockets create pollution such as nitrates in their exhausts due to high exhaust temperature, and can create greenhouse gases depending on propellant choices. Launch loops as a form of electric propulsion can be clean, and can be run on geothermal, nuclear, wind, solar or any other power source, even intermittent ones, as the system has huge built-in power storage capacity.

Unlike space elevators which would have to travel through the Van Allen belts over several days, launch loop passengers can be launched to low earth orbit, which is below the belts, or through them in a few hours. This would be a similar situation to that faced by the Apollo astronauts, who had radiation doses 200 times lower than the space elevator would give.

Unlike space elevators which are subjected to the risks of space debris and meteorites along their whole length, launch loops are to be situated at an altitude where orbits are unstable due to air drag. Since debris does not persist, it only has one chance to impact the structure. Whereas the collapse period of space elevators is expected to be of the order of years, damage or collapse of loops in this way is expected to be rare. In addition, launch loops themselves are not a significant source of space debris, even in an accident. All debris generated has a perigee that intersects the atmosphere or is at escape velocity.

Launch loops are intended for human transportation, to give a safe 3g acceleration which the vast majority of people would be capable of tolerating well, and would be a much faster way of reaching space than space elevators.

Launch loops would be quiet in operation, and would not cause any sound pollution, unlike rockets.

Finally, their low payload costs are compatible with large-scale commercial space tourism and even space colonisation.

Difficulties of launch loops

A running loop would have an extremely large amount of energy in the form of linear momentum. While the magnetic suspension system would be highly redundant, with failures of small sections having essentially no effect at all, if a major failure did occur the energy in the loop (1.5×10^{15} joules or 1.5 petajoules) would be approaching the same total *energy* release as a nuclear bomb explosion (350 kilotons of TNT equivalent), although not emitting nuclear radiation.

While this is a large amount of energy, it is unlikely that this would destroy very much of the structure due to its very large size, and because most of the energy would be deliberately dumped at preselected places when the failure is detected. Steps might need to be taken to lower the cable down from 80 km altitude with minimal damage, such as parachutes.

Therefore for safety and astrodynamics reasons, launch loops are intended to be installed over an ocean near the equator, well away from habitation.

The published design of a launch loop requires electronic control of the magnetic levitation to minimise power dissipation and to stabilise the otherwise under-damped cable.

The instabilities are primarily in the turnaround sections as well as the cable.

The turnaround sections are potentially unstable, since movement of the rotor away from the magnets gives reduced magnetic attraction, whereas movements closer gives increased attraction. In either case instability occurs. This problem is routinely solved with existing servocontrol systems that vary the strength of the magnets. Although servo reliability is a potential issue, at the high speed of the rotor, very many consecutive sections would need to fail for the rotor containment to be lost.

The cable sections also share this potential issue, although the forces are much lower. However, an additional instability is present in that the cable/sheath/rotor may undergo meandering modes (similar to a Lariat chain) that grow in amplitude without limit. Lofstrom believes that this instability also can be controlled in real time by servomechanisms, although this has never been attempted.

Competing and similar designs

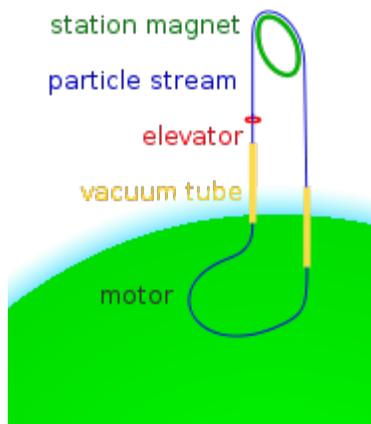
In works by Alexander Bolonkin it is suggested that Lofstrom's project has many non-solved problems and that it is very far from a current technology. For example, the Lofstrom project has expansion joints between 1.5 meter iron plates. Their speeds (under gravitation, friction) can be different and Bolonkin claims that they could wedge in the tube; and the force and friction in the ground 28 km diameter turnaround sections are gigantic. In 2008 Bolonkin proposed a simple rotated close-loop cable to launch the space apparatus in a way suitable for current technology.

Another project, the **space cable**, is a smaller design intended for launch assist for conventional rockets, and suborbital tourism.

Chapter- 3

Significant Space Launch Mechanisms

Space fountain



The Hyde Design for a space fountain

A **space fountain** is a proposed form of space elevator that does not require the structure to be in geosynchronous orbit, and does not rely on tensile strength for support. In contrast to the original space elevator design (a tethered satellite), a space fountain is a tremendously tall tower extending up from the ground. Since such a tall tower could not support its own weight using traditional materials, fast moving pellets are projected upward from the bottom of the tower and redirected back down once they reach the top, so that the force of redirection holds the top of the tower aloft. Satellite payloads ascend or descend by coupling with this stream of pellets or by climbing up the side of the tower. The space fountain has several key advantages over a space elevator in that it does not require materials with extreme strength, can be located at any point on a planet's surface instead of just the lower latitudes, and can be raised to any height required. Its major disadvantage is that it is an active structure, and so requires constant power input to make up energy losses and remain erect.

History

The concept originated in a conversation on a computer net in the 1980s when some scientists who usually worked in artificial intelligence, Marvin Minsky of MIT and John McCarthy and Hans Moravec of Stanford, were speculating about variations on the skyhook concept with Roderick Hyde and Lowell Wood, scientists at Lawrence Livermore National Laboratory who usually work on laser-initiated fusion. As a means of supporting the upper end of a traditional space elevator at an altitude much less than geostationary, they proposed a ring of space stations hovering 2000 kilometers above Earth, motionless relative to the surface. These stations would not be in orbit; they would support themselves by deflecting a ring of fast-moving pellets circling Earth. The pellets would be moving at far greater speed than the orbital velocity for that altitude, so if the stations stopped deflecting them the pellets would move outward and the stations would fall inward.

Robert L. Forward joined the conversation at this point, suggesting that instead of using a pellet stream to support the top of a traditional tensional cable, a vertical pellet stream shot straight up from Earth's surface could support a station and provide a path for payloads to travel without requiring a cable at all. Problems that were initially raised with this proposal were friction of the pellet stream with Earth's atmosphere at lower altitudes and the Coriolis forces due to the rotation of the Earth, but Roderick Hyde worked out all the engineering design details for a space fountain and showed that these issues could theoretically be overcome.

Design

The space fountain acts as a continuous coil gun with captive projectiles travelling in a closed loop.

In the Hyde design for a space fountain a stream of projectiles is shot up through the bore of a hollow tower. As the projectiles travel upward through the tower they are slowed down by electromagnetic drag devices that extract kinetic energy from the upgoing stream and turn it into electricity. As the projectiles are braked they also transfer some of their upward momentum to the tower structure, exerting a lifting force to support some of its weight. When the projectiles reach the station at the top of the tower they are turned around by a large bending magnet. In the turnaround process they exert an upward force on the station at the top of the tower, keeping it levitated above the launch point.

As the projectiles travel back down the tower they are accelerated by coil guns that use the electrical energy extracted from the upgoing stream of projectiles. This provides the rest of the upward lifting force required to support the weight of the tower. The projectiles reach the bottom of the tower with almost the same speed that they had when they were launched, losing a small amount of energy due to inefficiencies in the electromagnetic accelerators and decelerators in the tower. This can be minimized by the use of superconductors.

When the stream of high speed projectiles reaches the bottom of the tower it is then bent through 90 degrees by a magnet at the tower's base so that it is traveling parallel to

Earth's surface, through a large circular underground tunnel similar to a particle accelerator. Electromagnetic accelerators in this tunnel bring the projectiles back up to the original launch speed, and then the stream of projectiles is bent one more time by 90 degrees to send it back up the tower again to repeat the cycle.

The downward force from the weight of the tower is transmitted solely by the stream of projectiles to the bending magnet at the tower's base, and so no materials with extraordinary compressive strength are needed to support the tower itself. The tower's base requires a foundation capable of supporting the weight of the tower, but this can be constructed with conventional materials available cheaply on Earth's surface. Together, the stressed structure and flowing projectile stream form a rigid, stable structure that is not limited in height by the strength of materials.

The lower parts of the tower would have to be surrounded by an airtight tube to maintain a vacuum for the projectiles to travel through, reducing energy losses due to drag. After the first one hundred kilometers or so the tube would no longer be necessary and the only structure that would be needed is a minimal framework to hold communication and power lines, and the guide tracks for the elevator cars. When the projectiles return to the base of the tower they have nearly the same speed and energy as they started with, only with the opposite momentum (downward instead of upward). As a result, the input power required to support the space fountain is determined by the inefficiency in the electromagnetic motors and air drag on the projectiles.

The elevators that would take payloads up the space fountain could conceivably ride up tracks on the tower structure using electrical power supplied by the tower, treating the space fountain solely as a mechanical support. A more attractive option would be to design the tower structure so the elevator cars can interact directly with the projectile streams themselves, and not couple to the tower structure at all. In this manner the momentum needed to raise the elevator car up against Earth's gravity would come directly from the projectile stream.

Construction

In contrast to a traditional space elevator, which must be built from space downward, a space fountain concept can be built slowly from the ground up. The driver loop and the bending magnets at the base would be constructed first, then the top station with its turnaround magnets would be constructed right above it. The system could then be loaded with projectiles and turned on at low power, lifting the top station off the ground. The vacuum tube would be built as the top station rises, with the power increasing and more projectiles being added to the loop as the tower gets longer. The rate of construction is entirely controllable, and can be halted at any height. The tower would be capable of lifting payloads throughout its construction as well, including its own construction materials.

Safety measures

To provide redundancy, a space fountain could be built with more than one projectile loop and power supply. In the event of projectile loops failing, the remaining loops would be capable of supporting the structure until the others were repaired. A safety margin would be provided simply due to the extra lifting strength that would be required by the system to raise large payloads to orbit during routine operation. In an emergency, payloads in transit could be jettisoned from the tower to reduce tower loading. Valuable or manned payloads would likely be in capsules capable of emergency reentry as a matter of course.

Even if all of the tower's power sources failed simultaneously, it would still take a long time for the tower to begin suffering. The kinetic energy stored inside the circulating loop of projectiles is vastly greater than the amount lost to inefficiencies, so it would take many hours or even days for the velocity of the projectiles to drop enough to cause problems in supporting the tower's mass. The round trip time for the projectiles alone provides some safety margin; in Hyde's concept design it takes each projectile over three hours to complete one loop, so even if the projectile stream was completely cut off (by the destruction of the top or base station, for example) there would be some time for evacuation of the remaining tower structure and regions that might be affected by significant pieces of falling debris.

Variants

Two variant designs based on the space fountain are the launch loop and the orbital ring. In a sense they are variants of space fountains where the projectile stream is directed sideways.

Near-term applications

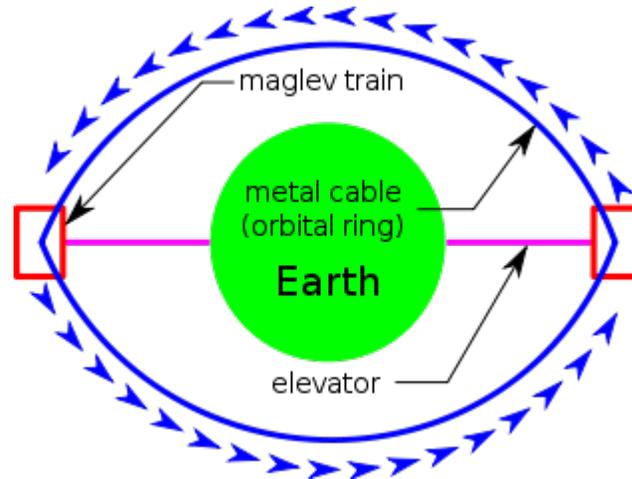
A closed loop projectile system could be used for energy storage, similar to a very large flywheel, providing load levelling for terrestrial power grids. If the closed loop were long enough it could even be used for power transmission.

A very small-scale fountain tower could be used for constructing tall antenna masts rapidly, perhaps for news events and military operations. A larger and more permanent fountain tower could be ten or twenty kilometers tall, allowing one facility to provide radio and television broadcasts to enormous areas such as the steppes of Asia. Fountain towers might also prove to be an economical alternative to communication satellites for point-to-point television and FM radio communication between the various islands of some of the smaller nations in the Pacific Ocean. An elevator and observation platform could also be added as a tourist attraction.

Arched fountain structures similar to the launch loop could also have useful small-scale applications, notably the construction of bridges. Projectile-supported fountain bridges could be made arbitrarily long, without the need for support pillars anywhere along their

span. However, they would of course require the continuous application of energy to maintain them, to make up for any losses.

Orbital ring



An **Orbital Ring** is a concept for a space elevator that consists of a ring in low earth orbit that rotates at above orbital speed, that has fixed tethers hanging down to the ground.

The structure is intended to be used for space launch.

The original orbital ring concept is related to the space fountain and launch loop and was explored in detail by Paul Birch and published in three parts in the Journal of the British Interplanetary Society in 1982.

History

Arthur C. Clarke published a book called *The Fountains of Paradise* about Space elevators, but which in an appendix referred to an idea to launch things off the Earth using a structure based on mass drivers. The idea apparently did not work, but this inspired further research.

Paul Birch publishes a series of articles in JBIS in 1982.

Yunitsky, Anatoly E. also published a similar idea in 1982.

Birch's model

In the simplest design of an orbital ring system, a rotating cable is placed in a low Earth orbit above the equator, rotating at faster than orbital speed. Not in orbit, but riding on

this ring, supported electromagnetically on superconducting magnets, are Ring Stations that stay in one place above some designated point on Earth. Hanging down from these Ring Stations are short space elevators made from cables with high tensile strength to mass ratio materials.

Although this simple model would work best above the equator, Paul Birch found that since the Ring Station can be used to accelerate the orbital ring eastwards as well as hold the tether, it is therefore possible to deliberately cause the orbital ring to precess around the Earth instead of staying fixed in space while the Earth rotates beneath it. By precessing the Ring once every 24 hours, the Orbital Ring will hover above any meridian selected on the surface of the Earth. The cables which dangle from the Ring are now geostationary without having to reach geostationary altitude or without having to be placed into the equatorial plane. This means that using the Orbital Ring concept, one or many pairs of Stations can be positioned above *any* points on Earth desired or can be moved everywhere on the globe. Thus, any point on Earth can be served by a space elevator. Also a whole network of Orbital Rings can be built, which, by crossing over the poles, could cover the whole planet and capable of taking over most of freight and passenger transport. By an array of elevators and several geostationary ring stations, asteroid or Moon material can be received and gently put down where land fills are needed. The electric energy generated in the process would pay for the system expansion and ultimately could pave the way for a solar-system-wide terraforming- and astroengineering-activity on a sound economical basis.

If built by launching the necessary materials from Earth, the estimated cost for the system in 1980s money was around \$31 trillion if launched using Shuttle-derived hardware, whereas it could fall to \$15 billion with bootstrapping, assuming a large orbital manufacturing facility is available to provide the initial 18000 tons of steel, aluminium, and slag at a low cost, and even lower with orbital rings around the moon. The system's cost per kilogram to place payloads in orbit would be around \$0.05.

Types of orbital rings

The simplest type would be a circular orbital ring in LEO.

Two other types were also defined by Paul Birch:

- Eccentric Orbital Ring Systems - these are rings that are in the form of a closed shape with varying altitude
- Partial Orbital Ring Systems - this is essentially a Launch loop

In addition, he proposed the concept of "supramundane worlds" such as **supra-jovian** and **supra-stellar** "planets". These are artificial planets that would be supported by a grid of orbital rings that would be positioned above a planet, supergiant or even a star.

Orbital rings in fiction

Donald Kingsbury described a partial ring (a few hundred kilometers long) in his novel *The Moon Goddess and the Son*.

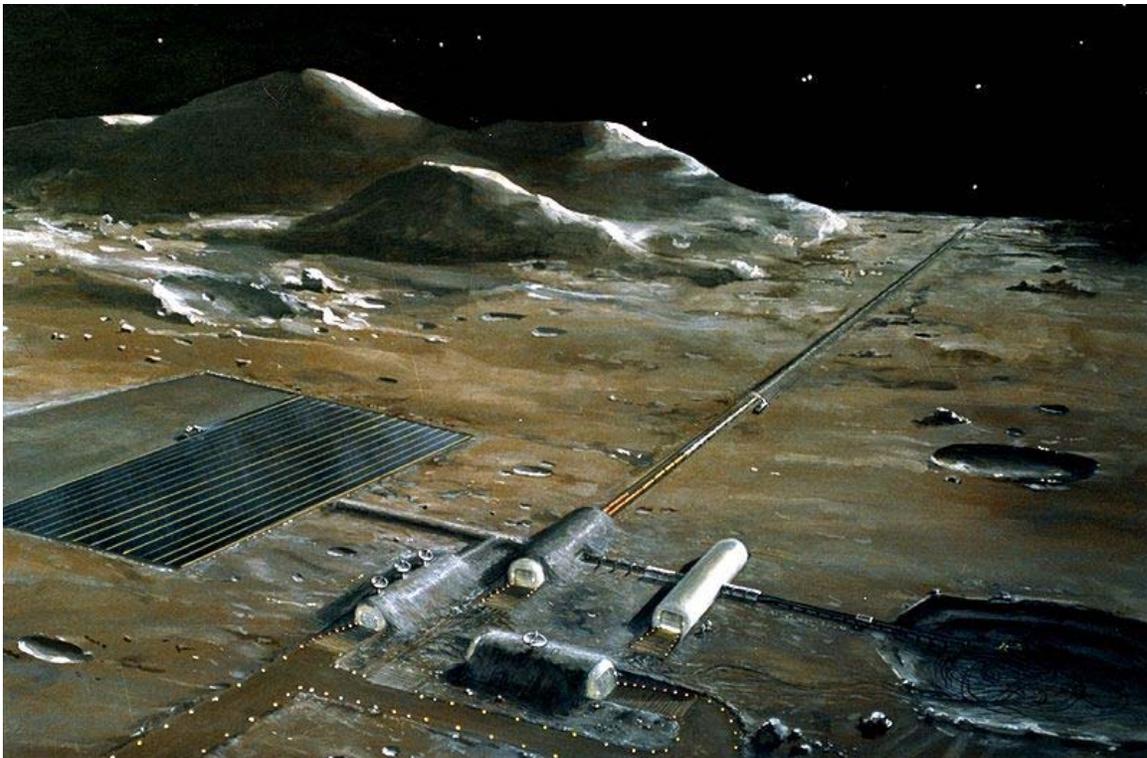
The manga *Battle Angel Alita* prominently features a slightly deteriorated orbital ring.

The second iteration of the anime series *Tekkaman* features a complete ring, though abandoned and in disrepair due to war, and without surface tethers.

The anime series *Kiddy Grade* also uses orbital rings as a launch and docking bay for spaceships. These rings are connected to large towers extending from the planet's surface.

Orbital rings are used extensively in the collaborative fiction worldbuilding website *Orion's Arm*.

Mass driver



A mass driver for lunar launch (artist's conception)

A **mass driver** or **electromagnetic catapult** is a proposed method of non-rocket spacelaunch which would use a linear motor to accelerate and catapult payloads up to high speeds. All existing and contemplated mass drivers use coils of wire energized by electricity to make electromagnets. Sequential firing of a row of electromagnets

accelerates the payload along a path. After leaving the path, the payload continues to move due to inertia.

A mass driver is essentially a coilgun that magnetically accelerates a package consisting of a magnetisable holder containing a payload. Once the payload has been accelerated, the two separate, and the holder is slowed and recycled for another payload.

Mass drivers can be used to propel spacecraft in two different ways: A large, ground-based mass driver could be used to launch spacecraft away from the Earth or another planet. A spacecraft could have a mass driver on board, flinging large pieces of material into space to propel itself. A hybrid design is also possible.

Miniaturized mass drivers can also be used as weapons in a similar manner as classic firearms or cannon using chemical combustion.

Fixed mass drivers

Generally speaking, mass drivers are practical for small objects at a few kilometers per second; for example 1 kg at 2.5 km/s. Heavier objects go proportionally more slowly; and lighter objects may be projected at 20 km/s or more. The limits are generally the cost of the silicon to switch the current and the cost of the power supply and temporary energy storage for it. However, energy can be stored inductively in superconducting coils. A 1 km long mass driver made of superconducting coils can accelerate a 20 kg vehicle to 10.5 km/s at a conversion efficiency of 80%, and average acceleration of 5,600 g. Even so, Earth-based Mass drivers for propelling one-tonne vehicles to orbit are unlikely to be cost effective in the near future.

The Earth's strong gravity and thick atmosphere make such an installation difficult, so many proposals have been put forward to install mass drivers on the moon where the lower gravity and lack of atmosphere significantly reduce the required velocity to reach lunar orbit.

Most serious mass driver designs use superconducting coils to achieve reasonable energetic efficiency (approximately 50%). The best known performance occurs with an aluminum coil as the payload. The coils of the mass-driver induce eddy-currents in the payload's coil, and then act on the resulting magnetic field. There are two sections of a mass-driver. The maximum acceleration part spaces the coils at constant distances, and synchronize the coil currents to the bucket. In this section, the acceleration increases as the velocity increases, up to the maximum that the bucket can take. After that, the constant acceleration region begins. This region spaces the coils at increasing distances to give a fixed amount of velocity increase per unit of time.

In this mode, the major proposal for use of mass-drivers was to transport lunar surface material to space habitats so that it could be processed using solar energy. The Space Studies Institute showed that this application was reasonably practical.

In the prototypes, the payload would be held in a bucket and then released, so that the bucket can be decelerated and reused. A disposable bucket, on the other hand, would avail acceleration along the whole track.

On Earth

In contrast to a space gun, a mass driver can have a length of hundreds of kilometers and therefore achieve acceleration without excessive g forces to the passengers. It can be constructed as a very long and mainly horizontally aligned launch track for spacelaunch, targeted upwards at the end, partly by bending of the track upwards and partly by Earth's curvature in the other direction.

Natural elevations, such as mountains, may facilitate the construction of the distant, upwardly targeted part. The higher up the track terminates, the less resistance from the atmosphere the launched object will receive.

By being mainly located slightly above, on or beneath the ground, a mass driver may be easier to maintain compared with many other structures of non-rocket spacelaunch. If not underground then it still needs to be housed in a pipe that is constantly vacuum pumped in order to reduce drag.

In order to be able to launch humans and delicate instruments, it would need to be several hundreds of kilometres long. For rugged objects, with magnetic assistance, a significantly smaller, circular, track may suffice.

A mass driver on Earth would be a compromise system. A mass driver would accelerate a payload up to some high speed which would not be high enough for orbit. It would then release the payload, which would complete the launch with rockets. This would drastically reduce the amount of velocity needed to be provided by rockets to reach orbit. On Earth, a mass driver design could possibly use well-tested maglev components.

Spacecraft-based mass drivers

A spacecraft could carry a mass driver as its primary engine. With a suitable source of electrical power (probably a nuclear reactor) the spaceship could then use the mass driver to accelerate pieces of matter of almost any sort, boosting itself in the opposite direction. At the smallest scale of reaction mass, this type of drive is called an ion drive.

No theoretical limit is known for the size, acceleration or muzzle energy of linear motors. However, at higher muzzle velocities, energetic efficiency is inevitably very poor. While linear motors can, with current technology, convert up to about 50% of the electrical energy into kinetic energy of the projectile, the energy of interest is the kinetic energy of the vehicle, and as the muzzle velocity increases, this is a smaller and smaller percentage of the generated power.

Since kinetic energy of the projectile is $\frac{1}{2}mv^2$, the energy requirements vary with the square of the specific impulse, so in a design one must choose a tradeoff between energy consumption and consumption of reaction mass. In addition, since momentum of a particle of mass m has momentum mv - proportional to velocity, but energy is a square law, so the average thrust for a given energy is inversely proportional to the velocity of the particles. In other words, heavier projectile masses give lower specific impulse but proportionately higher thrust.

Since a mass driver could use any type of mass for reaction mass to move the spacecraft, this, or some variation, seems ideal for deep-space vehicles that scavenge reaction mass from found resources.

One possible drawback of the mass driver is that it has the potential to send solid reaction mass travelling at dangerously high relative speeds into useful orbits and traffic lanes. To overcome this problem, most schemes plan to throw finely-divided dust. Alternately, liquid oxygen could be used as reaction mass, which upon release would boil down to its molecular state. Propelling the reaction mass to solar escape velocity is another way to ensure that it will not remain a hazard.

Space is almost completely empty, so propellant sources are only to be found at asteroids, comets, moons and planets.

Hybrid mass drivers

Another variation is to have a mass-driver on a spacecraft, and use it to "reflect" masses from a stationary mass-driver. Each deceleration and acceleration of the mass contributes to the momentum of the spacecraft. The spacecraft need not carry reaction mass, and doesn't even need much electricity, beyond the amount needed to replace losses in the electronics. The system could also be used to deliver pellets of fuel to the spacecraft for use in powering some other propulsion system. This could be considered a form of beam-powered propulsion.

Another theoretical use for this concept of propulsion can be found in space fountains, a system in which a continuous stream of pellets in a circular track holds up a tall (and heavy) structure.

Mass drivers as weapons

High-acceleration linear motors are currently undergoing active research by the military for use as (ground-based or ship-based) armor-piercing weapons. Since a mass driver is essentially a very large, very high-velocity linear motor, it could in principle be used as a very large weapon, either firing directly on a target in space, or used to attack a location on a planet's surface from a position in orbit, long range over-the-horizon indirect fire, or from a nearby planetary body, such as a moon.

Practical attempts

Prototype mass drivers have existed since 1976 (Mass Driver 1). Most were constructed by the US Space Studies Institute in order to prove their properties and practicality.

Rocket sled launch

A **rocket sled launch** uses a rail or maglev track and rocket or jet boosters to accelerate a sled holding a rocket up an eastward facing mountain slope. By starting 2000 meters above sea level and accelerating to Mach 0.8 to Mach 3 substantial fuel savings can be gained allowing a single stage to orbit reusable vehicle.

This would require little new engineering as the test tracks at Holloman Air force base have tested Rocket Sleds moving at well above Mach 3. NASA studies of maglev sleds concluded that using current technology they could not magnetically accelerate rockets fast enough. But most designs for use jet engines or rockets to accelerate the spacecraft mounted on it. Effectively a sky ramp makes the first stage of a rocket fully reusable since the sled is returned to its starting position, refueled and may be reused at once.

Overview of the Problem

NASA studies have shown that the Space Shuttle uses half of its fuel just to reach 1000 mph (Mach 1.3) . If the rocket was already moving Mach 1.3 at launch, it could make orbit as SSTO. This would allow either a smaller spacecraft with less fuel or a more massive payload.

High altitude launches

An advantage to any launch system that starts from high altitudes will reduce gravity drag (the cost of lifting fuel in a gravity well). The thinner air will reduce air resistance and allow more efficient engine geometries. (Rocket nozzles have different shapes to maximize thrust at different air pressures. NASA's aerospike engine for the Lockheed Martin X-33 was designed to change geometry to remain efficient at a variety of different pressures, but the aerospike engine was heavy and complex and the project was eventually canceled.)

For example, the air is 39% thinner at 2500 meters. The more efficient rocket plume geometry and the reduced air friction allows the engine to be 5% more efficient per amount of fuel burned.

Debora A. Grant and James L. Rand in: "The Balloon Assisted Launch System - A Heavy Lift Balloon" wrote: "It was established some time ago that a ground launched rocket capable of reaching 20 km would be able to reach an altitude of almost 100km if it was launched from 20km." They suggest that small rockets are lifted above the majority of the atmosphere by balloon in order to avoid the problems discussed above.

Reusable launch vehicle

Rocket sleds at China Lake testing ground have reached Mach 4 while carrying 60,000 kg masses.

Other technologies used

Note that a sled launch can be combined with other technologies to further reduce the cost to orbit. For example, a sled can launch a spacecraft at Mach 3, which is moving fast enough to allow a scramjet to operate. A small laser launch system could be used at the end of a vehicle to further superheat the exhaust and improve the Specific impulse (Isp). A large track could launch craft to reach the tether end of a rotating skyhook (structure).

Rocket sled launches in fiction

- A sled was used in the movie *When Worlds Collide* to help launch the Ark to Bronson Beta.
- Robert A. Heinlein used a sled in *Space Cadet* and a lunar maglev launcher in *The Moon is a Harsh Mistress*.
- Dean Ing used a similar system in his 1988 novel "The Big Lifters".
- Fireball XL5 was launched on a sled from sea level.

Summary

A sled track that gave a Mach 2 launch assist would reduce the fuel to orbit by 40%. Thus a track angled at 45 degrees to vertical on a tall mountain would allow a single stage to orbit reusable vehicle with no new technology. This would reduce the price to orbit by about 20 fold.

Space gun

A **space gun** is a method of launching an object into outer space using a large gun, or cannon. It provides a method of non-rocket spacelaunch.

In the HARP Project a U.S. Navy 16 inch (406 mm) 100 caliber gun (40 m) was used to fire a 180 kilogram slug at 3,600 meters per second, reaching an apogee of 180 kilometers, hence performing a suborbital spaceflight.

However, a space gun has never been successfully used to launch an object into orbit.

Technical issues

The large g-force experienced by a ballistic projectile would likely mean that a space gun would be incapable of safely launching humans or delicate instruments, rather being restricted to freight or ruggedized satellites.

Atmospheric drag also makes it more difficult to control the trajectory of any projectile launched, subjects the projectile to extremely high forces, and causes severe energy losses that may not be easily overcome. A space gun with a "gun barrel" reaching above the lower troposphere, where the atmosphere is most densely packed, may mitigate the issue.

A space gun, by itself, is generally not capable of placing objects into stable orbit around the planet, unless the objects are able to perform course corrections after launch.

If acceptable solutions to these fundamental issues could be achieved, a space gun could offer access to space at an unprecedented low cost.

Getting to orbit

A space gun, by itself, is not capable of placing objects into stable orbit. The laws of gravitation make it impossible to reach a stable orbit without an active payload which performs orbital correction burns to change the shape of its orbit after launch. The orbit is a parabolic orbit, a hyperbolic orbit, or part of an elliptic orbit which ends at the planet's surface at the point of launch or another point. This means that an uncorrected ballistic payload will always strike the planet within its first orbit unless the velocity was so high as to reach or exceed escape velocity.

Isaac Newton avoided this objection in his thought experiment by positing an impossibly tall mountain from which his cannon was fired. The projectile, however, would still tend to circle the planet and strike the point of launch.

As a result, all payloads intended to reach a closed orbit would have at least to perform some sort of course correction to create another orbit that does not intersect the planet's surface. In addition a rocket can be used for additional boost, as planned in the Quicklaunch project.

It is conceivable that in a multi-body gravitational system, like the Earth-Moon system, that a trajectory could be found that does not re-intersect the Earth's surface, although these paths would likely not be very simple nor desirable, and would require much more energy.

Acceleration

A space gun with a "gun barrel" of length (l), and the needed velocity (v_e), the acceleration (a) is provided by the following formula:

$$a = \frac{v_e^2}{2l}$$

For instance, with a space gun with a vertical "gun barrel" through both the Earth's crust and the troposphere, totalling ~60 km of length (l), and a velocity (v_e) enough to escape

the Earth's gravity (escape velocity, which is 11.2 km/s on Earth), the acceleration (a) would theoretically be more than 1000 m/s^2 , which is more than 100 g-forces, which is about 3 times the human tolerance to g-forces of maximum 20 to 35 g during the ~10 seconds such a firing would take.

Any doubling of the barrel length would theoretically cut the generated g-force in half.

Practical attempts

The German V-3 cannon program (less well known than the V-2 rocket or V-1 flying bomb), during the Second World War was an attempt to build something approaching a space gun. Based in the Pas-de-Calais area of France it was planned to be more devastating than the other Nazi 'Vengeance weapons'. It was destroyed by RAF bombing using 'Tallboy' blockbuster bombs in July 1944.



Two sections of the Project Babylon gun



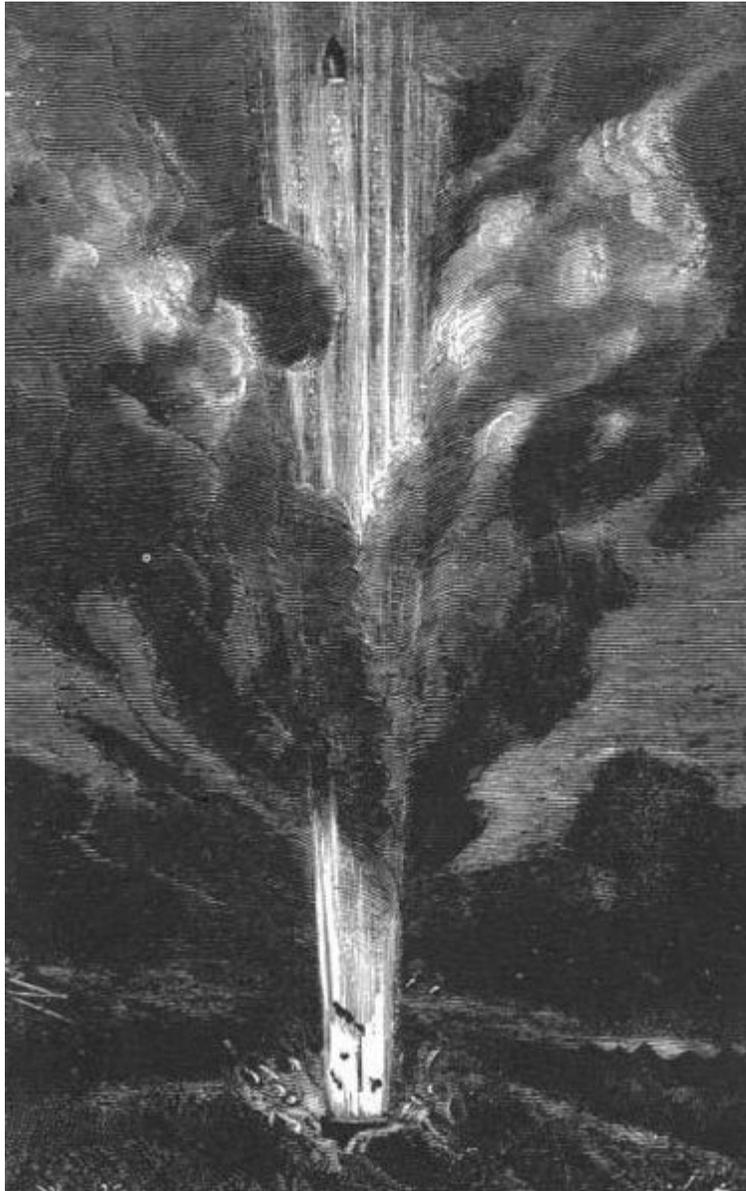
Project HARP, a prototype of a space gun.

On the practical side, the most prominent recent attempt to make a space gun was artillery engineer Gerald Bull's Project Babylon, which was also known as the 'Iraqi supergun' by the media. During Project Babylon, Bull used his experience from Project HARP to build a massive cannon for Saddam Hussein leader of Ba'athist Iraq. This gun, had it been completed, would have been the first true space gun capable of launching objects into space. However, Bull was assassinated before the project was completed.

Since Bull's death, few have seriously attempted to build a space gun. Perhaps most promisingly, the US Ballistic Missile Defense program sponsored the Super High Altitude Research Project in the 1980s. Developed at Lawrence Livermore Laboratory, it is a light gas gun and has been used to test fire objects at Mach 9. One of the lead developers John Hunter has since founded the Jules Verne Launcher Company in 1996, though has as yet been unable to find funding for the multi-billion dollar project. He has now founded the Quicklaunch company.

Ram accelerators have also been proposed as an alternative to light gas guns. Other proposals use electromagnetic techniques for accelerating the payload, such as coilguns and railguns.

In fiction



The firing of a space gun in Jules Verne's *From the Earth to the Moon*

The first publication of the concept may be Newton's cannonball in the 1728 book *A Treatise of the System of the World*, although it was primarily used as a thought experiment regarding gravity.

Perhaps the most famous representation of a space gun is Jules Verne's novel, *From the Earth to the Moon* (made into a silent movie called *Le Voyage dans la Lune*), in which astronauts fly to the moon aboard a ship launched from a cannon. Another famous example is the hydrogen accelerator cannon used by the Martians to launch their invasion in H. G. Wells' book *The War of the Worlds*. Wells also used the concept in the climax of the 1936 movie *Things to Come*. The device was featured in films as late as 1967, such as *Jules Verne's Rocket to the Moon*.

In the Squaresoft (now Square-Enix) video game *Final Fantasy VIII*, humans are sent to a space base by the use of hybrid rail/coil gun. In the video game *Ultima: Worlds of Adventure 2: Martian Dreams*, Percival Lowell builds a space gun to send a ship to Mars.

In the Nintendo game *Paper Mario: The Thousand Year Door* the protagonist is fired to the moon from a large cannon powered by the explosion of thousands of anthropomorphic bombs. This is depicted in a somewhat comical fashion.

Additionally, a book about the Halo universe, *Halo: Contact Harvest* included a 'magnetic accelerator cannon(coil gun)' ,also known as MAC, used as both a surface-to-air/space weapon and to lift objects into space from a planetary surface(known as mass driver).

Beam-powered propulsion

Beam-powered propulsion is a class of spacecraft propulsion mechanisms that use energy beamed to the spacecraft from a remote power plant to provide energy. Most designs are rocket engines where the energy is provided by the beam, and is used to superheat propellant that then provides propulsion, although some obtain propulsion directly from light pressure acting on a light sail structure, and at low altitude heating air gives extra thrust.

The beam would typically either be a beam of microwaves or a laser. Lasers are subdivided into either pulsed or continuous beamed.

The rule of thumb that is usually quoted is that it takes a megawatt of power beamed to a vehicle per kg of payload while it is being accelerated to permit it to reach low earth orbit.

Other than launching to orbit, applications for moving around the world quickly have also been proposed.

Background

Rockets are momentum machines; they use mass ejected from the rocket to provide momentum to the rocket. Momentum is the product of mass and velocity, so rockets generally attempt to put as much velocity into their working mass as possible, thereby

minimizing the amount of working mass that is needed. In order to accelerate the working mass, energy is required. In a conventional rocket, the fuel is chemically combined to provide the energy, and the resulting fuel products, the ash or exhaust, are used as the working mass.

There is no particular reason why the same fuel has to be used for both energy and momentum. In the jet engine, for instance, the fuel is used only to produce energy, the working mass is provided from the air that the jet aircraft flies through. In modern jet engines, the amount of air propelled is much greater than the amount of air used for energy, bypass ratios of 10 to 1 or greater are typical. This is not a solution for the rocket, however, as they quickly climb to altitudes where the air is too thin to be useful as a source of working mass.

Rockets can, however, carry their working mass and use some other source of energy. The problem is finding an energy source with a power-to-weight ratio that competes with chemical fuels. Small nuclear reactors can compete in this regard, and considerable work on nuclear thermal propulsion was carried out in the 1960s, but environmental concerns and rising costs led to the ending of most of these programs.

A further improvement can be made by removing the energy creation off of the spacecraft entirely. If the nuclear reactor is left on the ground and its energy transmitted to the spacecraft, the weight of the reactor is removed as well. The issue then is to get the energy into the spacecraft. This is the idea behind beamed power.

Thermal propulsion

With beamed propulsion one can leave the power-source stationary on the ground, and directly (or via a heat exchanger) heat propellant on the spacecraft with a maser or a laser beam from a fixed installation. This permits the spacecraft to leave its power-source at home, saving significant amounts of mass, greatly improving performance.

Since a laser can heat propellant to extremely high temperatures, this potentially greatly improves the efficiency of a rocket, as exhaust velocity is proportional to the square root of the temperature. Normal chemical rockets have an exhaust speed limited by the fixed amount of energy in the propellants, but beamed propulsion systems have no particular theoretical limit (although in practice there are temperature limits).

Ablative Laser Propulsion is a form of laser propulsion that uses a laser to create a plasma plume from a metal propellant, thus producing thrust.

In addition, microwaves can be used to heat a suitable heat exchanger, which in turn heats a propellant (very typically hydrogen). This can give a combination of high specific impulse (700-900 seconds) as well as good thrust/weight ratio (50-150).

A variation, developed by brothers James Benford and Gregory Benford, is to use thermal desorption of propellant trapped in the material of a very large microwave-sail. This produces a very high acceleration compared to microwave pushed sails alone.

Electric propulsion

Some proposed spacecraft propulsion mechanisms use power in the form of electricity. Usually these schemes assume either solar panels, or an on-board reactor. However, both power sources are heavy.

Beamed propulsion in the form of laser can be used to send power to a photovoltaic panel, for *Laser electric propulsion*. In this system, careful design of the panels is necessary as the extra power tends to cause a fall-off of the conversion efficiency due to heating effects.

A microwave beam could be used to send power to a rectenna, for *microwave electric propulsion*. Microwave broadcast power has been practically demonstrated several times (e.g. Goldstone, California in 1974), rectennas are potentially lightweight and can handle high power at high conversion efficiency. However, rectennas tend to need to be very large for a significant amount of power to be captured.

Direct Impulse

A beam could also be used to provide impulse by directly "pushing" on the sail.

One example of this would be using a solar sail to reflect a laser beam. This concept, called a *laser-pushed lightsail*, was analyzed by physicist Robert L. Forward in 1989 as a method of Interstellar travel that would avoid extremely high mass ratios by not carrying fuel. His work elaborated on a proposal initially made by Marx . Further analysis of the concept was done by Landis , Mallove and Matloff , Andrews and others.

In a later paper, Forward proposed pushing a sail with a microwave beam . This has the advantage that the sail need not be a continuous surface. Forward tagged his proposal for an ultralight sail "Starwisp". A later analysis by Landis suggested that the Starwisp concept as originally proposed by Forward would not work, but variations on the proposal continue to be proposed.

The beam has to have a large diameter so that only a small portion of the beam misses the sail due to diffraction and the laser or microwave antenna has to have a good pointing stability so that the craft can tilt its sails fast enough to follow the center of the beam. This gets more important when going from interplanetary travel to interstellar travel, and when going from a fly-by mission, to a landing mission, to a return mission. The laser or the microwave sender would probably be a large phased array of small devices, which get their energy directly from solar radiation. The size of the array obsoletes any lens or mirror.

Another beam-pushed concept would be to use a magnetic sail or MMPP sail to divert a beam of charged particles from a particle accelerator or plasma jet . Jordin Kare has proposed a variant to this whereby a "beam" of small laser accelerated light sails would transfer momentum to a magsail vehicle.

Another beam-pushed concept uses ordinary matter and works in vacuum. The matter from a stationary mass-driver is "reflected" by the spacecraft, cf. mass driver. The spacecraft neither needs energy nor reaction mass for propulsion of its own.

Proposed systems

Lightcraft

A **lightcraft** is a vehicle currently under development that uses an external pulsed source of laser or maser energy to provide power for producing thrust.

The laser shines on a parabolic reflector on the underside of the vehicle that concentrates the light to produce a region of extremely high temperature. The air in this region is heated and expands violently, producing thrust with each pulse of laser light. In space, a lightcraft would need to provide this gas itself from onboard tanks or from an ablative solid. By leaving the vehicle's power source on the ground and by using ambient atmosphere as reaction mass for much of its ascent, a lightcraft would be capable of delivering a very large percentage of its launch mass to orbit. It could also potentially be very cheap to manufacture.

Testing

Early in the morning of 2 October 2000 at the High Energy Laser Systems Test Facility (HELSTF), Lightcraft Technologies, Inc. (LTI) with the help of Franklin B. Mead of the U.S. Air Force Research Laboratory and Leik Myrabo set a new world's altitude record of 233 feet (71 m) for its 4.8 inch (12.2 cm) diameter, 1.8 ounce, laser-boosted rocket in a flight lasting 12.7 seconds. Although much of the 8:35 am flight was spent hovering at 230+ feet, the Lightcraft earned a world record for the longest ever laser-powered free flight and the greatest "air time" (i.e., launch-to-landing/recovery) from a light-propelled object. This is comparable to Robert Goddard's first test flight of his rocket design. Increasing the laser power to 100 kilowatts will enable flights up to a 30-kilometer altitude. Their goal is to accelerate a one-kilogram microsatellite into low Earth orbit using a custom-built, one megawatt ground-based laser. Such a system would use just about 20 dollars' worth of electricity, placing launch costs per kilogram to many times less than current launch costs (which are measured in thousands of dollars).

Myrabo's "lightcraft" design is a reflective funnel-shaped craft that channels heat from the laser, towards the center, using a reflective parabolic surface causing the laser to literally explode the air underneath it, generating lift. Reflective surfaces in the craft focus the beam into a ring, where it heats air to a temperature nearly five times hotter than the surface of the sun, causing the air to expand explosively for thrust.

Jordin Kare's heat exchanger system

Jordin Kare has proposed a simpler, nearer term concept which has a rocket containing liquid hydrogen and water. The propellant is heated in a heat exchanger that the laser beam shines on before leaving the vehicle via a conventional nozzle. This concept can use continuous beam lasers, and the semiconductor lasers are now cost effective for this application.

Non-spacecraft applications

In 1964 William C. Brown demonstrated a miniature helicopter equipped with a combination antenna and rectifier device called a rectenna. The rectenna converted microwave power into electricity, allowing the helicopter to fly .

In 2002 a Japanese group propelled a tiny aluminium airplane by using a laser to vaporize a water droplet clinging to it, and in 2003 NASA researchers flew an 11 ounce (312 g) model airplane with a propeller powered with solar panels illuminated by a laser. It is possible that such beam-powered propulsion could be useful for long-duration high altitude unmanned aircraft or balloons, perhaps designed to serve as communication relays or surveillance platforms.

A "laser broom" has been proposed to sweep space debris from Earth orbit. This is another proposed use of beam-powered propulsion, used on objects that were not designed to be propelled by it, for example small pieces of scrap knocked off ("spalled") satellites. The technique works since the laser power ablates one side of the object, giving an impulse that changes the eccentricity of the objects orbit. The orbit would then intersect the atmosphere and burn up.

"Lasermotive" demonstrated laser powerbeaming at one kilometer during NASA's 2009 powerbeaming contest. Also "Lighthouse DEV" (a spin off of NASA Power Beaming Team) along with "University of Maryland" is developing an eye safe laser system to power a small UAV.

High Altitude Platforms



A High Altitude Platform can be an Aeroplane, Balloon or an Airship.

A High Altitude Platform (HAP) is a quasi-stationary aircraft which provide means of delivering a service to a large area while staying thousands of feet above in the air for long periods of time. A HAP differs from other aircraft in the sense that it is specially designed to operate at a very high altitude (17–22 km) and is able to stay there for hours, even days. The new generation of HAPs, however, will expand this period to several years. .

Limitation due to power

A HAP can be a manned or unmanned aeroplane, balloon, or an airship. All require electrical power to keep themselves and their payload functional. While current HAPs are powered by batteries or engines, mission time is limited by the need for recharging/refueling. Therefore, alternative means are being considered for the future. Solar energy is one of best options currently being used for under trial HAPs (Helios, Lindstrand HALE)

Laser propulsion (Lightcraft) might be useful as an additional ground based power source.

Altitude selection for HAPs

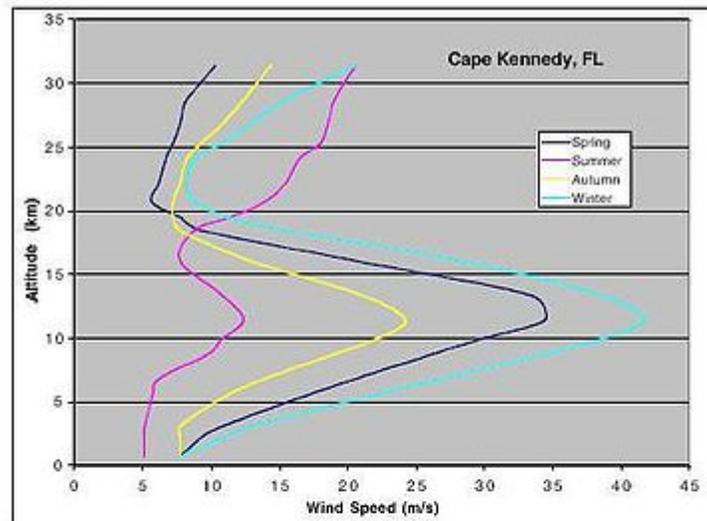


Figure 15 Mean Winds for Cape Kennedy, FL. Throughout the Year [21]

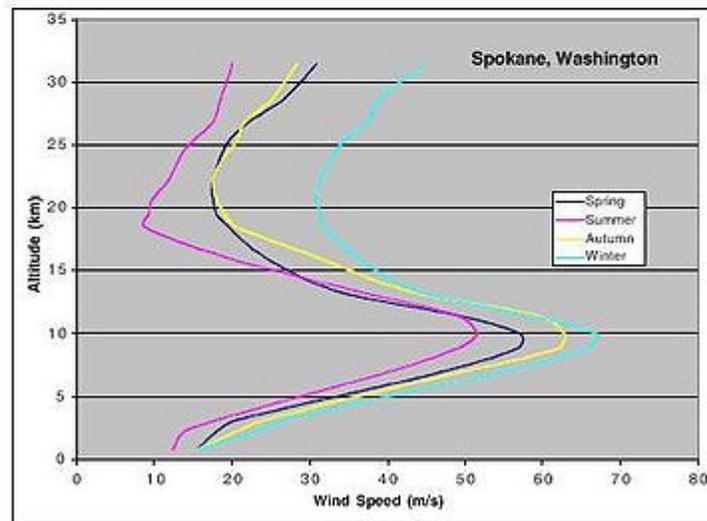


Figure 16 Mean Winds for Albuquerque, NM Throughout the Year [21]

Wind Profile variation with Altitude showing minimum wind speeds between 17-22 km altitude. (Although the absolute value of the wind speed will vary with Altitude, the trends (shown in these figures) are similar for most locations.)

Whether an airship or an aeroplane, a major challenge is the ability of the HAP to maintain stationkeeping in the face of winds. An operating altitude of between 17 and 22 km is chosen because in most regions of the world this represents a layer of relatively

mild wind and turbulence. Although the wind profile may vary considerably with latitude and with season, a form similar to that shown will usually obtain. This altitude (>17 km) is also above commercial air-traffic heights, which would otherwise prove a potentially prohibitive constraint.

Comparison to satellites

Since HAPs operate at much lower altitudes than satellite, it is possible to cover a small region much more effectively. Lower altitude also means much lower link budget (hence lower power consumption) and smaller round trip delay compared to satellites. Furthermore, deploying a satellite drains significant time and monetary resources, in terms of development and launch. HAPs, on the other hand, do not cost much and are rapidly deployable. Another major difference is that a satellite, once launched, does not allow for full maintenance, while HAPs do.

Applications

For high speed wireless communications

One of latest use of HAPs has been for wireless communications. Research on HAPs is being actively carried largely in Europe, where scientists are considering them as a platform to deliver high speed connectivity to users, over areas of up to 400 km. It has gained significant interest because HAPs will be able to deliver bandwidth and capacity similar to a broadband wireless access network (such as WiMAX) while providing a coverage area similar to that of a satellite.

For surveillance and intelligence gathering

One of the best example of a High Altitude Platform used for Surveillance and Security is RQ-4 Global Hawk UAV used by the US Air Force. It has a service ceiling of 20 km and can stay in the air for continuous 36 hours. It carries a highly sophisticated sensor system including radar, optical, and infrared imagers. It is powered by a turbofan engine and is able to deliver digital sensor data in realtime to a ground station.

For real-time monitoring of a region

Another future use which is currently being investigated is monitoring of a particular area or region for activities such as flood detection, seismic monitoring, remote sensing as well as for disaster management.

For weather/environmental monitoring and studying

Perhaps the most common use of high altitude platforms is for environment/weather monitoring. Numerous experiments are conducted through high altitude balloon mounted with scientific equipment, which is used to measure environmental changes or to keep

track of weather. Recently, NASA in partnership with The National Oceanic and Atmospheric Administration (NOAA), has started using Global Hawk UAV to study Earth's Atmosphere.

As a space port

Due to the height more than 90% of atmospheric matter is below the HAP. This reduces atmospheric drag for starting rockets. *As a rough estimate, a rocket that reaches an altitude of 20 km when launched from the ground will reach 100 km if launched at an altitude of 20 km from a balloon.* It also allows the usage of (long) mass drivers for launching goods or humans into orbits.

Chapter- 4

Reaction Engine & Electrically Powered Spacecraft Propulsion

Reaction engine

A **reaction engine** is an engine or motor which provides propulsion by expelling reaction mass, in accordance with Newton's third law of motion. This law of motion is most commonly paraphrased as: "For every action force there is an equal, but opposite, reaction force".

Examples include both jet engines and rocket engines, and more uncommon variations such as Hall effect thrusters, ion drives, mass drivers and nuclear pulse propulsion.

Thrust

The force generated by a reaction engine is in accordance with Newton's second law:

$$\vec{F} = \frac{d(m\vec{v})}{dt}$$

where:

\vec{F} is the net force vector
 m is mass of propellant and any inlet air/fluid
 \vec{v} is the velocity vector
 t is time.

Energy use

Propulsive efficiency

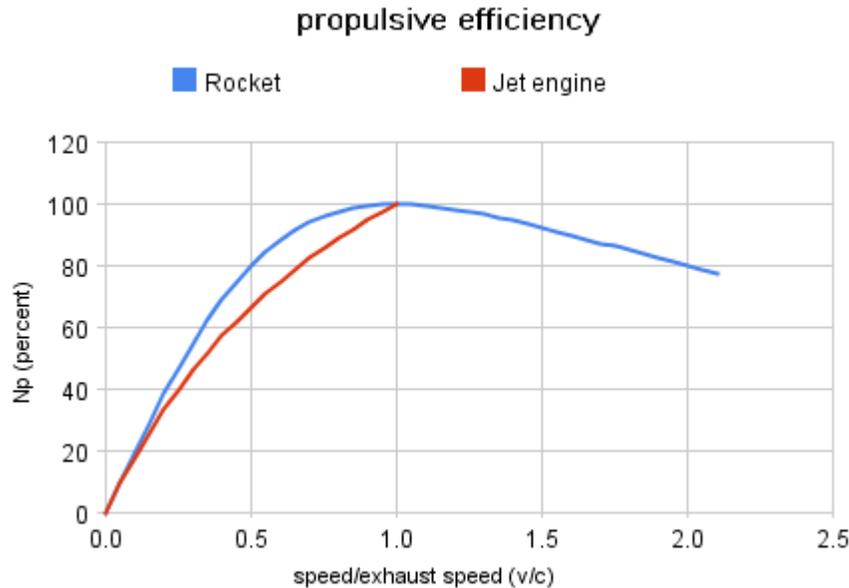
For all reaction engines which carry their propellant onboard prior to use (such as rocket engines and electric propulsion drives) some energy must go into accelerating the

reaction mass. Every engine will waste some energy, but even assuming 100% efficiency, the engine will need energy amounting to

$$\frac{1}{2}MV_e^2$$

(where M is the mass of propellant expended and V_e is the exhaust velocity)

which is simply the energy to accelerate the exhaust.



Due to energy carried away in the exhaust the energy efficiency of a reaction engine varies with the speed of the exhaust relative to the speed of the vehicle, this is called propulsive efficiency, blue is the curve for rocket-like reaction engines, red is for air-breathing (duct) reaction engines

Comparing the rocket equation (which shows how much energy ends up in the final vehicle) and the above equation (which shows the total energy required) shows 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.

Interestingly, if the I_{sp} is fixed, for a mission delta-v, there is a particular I_{sp} that minimises the overall energy used by the rocket. This comes to an exhaust velocity of about $\frac{2}{3}$ of the mission delta-v. Drives with a specific impulse that is both high and fixed such as Ion thrusters have exhaust velocities that can be enormously higher than this ideal, and thus end up powersource limited and give very low thrust. Where the vehicle performance is power limited, e.g. if solar power or nuclear 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 proportional to v_e . Thus the latter should not be too large.

On the other hand if the exhaust velocity can be made to vary so that at each instant it is equal and opposite to the vehicle velocity then the absolute minimum energy usage is achieved. When this is achieved, the exhaust stops in space ^ and has no kinetic energy; and the propulsive efficiency is 100% all the energy ends up in the vehicle (in principle such a drive would be 100% efficient, in practice there would be thermal losses from within the drive system and residual heat in the exhaust). However in most cases this uses an impractical quantity of propellant, but is a useful theoretical consideration.

Some drives (such as VASIMR or Electrodeless plasma thruster) actually can significantly vary their exhaust velocity. This can help reduce propellant usage and improve acceleration at different stages of the flight. However the best energetic performance and acceleration is still obtained when the exhaust velocity is close to the vehicle speed. Proposed ion and plasma drives usually have exhaust velocities enormously higher than that ideal (in the case of VASIMR the lowest quoted speed is around 15000 m/s compared to a mission delta-v from high Earth orbit to Mars of about 4000m/s).

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.

Cycle efficiency

All reaction engines lose some energy- mostly as heat.

Different reaction engines have different efficiencies and losses. For example rocket engines can be up to 60-70% energy efficient in terms of accelerating the propellant- the rest is lost as heat primarily in the exhaust, but also a small amount lost as thermal radiation.

Oberth effect

Reaction engines are more energy efficient when they emit their reaction mass when the vehicle is travelling at high speed.

This is because the useful mechanical energy generated is simply force times distance, and when a thrust force is generated while the vehicle moves, then:

$$E = F \times d$$

where F is the force and d is the distance moved.

Dividing by length of time of motion we get:

$$\frac{E}{t} = P = \frac{F \times d}{t} = F \times v$$

Hence:

$$P = F \times v$$

where P is the useful power and v is the speed.

Hence you want v to be as high as possible; and a stationary engine does no useful work.

Types of reaction engines

- Rocket-like
 - Rocket engine
 - VASIMR
 - Electric propulsion
- Airbreathing
 - turbojet
 - turbofan
 - Pulsejet
 - Ramjet
 - Scramjet
- Liquid
 - Pump-jet
- Rotary
 - aeolipile
- solid exhaust
 - mass driver

Electrically powered spacecraft propulsion

An **electrically powered spacecraft propulsion** system is any of a number of forms of electric motors which spacecraft can employ to gain mechanical energy in outer space. Most of these kinds of spacecraft propulsion work by electrically powering propellant to high speed, but electrodynamic tethers work by interacting with a planet's magnetosphere.

Electric thrusters typically offer much higher specific impulse, however, due to practical power source constraints thrust is weaker compared to chemical thrusters by several orders of magnitude. Russian satellites have used electric propulsion for decades, and

newer Western geo-orbiting spacecraft are starting to use them for north-south stationkeeping.

History

The idea of electric propulsion dates back to 1906, when Robert Goddard considered the possibility in his personal notebook. Konstantin Tsiolkovsky published the idea in 1911.

Types of electric propulsion

Ion/plasma drives

This type of rocket-like reaction engine uses electric energy to obtain thrust from propellant carried with the vehicle. Unlike rocket engines, these kinds of engines do not necessarily have rocket nozzles, and thus many types are not considered true rockets. Electric propulsion thrusters for spacecraft are usually grouped in three families based on the type of force used to accelerate the ions of the plasma:

Electrostatic

If the acceleration is caused mainly by the Coulomb Force (i.e application of a static electric field in the direction of the acceleration) the device is considered electrostatic.

- Electrostatic ion thruster
- Hall effect thruster
- Field Emission Electric Propulsion
- Colloid thruster

Electrothermal

The electrothermal category groups the devices where electromagnetic fields are used to generate a plasma to increase the heat of the bulk propellant. The thermal energy imparted to the propellant gas is then converted into kinetic energy by a nozzle of either solid material or magnetic fields. Low molecular weight gases (e.g. hydrogen, helium, ammonia) are preferred propellants for this kind of system.

Performance of electrothermal systems in terms of specific impulse (Isp) is somewhat modest (500 to ~1000 seconds), but exceeds that of cold gas thrusters, monopropellant rockets, and even most bipropellant rockets. In the USSR, electrothermal engines were used since 1971; the Soviet "Meteor-3", "Meteor-Priroda", "Resurs-O" satellite series and the Russian "Elektro" satellite are equipped with them. Electrothermal systems by Aerojet (MR-510) are currently used on Lockheed-Martin A2100 satellites using hydrazine as a propellant.

- DC arcjet

- microwave arcjet
- Pulsed plasma thruster

Electromagnetic

If ions are accelerated either by the Lorentz Force or by the effect of an electromagnetic fields where the electric field is not in the direction of the acceleration, the device is considered electromagnetic.

- Electrodeless plasma thruster
- MPD thruster
- Pulsed inductive thruster
- Helicon Double Layer Thruster
- VASIMR

Other

- Vacuum arc thruster

Steady vs. unsteady

Electric propulsion systems can also be characterized as either **steady** (continuous firing for a prescribed duration) or **unsteady** (pulsed firings accumulating to a desired impulse). However, these classifications are not unique to electric propulsion systems and can be applied to all types of propulsion engines.

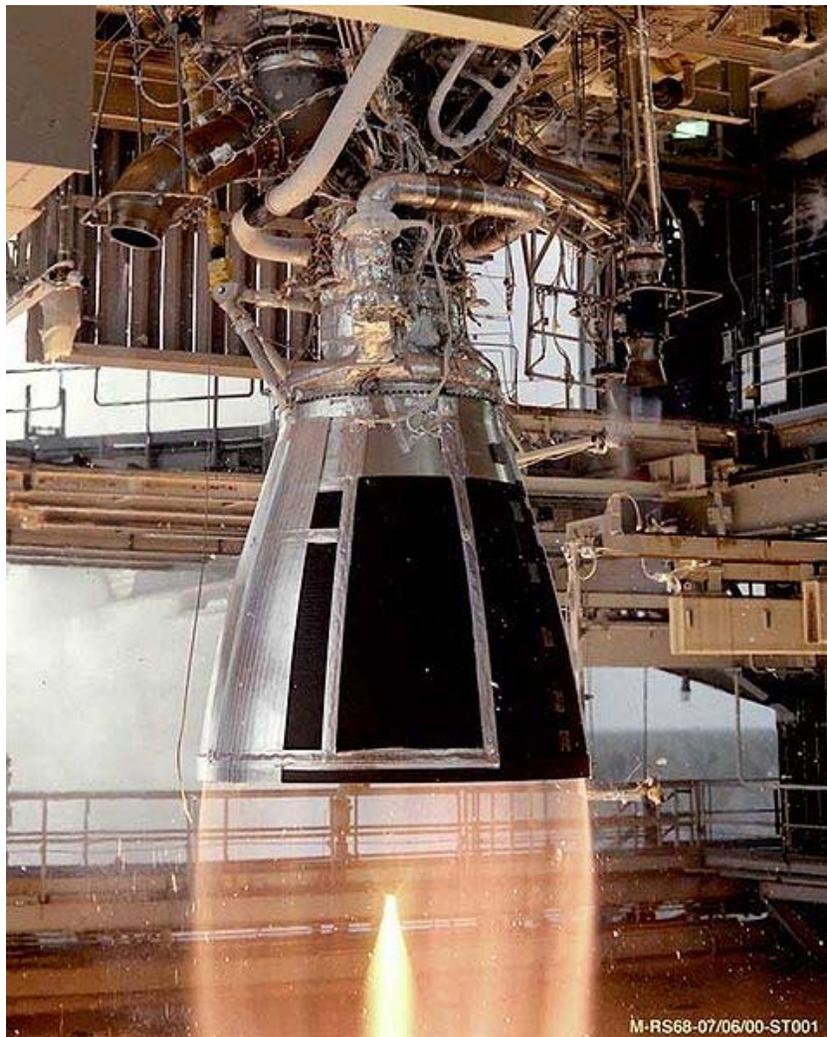
Non ion drives

Electrodynamic tether

Electrodynamic tethers are long conducting wires, such as one deployed from a tether satellite, which can operate on electromagnetic principles as generators, by converting their kinetic energy to electrical energy, or as motors, converting electrical energy to kinetic energy. Electric potential is generated across a conductive tether by its motion through the Earth's magnetic field. The choice of the metal conductor to be used in an electrodynamic tether is determined by a variety of factors. Primary factors usually include high electrical conductivity, and low density. Secondary factors, depending on the application, include cost, strength, and melting point.

Chapter- 5

Rocket Engine



RS-68 being tested at NASA's Stennis Space Center. The nearly transparent exhaust is due to this engine's exhaust being mostly superheated steam (water vapor from its propellants, hydrogen and oxygen)



Viking 5C rocket engine

A **rocket engine**, or simply "rocket," is a jet engine that uses only propellant mass for forming its high speed propulsive jet. Rocket engines are reaction engines and obtain thrust in accordance with Newton's third law. Since they need no external material to form their jet, rocket engines can be used for spacecraft propulsion as well as terrestrial uses, such as missiles. Most rocket engines are internal combustion engines, although non-combusting forms also exist.

Rocket engines as a group, have the highest exhaust velocities, are by far the lightest, and are the most energy efficient (at least at very high speed) of all types of jet engines. However, for the thrust they give, due to the high exhaust velocity and relatively low specific energy of rocket propellant, they consume propellant very rapidly.

Terminology

Chemical rockets are rockets powered by exothermic chemical reactions of the propellant.

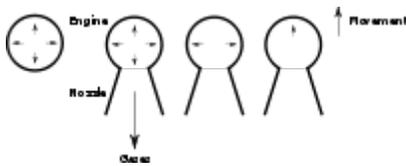
Rocket motor (or **solid-propellant rocket motor**) is a synonymous term with rocket engine that usually refers to solid rocket engines.

Liquid rockets (or **liquid-propellant rocket engine**) use one or more liquid propellants that are held in tanks prior to burning.

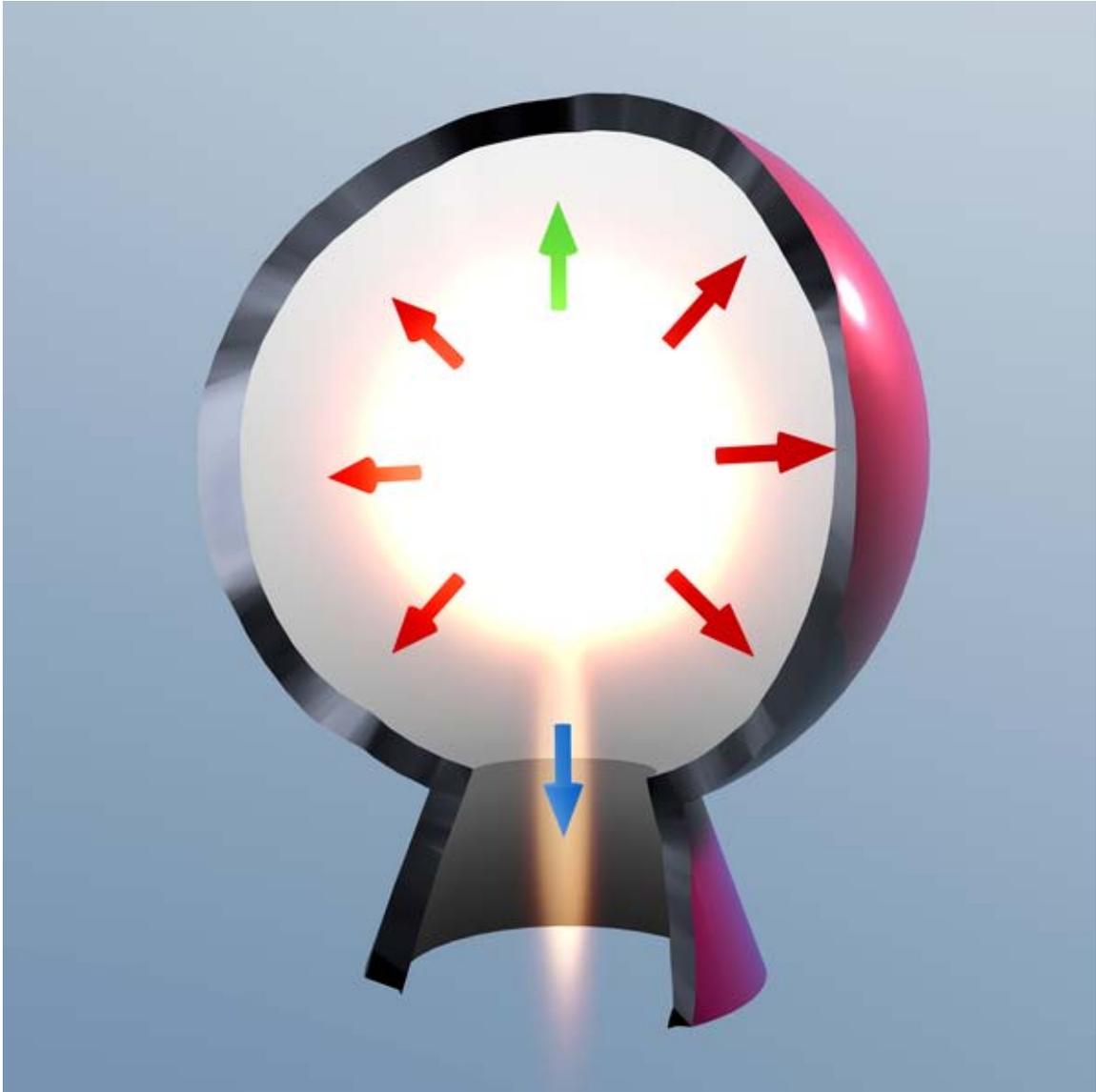
Hybrid rockets have a solid propellant in the combustion chamber and a second liquid or gas propellant is added to permit it to burn.

Thermal rockets are rockets where the propellant is inert, but is heated by a power source such as solar or nuclear power or beamed energy.

Principle of operation



How rocket engines work



Rocket engines give part of their thrust due to unopposed pressure on the combustion chamber

Rocket engines produce thrust by the expulsion of a high-speed fluid exhaust. This fluid is nearly always a gas which is created by high pressure (10-200 bar) combustion of solid or liquid propellants, consisting of fuel and oxidiser components, within a combustion chamber.

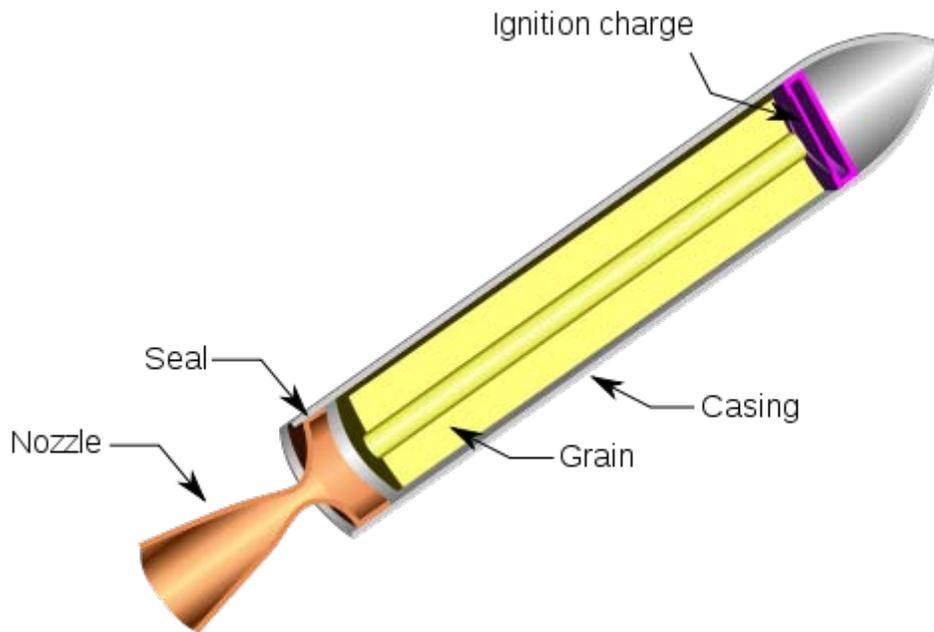
The fluid exhaust is then passed through a propelling nozzle which typically uses the heat energy of the gas to accelerate the exhaust to very high speed, and the reaction to this pushes the engine in the opposite direction.

In rocket engines, high temperatures and pressures are highly desirable for good performance as this permits a longer nozzle to be fitted to the engine, which gives higher exhaust speeds, as well as giving better thermodynamic efficiency.

Introducing propellant into a combustion chamber

Rocket propellant is mass that is stored, usually in some form of propellant tank, prior to being ejected from a rocket engine in the form of a fluid jet to produce thrust.

Chemical rocket propellants are most commonly used, which undergo exothermic chemical reactions which produce hot gas which is used by a rocket for propulsive purposes. Alternatively, a chemically inert reaction mass can be heated using a high-energy power source via a heat exchanger, and then no combustion chamber is used.



A solid rocket motor.

Solid rocket propellants are prepared as a mixture of fuel and oxidizing components called 'grain' and the propellant storage casing effectively becomes the combustion chamber. Liquid-fueled rockets typically pump separate fuel and oxidiser components into the combustion chamber, where they mix and burn. Hybrid rocket engines use a combination of solid and liquid or gaseous propellants. Both liquid and hybrid rockets use *injectors* to introduce the propellant into the chamber. These are often an array of simple jets- holes through which the propellant escapes under pressure; but sometimes may be more complex spray nozzles. When two or more propellants are injected the jets usually deliberately collide the propellants as this breaks up the flow into smaller droplets that burn more easily.

Combustion chamber

For chemical rockets the combustion chamber is typically just a cylinder, and flame holders are rarely used. The dimensions of the cylinder are such that the propellant is able to combust thoroughly; different propellants require different combustion chamber sizes for this to occur. This leads to a number called L^* :

$$L^* = \frac{V_c}{A_t}$$

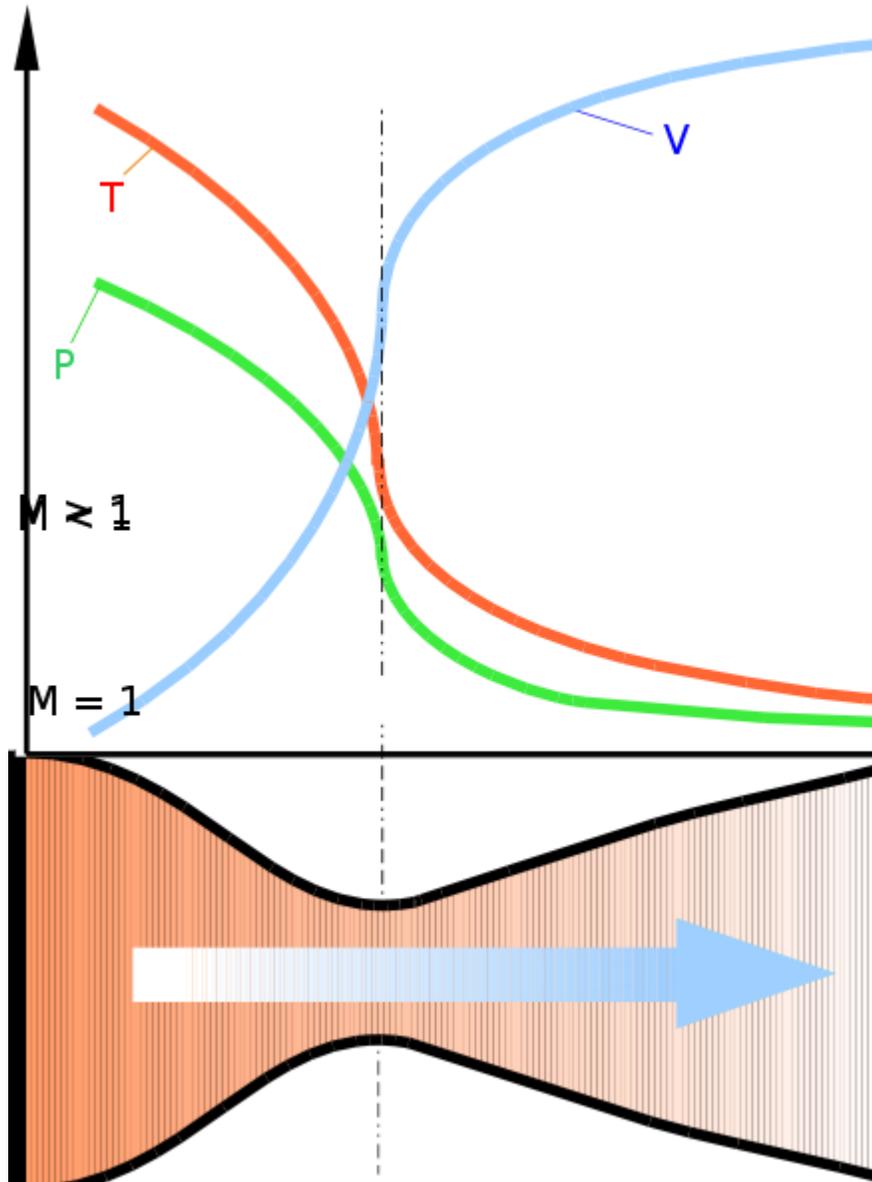
where:

- V_c is the volume of the chamber
- A_t is the area of the throat

L^* is typically in the range of 25–60 inches (0.63–1.5 m).

The combination of temperatures and pressures typically reached in a combustion chamber is usually extreme by any standards. Unlike in air-breathing jet engines, no atmospheric nitrogen is present to dilute and cool the combustion, and the temperature can reach true stoichiometric. This, in combination with the high pressures, means that the rate of heat conduction through the walls is very high.

Rocket nozzles



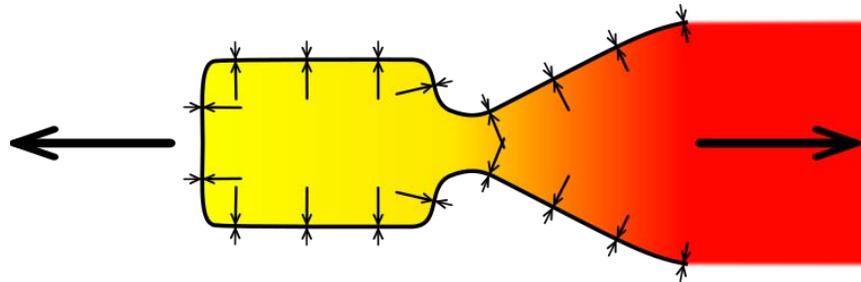
Typical temperatures (T) and pressures (p) and speeds (v) in a De Laval Nozzle

The large bell or cone shaped expansion nozzle gives a rocket engine its characteristic shape.

In rockets the hot gas produced in the combustion chamber is permitted to escape from the combustion chamber through an opening (the "throat"), within a high expansion-ratio 'de Laval' nozzle.

Provided sufficient pressure is provided to the nozzle (about 2.5-3x above ambient pressure) the nozzle *chokes* and a supersonic jet is formed, dramatically accelerating the gas, converting most of the thermal energy into kinetic energy.

The exhaust speeds vary, depending on the expansion ratio the nozzle is designed to give, but exhaust speeds as high as ten times the speed of sound of sea level air are not uncommon.



Rocket thrust is caused by pressures acting in the combustion chamber and nozzle. From Newton's third law, equal and opposite pressures act on the exhaust, and this accelerates it to high speeds.

About half of the rocket engine's thrust comes from the unbalanced pressures inside the combustion chamber and the rest comes from the pressures acting against the inside of the nozzle. As the gas expands (adiabatically) the pressure against the nozzle's walls forces the rocket engine in one direction while accelerating the gas in the other.

Propellant efficiency

For a rocket engine to be propellant efficient, it is important that the maximum pressures possible be created on the walls of the chamber and nozzle by a specific amount of propellant; as this is the source of the thrust. This can be achieved by all of:

- heating the propellant to as high a temperature as possible (using a high energy fuel, containing hydrogen and carbon and sometimes metals such as aluminium, or even using nuclear energy)
- using a low specific density gas (as hydrogen rich as possible)
- using propellants which are, or decompose to, simple molecules with few degrees of freedom to maximise translational velocity

Since all of these things minimise the mass of the propellant used, and since pressure is proportional to the mass of propellant present to be accelerated as it pushes on the engine, and since from Newton's third law the pressure that acts on the engine also reciprocally acts on the propellant, it turns out that for any given engine the speed that the propellant leaves the chamber is unaffected by the chamber pressure (although the thrust is proportional). However, speed is significantly affected by all three of the above factors and the exhaust speed is an excellent measure of the engine propellant efficiency. This is termed *exhaust velocity*, and after allowance is made for factors that can reduce it, the **effective exhaust velocity** is one of the most important parameters of a rocket engine (although weight, cost, ease of manufacture etc. are usually also very important).

For aerodynamic reasons the flow goes sonic ("chokes") at the narrowest part of the nozzle, the 'throat'. Since the speed of sound in gases increases with the square root of temperature, the use of hot exhaust gas greatly improves performance. By comparison, at room temperature the speed of sound in air is about 340 m/s while the speed of sound in the hot gas of a rocket engine can be over 1700 m/s; much of this performance is due to the higher temperature, but additionally rocket propellants are chosen to be of low molecular mass, and this also gives a higher velocity compared to air.

Expansion in the rocket nozzle then further multiplies the speed, typically between 1.5 and 2 times, giving a highly collimated hypersonic exhaust jet. The speed increase 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, but detailed properties of the gas are also important. Larger ratio nozzles are more massive but are able to extract more heat from the combustion gases, increasing the exhaust velocity.

Nozzle efficiency is affected by operation in the atmosphere because atmospheric pressure changes with altitude; but due to the supersonic speeds of the gas exiting from a rocket engine, the pressure of the jet may be either below or above ambient, and equilibrium between the two is not reached at all altitudes.

Back pressure and optimal expansion

For optimal performance the pressure of the gas at the end of the nozzle should just equal the ambient pressure: if the exhaust's pressure is lower than the ambient pressure, then the vehicle will be slowed by the difference in pressure between the top of the engine and the exit; on the other hand, if the exhaust's pressure is higher, then exhaust pressure that could have been converted into thrust is not converted, and energy is wasted.

To maintain this ideal of equality between the exhaust's exit pressure and the ambient pressure, the diameter of the nozzle would need to increase with altitude, giving the pressure a longer nozzle to act on (and reducing the exit pressure and temperature). This increase is difficult to arrange in a lightweight fashion, although is routinely done with other forms of jet engines. In rocketry a lightweight compromise nozzle is generally used and some reduction in atmospheric performance occurs when used at other than the 'design altitude' or when throttled. 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 providing 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 altitudes.

When exhausting into a sufficiently low ambient pressure (vacuum) several issues arise. One is the sheer weight of the nozzle- beyond a certain point, for a particular vehicle, the extra weight of the nozzle outweighs any performance gained. Secondly, as the exhaust gases adiabatically expand within the nozzle they cool, and eventually some of the chemicals can freeze, producing 'snow' within the jet. This causes instabilities in the jet and must be avoided.

On a De Laval nozzle, exhaust gas flow detachment will occur in a grossly over-expanded nozzle. As the detachment point will not be uniform around the axis of the engine, a side force may be imparted to the engine. This side force may change over time and result in control problems with the launch vehicle.

Thrust vectoring

Many engines require the overall thrust to change direction over the length of the burn. A number of different ways to achieve this have been flown:

- The entire engine is mounted on a hinge or gimbal and any propellant feeds reach the engine via low pressure flexible pipes or rotary couplings.
- Just the combustion chamber and nozzle is gimbled, the pumps are fixed, and high pressure feeds attach to the engine
- multiple engines (often canted at slight angles) are deployed but throttled to give the overall vector that is required, giving only a very small penalty
- fixed engines with vernier thrusters
- high temperature vanes held in the exhaust that can be tilted to deflect the jet

Overall rocket engine performance

Rocket technology can combine very high thrust (meganewtons), very high exhaust speeds (around 10 times the speed of sound in air at sea level) and very high thrust/weight ratios (>100) *simultaneously* as well as being able to operate outside the atmosphere, and while permitting the use of low pressure and hence lightweight tanks and structure.

Rockets can be further optimised to even more extreme performance along one or more of these axes at the expense of the others.

Specific impulse

The most important metric for the efficiency of a rocket engine is impulse per unit of propellant, this is called specific impulse (usually written I_{sp}). This is either measured as a speed (the *effective exhaust velocity* V_e in metres/second or ft/s) or as a time (seconds). An engine that gives a large specific impulse is normally highly desirable.

The specific impulse that can be achieved is primarily a function of the propellant mix (and ultimately would limit the specific impulse), but practical limits on chamber pressures and the nozzle expansion ratios reduce the performance that can be achieved.

Typical performances of common propellants

Propellant mix	Vacuum Isp (seconds)	Effective exhaust velocity (m/s)
liquid oxygen/ liquid hydrogen	455	4462

liquid oxygen/ kerosene (RP-1)	358	3510
nitrogen tetroxide/ hydrazine	305	2993

n.b. All performances at a nozzle expansion ratio of 40

Net thrust

Below is an approximate equation for calculating the net thrust of a rocket engine:

$$F_n = \dot{m} V_e = \dot{m} V_{e-act} + A_e(P_e - P_{amb})$$

where:

\dot{m} = exhaust gas mass flow

V_e = effective exhaust velocity

V_{e-act} = actual jet velocity at nozzle exit plane

A_e = flow area at nozzle exit plane (or the plane where the jet leaves the nozzle if separated flow)

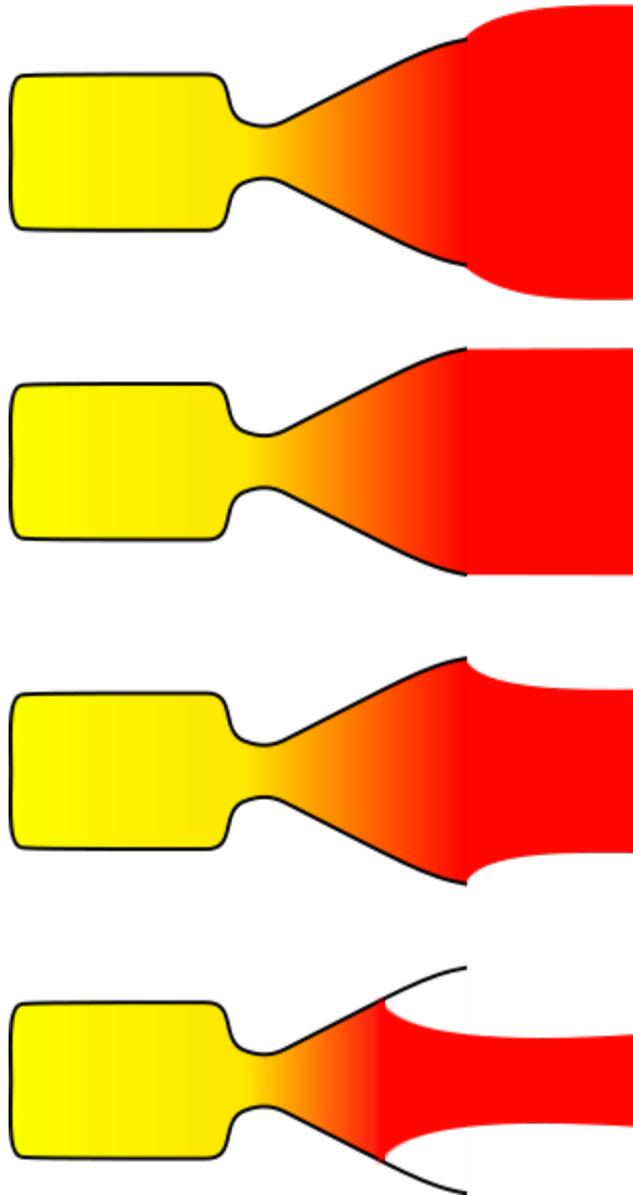
P_e = static pressure at nozzle exit plane

P_{amb} = ambient (or atmospheric) pressure

Since, unlike a jet engine, a conventional rocket motor lacks an air intake, there is no 'ram drag' to deduct from the gross thrust. Consequently the net thrust of a rocket motor is equal to the gross thrust (apart from static back pressure).

The $\dot{m} V_{e-act}$ term represents the momentum thrust, which remains constant at a given throttle setting, whereas the $A_e(P_e - P_{amb})$ term represents the pressure thrust term. At full throttle, the net thrust of a rocket motor improves slightly with increasing altitude, because as atmospheric pressure decreases with altitude, the pressure thrust term increases. At the surface of the Earth the pressure thrust may be reduced by up to 30%, depending on the engine design. This reduction drops roughly exponentially to zero with increasing altitude.

Maximum thrust for a rocket engine is achieved by maximizing the momentum contribution of the equation without incurring penalties from over expanding the exhaust. This occurs when $P_e = P_{amb}$. Since ambient pressure changes with altitude, most rocket engines spend very little time operating at peak efficiency.



If the pressure of the exhaust jet varies from atmospheric pressure, nozzles can be said to be (top to bottom):

Underexpanded

Ambient

Overexpanded

Grossly overexpanded

If under or overexpanded then loss of efficiency occurs, grossly overexpanded nozzles lose less efficiency, but can cause mechanical issues with the nozzle. Rockets become progressively more underexpanded as they gain altitude. Note that almost all rocket engines will be momentarily grossly overexpanded during startup in an atmosphere.

Vacuum Isp

Due to the specific impulse varying with pressure, a quantity that is easy to compare and calculate with is useful. Because rockets choke at the throat, and because the supersonic exhaust prevents external pressure influences travelling upstream, it turns out that the pressure at the exit is ideally exactly proportional to the propellant flow \dot{m} , provided the mixture ratios and combustion efficiencies are maintained. It is thus quite usual to rearrange the above equation slightly:

$$F_{vac} = C_f \dot{m} c^*$$

and so define the *vacuum Isp* to be:

$$V_{evac} = C_f c^*$$

Where:

$$c^* = \text{the speed of sound constant at the throat}$$

$$C_f = \text{the thrust coefficient constant of the nozzle (typically about 2)}$$

And hence:

$$F_n = \dot{m} V_{evac} - A_e P_{amb}$$

Throttling

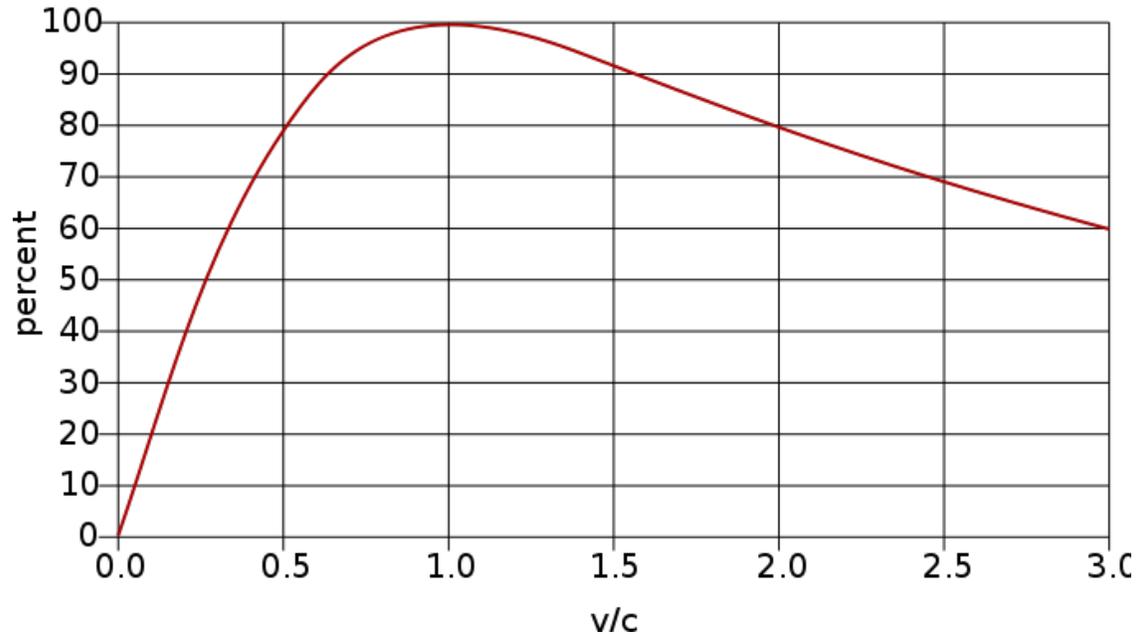
Rockets can be throttled by controlling the propellant combustion rate \dot{m} (usually measured in kg/s or lb/s). In liquid and hybrid rockets, the propellant flow entering the chamber is controlled using valves, in solid rockets it is controlled by changing the area of propellant that is burning and this can be designed into the propellant grain (and hence cannot be controlled in real-time).

Rockets can usually be throttled down to an exit pressure of about one-third of ambient pressure (often limited flow separation in nozzles) and up to a maximum limit determined only by the mechanical strength of the engine.

In practice, the degree to which rockets can be throttled varies greatly, but most rockets can be throttled by a factor of 2 without great difficulty; the typical limitation is combustion stability, as for example, injectors need a minimum pressure to avoid triggering damaging oscillations (chugging or combustion instabilities); but injectors can often be optimised and tested for wider ranges. Solid rockets can be throttled by using shaped grains that will vary their surface area over the course of the burn.

Energy efficiency

Propulsive efficiency



Rocket energy efficiency as a function of vehicle speed divided by effective exhaust speed

Rocket engine nozzles are surprisingly efficient heat engines for generating a high speed jet, as a consequence of the high combustion temperature and high compression ratio. Rocket nozzles give an excellent approximation to adiabatic expansion which is a reversible process, and hence they give efficiencies which are very close to that of the Carnot cycle. Given the temperatures reached, over 60% efficiency can be achieved with chemical rockets.

For a *vehicle* employing a rocket engine the energetic efficiency is very good if the vehicle speed approaches or somewhat exceeds the exhaust velocity (relative to launch); but at low speeds the energy efficiency goes to 0% at zero speed (as with all jet propulsion.)

Thrust to weight ratio

Rockets, of all the jet engines, indeed of essentially all engines, have the highest thrust to weight ratio. This is especially true for liquid rocket engines.

This high performance is due to the small volume of pressure vessels that make up the engine- the pumps, pipes and combustion chambers involved. The lack of inlet duct and the use of dense liquid propellant allows the pressurisation system to be small and lightweight, whereas duct engines have to deal with air which has a density about one thousand times lower.

Jet or Rocket engine	Mass, kg	Jet or rocket thrust, kN	Thrust-to-weight ratio
RD-0410 nuclear rocket engine	2000	35.2	1.8
J-58 (SR-71 Blackbird jet engine)	2722	150	5.2
Concorde's Rolls-Royce/Snecma Olympus 593 turbojet with reheat	3175	169.2	5.4
RD-0750 rocket engine, three-propellant mode	4621	1413	31.2
RD-0146 rocket engine	260	98	38.5
Space Shuttle's SSME rocket engine	3177	2278	73.2
RD-180 rocket engine	5393	4152	78.6
F-1 (Saturn V first stage)	8391	7740.5	94.1
NK-33 rocket engine	1222	1638	136.8

Rocket thrusts are vacuum thrusts unless otherwise noted

Of the liquid propellants used, density is worst for liquid hydrogen. Although this propellant is marvellous in many ways, it has a very low density, about one fourteenth that of water. This makes the turbopumps and pipework larger and heavier, and this is reflected in the thrust-to-weight ratio of engines that use it (for example the SSME) compared to those that do not (NK-33).

Cooling

For efficiency reasons, and because they physically can, rockets run with combustion temperatures that can reach ~3500 K (~5800 °F)(~3227 °C).

Most other jet engines have gas turbines in the hot exhaust. Due to their larger surface area, they are harder to cool and hence there is a need to run the combustion processes at much lower temperatures, losing efficiency. In addition duct engines use air as an oxidant, which contains 80% largely unreactive nitrogen, which dilutes the reaction and lowers the temperatures. Rockets have none of these inherent disadvantages.

Therefore in rockets temperatures employed are very often far higher than the melting point of the nozzle and combustion chamber materials, two exceptions are graphite and tungsten (~1200 K for copper), however both are subject to oxidation if not protected. Indeed many construction materials can make perfectly acceptable propellants in their own right. It is important that these materials be prevented from combusting, melting or vaporising to the point of failure. This is sometimes somewhat facetiously termed an 'engine rich exhaust'. Materials technology could potentially place an upper limit on the exhaust temperature of chemical rockets.

Alternatively, rockets may use more common construction materials such as aluminium, steel, nickel or copper alloys and employ cooling systems that prevent the construction 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, are employed to give longer nozzle and chamber life. These techniques ensure that a gaseous thermal boundary layer touching the material is kept below the temperature which would cause the material to catastrophically fail.

In rockets, the heat fluxes that can pass through the wall are among the highest in engineering, fluxes are generally in the range of 1-200 MW/m². The strongest heat fluxes are found at the throat, which often sees twice that found in the associated chamber and nozzle. This is due to the combination of high speeds (which gives a very thin boundary layer), and although lower than the chamber, the high temperatures seen there.

In rockets the coolant methods include:

1. uncooled (used for short runs mainly during testing)
2. ablative walls (walls are lined with a material that is continuously vaporised and carried away).
3. radiative cooling (the chamber becomes almost white hot and radiates the heat away)
4. dump cooling (a propellant, usually hydrogen, is passed around the chamber and dumped)
5. regenerative cooling (liquid rockets use the fuel, or occasionally the oxidiser, to cool the chamber via a cooling jacket before being injected)
6. curtain cooling (propellant injection is arranged so the temperature of the gases is cooler at the walls)
7. film cooling (surfaces are wetted with liquid propellant, which cools as it evaporates)

In all cases the cooling effect that prevents the wall from being destroyed is caused by a thin layer of insulating fluid (a boundary layer) that is in contact with the walls that is far cooler than the combustion temperature. Provided this boundary layer is intact the wall will not be damaged.

Disruption of the boundary layer may occur during cooling failures or combustion instabilities, and wall failure typically occurs soon after.

With regenerative cooling a second boundary layer is found in the coolant channels around the chamber. This boundary layer thickness needs to be as small as possible, since the boundary layer acts as an insulator between the wall and the coolant. This may be achieved by making the coolant velocity in the channels as high as possible.

In practice, regenerative cooling is nearly always used in conjunction with curtain cooling and/or film cooling.

Liquid fuelled engines are often run fuel rich, which results in a cooler burning exhaust. Cooler exhaust reduces heat loads on the engine allowing lower cost materials, a simplified cooling system, and a lower performance engine.

Mechanical issues

Rocket combustion chambers are normally operated at fairly high pressure, typically 10-200 bar (1 to 20 MPa, 150-3000 psi). When operated within significant atmospheric pressure, higher combustion chamber pressures give better performance by permitting a larger and more efficient nozzle to be fitted without it being grossly overexpanded.

However, these high pressures cause the outermost part of the chamber to be under very large hoop stresses – rocket engines are pressure vessels.

Worse, due to the high temperatures created in rocket engines the materials used tend to have a significantly lowered working tensile strength.

In addition, significant temperature gradients are set up in the walls of the chamber and nozzle, these cause differential expansion of the inner liner that create internal stresses.

Acoustic issues

In addition, the extreme vibration and acoustic environment inside a rocket motor commonly result in peak stresses well above mean values, especially in the presence of organ pipe-like resonances and gas turbulence.

Combustion instabilities

The combustion may display undesired instabilities, of sudden or periodic nature. The pressure in the injection chamber may increase until the propellant flow through the injector plate decreases; a moment later the pressure drops and the flow increases, injecting more propellant in the combustion chamber which burns a moment later, and again increases the chamber pressure, repeating the cycle. This may lead to high-amplitude pressure oscillations, often in ultrasonic range, which may damage the motor. Oscillations of ± 200 psi at 25 kHz were the cause of failures of early versions of the Titan II missile second stage engines. The other failure mode is a deflagration to detonation transition; the supersonic pressure wave formed in the combustion chamber may destroy the engine.

The combustion instabilities can be provoked by remains of cleaning solvents in the engine, reflected shock wave, initial instability after ignition, explosion near the nozzle that reflects into the combustion chamber, and many more factors. In stable engine designs the oscillations are quickly suppressed; in unstable designs they persist for prolonged periods. Oscillation suppressors are commonly used.

Periodic variations of thrust, caused by combustion instability or longitudinal vibrations of structures between the tanks and the engines which modulate the propellant flow, are known as "pogo oscillations" or "pogo", named after the pogo stick.

Three different types of combustion instabilities occur:

Chugging

This is a low frequency oscillation at a few Hertz in chamber pressure usually caused by pressure variations in feed lines due to variations in acceleration of the vehicle. This can cause cyclic variation in thrust, and the effects can vary from merely annoying to actually damaging the payload or vehicle. Chugging can be minimised by using gas-filled damping tubes on feed lines of high density propellants.

Buzzing

This can be caused due to insufficient pressure drop across the injectors. It generally is mostly annoying, rather than being damaging. However, in extreme cases combustion can end up being forced backwards through the injectors – this can cause explosions with monopropellants.

Screeching

This is the most immediately damaging, and the hardest to control. It is due to acoustics within the combustion chamber that often couples to the chemical combustion processes that are the primary drivers of the energy release, and can lead to unstable resonant "screeching" that commonly leads to catastrophic failure due to thinning of the insulating thermal boundary layer. Such effects are very difficult to predict analytically during the design process, and have usually been addressed by expensive, time consuming and extensive testing, combined with trial and error remedial correction measures.

Screeching is often dealt with by detailed changes to injectors, or changes in the propellant chemistry, or vaporizing the propellant before injection, or use of Helmholtz dampers within the combustion chambers to change the resonant modes of the chamber.

Testing for the possibility of screeching is sometimes done by exploding small explosive charges outside the combustion chamber with a tube set tangentially to the combustion chamber near the injectors to determine the engine's impulse response and then evaluating the time response of the chamber pressure- a fast recovery indicates a stable system.

Exhaust noise

For all but the very smallest sizes, rocket exhaust compared to other engines is generally very noisy. As the hypersonic exhaust mixes with the ambient air, shock waves are formed. The Space Shuttle generates over 200 dB(A) of noise around its base.

The Saturn V launch was detectable on seismometers a considerable distance from the launch site. The sound intensity from the shock waves generated depends on the size of the rocket and on the exhaust velocity. Such shock waves seem to account for the characteristic crackling and popping sounds produced by large rocket engines when heard live. These noise peaks typically overload microphones and audio electronics, and so are generally weakened or entirely absent in recorded or broadcast audio reproductions. For large rockets at close range, the acoustic effects could actually kill.

More worryingly for space agencies, such sound levels can also damage the launch structure, or worse, be reflected back at the comparatively delicate rocket above. This is why so much water is typically used at launches. The water spray changes the acoustic qualities of the air and reduces or deflects the sound energy away from the rocket.

Generally speaking noise is most intense when a rocket is close to the ground, since the noise from the engines radiates up away from the plume, as well as reflecting off the ground. Also, when the vehicle is moving slowly, little of the chemical energy input to the engine can go into increasing the kinetic energy of the rocket (since useful power P transmitted to the vehicle is $P = F * V$ for thrust F and speed V). Then the largest portion of the energy is dissipated in the exhaust's interaction with the ambient air, producing noise. This noise can be reduced somewhat by flame trenches with roofs, by water injection around the plume and by deflecting the plume at an angle.

Testing

Rocket engines are usually statically tested at a test facility before being put into production. For high altitude engines, either a shorter nozzle must be used, or the rocket must be tested in a large vacuum chamber.

Safety

Rockets have a reputation for unreliability and danger; especially catastrophic failures. Contrary to this reputation, carefully designed rockets can be made arbitrarily reliable. In military use, rockets are not unreliable. However, one of the main non-military uses of rockets is for orbital launch. In this application, the premium is on minimum weight, and it is difficult to achieve high reliability and low weight simultaneously. In addition, if the number of flights launched is low, there is a very high chance of a design, operations or manufacturing error causing destruction of the vehicle. Essentially all launch vehicles are test vehicles by normal aerospace standards (as of 2006).

The X-15 rocket plane achieved a 0.5% failure rate, with a single catastrophic failure during ground test, and the SSME has managed to avoid catastrophic failures in over 350 engine-flights.

Chemistry

Rocket propellants require a high specific energy (energy per unit mass), because ideally all the reaction energy appears as kinetic energy of the exhaust gases, and exhaust velocity is the single most important performance parameter of an engine, on which vehicle performance depends.

Aside from inevitable losses and imperfections in the engine, incomplete combustion, etc., after specific reaction energy, the main theoretical limit reducing the exhaust velocity obtained is that, according to the laws of thermodynamics, a fraction of the chemical energy may go into rotation of the exhaust molecules, where it is unavailable for producing thrust. Monatomic gases like helium have only three degrees of freedom, corresponding to the three dimensions of space, $\{x,y,z\}$, and only such spherically symmetric molecules escape this kind of loss. A diatomic molecule like H_2 can rotate about either of the two axes perpendicular to the one joining the two atoms, and as the equipartition law of statistical mechanics demands that the available thermal energy be divided equally among the degrees of freedom, for such a gas in thermal equilibrium $3/5$ of the energy can go into unidirectional motion, and $2/5$ into rotation. A triatomic molecule like water has six degrees of freedom, so the energy is divided equally among rotational and translational degrees of freedom. For most chemical reactions the latter situation is the case. This issue is traditionally described in terms of the ratio, gamma, of the specific heat of the gas at constant volume to that at constant pressure. The rotational energy loss is largely recovered in practice if the expansion nozzle is large enough to allow the gases to expand and cool sufficiently, the function of the nozzle being to convert the random thermal motions of the molecules in the combustion chamber into the unidirectional translation that produces thrust. As long as the exhaust gas remains in equilibrium as it expands, the initial rotational energy will be largely returned to translation in the nozzle.

Although the specific reaction energy per unit mass of reactants is key, low mean molecular weight in the reaction products is also important in practice in determining exhaust velocity. This is because the high gas temperatures in rocket engines pose serious problems for the engineering of survivable motors. Because temperature is proportional to the mean *energy per molecule*, a given amount of energy distributed among more molecules of lower mass permits a higher exhaust velocity at a given temperature. This means low atomic mass elements are favoured. Liquid hydrogen (LH2) and oxygen (LOX, or LO2), are the most effective propellants in terms of exhaust velocity that have been widely used to date, though a few exotic combinations involving boron or liquid ozone are potentially somewhat better in theory if various practical problems could be solved.

It is important to note in computing the specific reaction energy, that the *entire mass of the propellants, including both fuel and oxidizer*, must be included. The fact that air-breathing engines are typically able to obtain oxygen "for free" without having to carry it along, accounts for one factor of why air-breathing engines are very much more propellant-mass efficient, and one reason that rocket engines are far less suitable for most ordinary terrestrial applications. Fuels for automobile or turbojet engines, utilize

atmospheric oxygen and so have a much better effective energy output per unit mass of propellant that must be carried, but are similar per unit mass of fuel.

Computer programs that predict the performance of propellants in rocket engines are available.

Ignition

With liquid and hybrid rockets, immediate ignition of the propellant(s) as they first enter the combustion chamber is essential.

With liquid propellants (but not gaseous), failure to ignite within milliseconds usually causes too much liquid propellant to be within the chamber, and if/when ignition occurs the amount of hot gas created will often exceed the maximum design pressure of the chamber. The pressure vessel will often fail catastrophically. This is sometimes called a *hard start*.

Ignition can be achieved by a number of different methods; a pyrotechnic charge can be used, a plasma torch can be used, or electric spark plugs may be employed. Some fuel/oxidizer combinations ignite on contact (hypergolic), and non-hypergolic fuels can be "chemically ignited" by priming the fuel lines with hypergolic propellants (popular in Russian engines).

Gaseous propellants generally will not cause hard starts, with rockets the total injector area is less than the throat thus the chamber pressure tends to ambient prior to ignition and high pressures cannot form even if the entire chamber is full of flammable gas at ignition.

Solid propellants are usually ignited with one-shot pyrotechnic devices.

Once ignited, rocket chambers are self sustaining and igniters are not needed. Indeed chambers often spontaneously reignite if they are restarted after being shut down for a few seconds. However, when cooled, many rockets cannot be restarted without at least minor maintenance, such as replacement of the pyrotechnic igniter.

Plume physics



Armadillo aerospace's quad vehicle showing visible banding (shock diamonds) in the exhaust plume

Rocket plume varies depending on the rocket engine, design altitude, altitude, thrust and other factors.

Carbon rich exhausts from kerosene fuels are often orange in colour due to the black body radiation of the unburned particles, in addition to the blue Swan bands. Peroxide oxidiser based rockets and hydrogen rocket plumes contain largely steam and are nearly invisible to the naked eye but shine brightly in the ultraviolet and infrared. Plumes from solid rockets can be highly visible as the propellant frequently contains metals such as elemental aluminium which burns with a orange-white flame and adds energy to the combustion process.

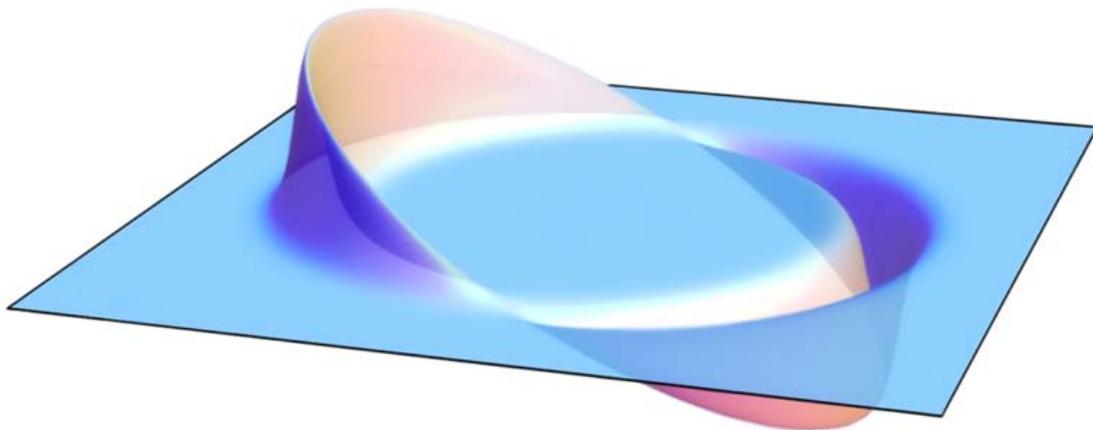
Some exhausts, notably alcohol fuelled rockets, can show visible shock diamonds. These are due to cyclic variations in the plume pressure relative to ambient creating shock waves that form 'mach disks'.

The shape of the plume varies from the design altitude, at high altitude all rockets are grossly under-expanded, and a quite small percentage of exhaust gases actually end up expanding forwards.

Chapter- 6

Hypothetical Methods of Spacecraft Propulsion

Alcubierre drive



Concept of the Alcubierre drive, showing the opposing regions of expanding and contracting spacetime that propel the central region

The **Alcubierre drive**, also known as the **Alcubierre metric**, is a speculative mathematical model of a spacetime exhibiting features reminiscent of the fictional "warp drive" from *Star Trek*, which can travel "faster than light", although not in a local sense.

In 1994, the Mexican physicist Miguel Alcubierre proposed a method of stretching space in a wave which would in theory cause the fabric of space ahead of a spacecraft to contract and the space behind it to expand. The ship would ride this wave inside a region known as a *warp bubble* of flat space. Since the ship is not moving within this bubble, but carried along as the region itself moves, conventional relativistic effects such as time dilation do not apply in the way they would in the case of a ship moving at high velocity through flat spacetime relative to other objects. Also, this method of travel does not

actually involve moving faster than light in a local sense, since a light beam within the bubble would still always move faster than the ship; it is only "faster than light" in the sense that, thanks to the contraction of the space in front of it, the ship could reach its destination faster than a light beam restricted to travelling outside the warp bubble. Thus, the Alcubierre drive does not contradict the conventional claim that relativity forbids a slower-than-light object to accelerate to faster-than-light speeds. However, there are no known methods to create such a warp bubble in a region that does not already contain one, or to leave the bubble once inside it, so the Alcubierre drive remains a hypothetical concept at this time.

Alcubierre Metric

The **Alcubierre Metric** defines the warp drive spacetime. This is a Lorentzian manifold which, if interpreted in the context of general relativity, allows a *warp bubble* to appear in previously flat spacetime and move off at effectively superluminal speed. Inhabitants of the bubble feel no inertial effects. The object(s) within the bubble are not moving (locally) faster than light, instead, the space around them shifts so that the object(s) arrives at its destination faster than light would in normal space.

Alcubierre chose a specific form for the function f , but other choices give a simpler spacetime exhibiting the desired "warp drive" effects more clearly and simply.

Mathematics of the Alcubierre drive

Using the 3+1 formalism of general relativity, the spacetime is described by a foliation of space-like hypersurfaces of constant coordinate time t . The general form of the Alcubierre metric is:

$$ds^2 = - \left(\alpha^2 - \beta_i \beta^i \right) dt^2 + 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j$$

where α is the lapse function that gives the interval of proper time between nearby hypersurfaces, β^i is the shift vector that relates the spatial coordinate systems on different hypersurfaces and γ_{ij} is a positive definite metric on each of the hypersurfaces. The particular form that Alcubierre studied is defined by:

$$\begin{aligned} \alpha &= 1 \\ \beta^x &= -v_s(t) f(r_s(t)), \\ \beta^y &= \beta^z = 0 \\ \gamma_{ij} &= \delta_{ij} \end{aligned}$$

where

$$v_s(t) = \frac{dx_s(t)}{dt},$$

$$r_s(t) = \sqrt{(x - x_s(t))^2 + y^2 + z^2}$$

and

$$f(r_s) = \frac{\tanh(\sigma(r_s + R)) - \tanh(\sigma(r_s - R))}{2 \tanh(\sigma R)}$$

with $R > 0$ and $\sigma > 0$ arbitrary parameters. Alcubierre's specific form of the metric can thus be written;

$$ds^2 = \left(v_s(t)^2 f(r_s(t))^2 - 1 \right) dt^2 - 2v_s(t) f(r_s(t)) dx dt + dx^2 + dy^2 + dz^2$$

With this particular form of the metric, it can be shown that the energy density measured by observers whose 4-velocity is normal to the hypersurfaces is given by

$$-\frac{c^4}{8\pi G} \frac{v_s^2 (y^2 + z^2)}{4g^2 r_s^2} \left(\frac{df}{dr_s} \right)^2$$

where g is the determinant of the metric tensor. Thus, as the energy density is negative, one needs exotic matter to travel faster than the speed of light. The existence of exotic matter is not theoretically ruled out, the Casimir effect and the accelerating universe both lending support to the proposed existence of such matter. However, generating enough exotic matter and sustaining it to perform feats such as faster-than-light travel (and also to keep open the 'throat' of a wormhole) is thought to be impractical. Low has argued that within the context of general relativity, it is impossible to construct a warp drive in the absence of exotic matter. It is generally believed that a consistent theory of quantum gravity will resolve such issues once and for all.

Physics of the Alcubierre drive

For those familiar with the effects of special relativity, such as Lorentz contraction and time dilation, the Alcubierre metric has some apparently peculiar aspects. In particular, Alcubierre has shown that even when the ship is accelerating, it travels on a free-fall geodesic. In other words, a ship using the warp to accelerate and decelerate is always in free fall, and the crew would experience no accelerational g-forces. Enormous tidal forces would be present near the edges of the flat-space volume because of the large space curvature there, but by suitable specification of the metric, these would be made very small within the volume occupied by the ship.

The original warp drive metric, and simple variants of it, happen to have the *ADM form* which is often used in discussing the initial-value formulation of general relativity. This may explain the widespread misconception that this spacetime is a *solution* of the field equation of general relativity. Metrics in ADM form are *adapted* to a certain family of

inertial observers, but these observers are not really physically distinguished from other such families. Alcubierre interpreted his "warp bubble" in terms of a contraction of "space" ahead of the bubble and an expansion behind. But this interpretation might be misleading, since the contraction and expansion actually refers to the relative motion of nearby members of the family of ADM observers.

In general relativity, one often first specifies a plausible distribution of matter and energy, and then finds the geometry of the spacetime associated with it; but it is also possible to run the Einstein field equations in the other direction, first specifying a metric and then finding the energy-momentum tensor associated with it, and this is what Alcubierre did in building his metric. This practice means that the solution can violate various energy conditions and require exotic matter. The need for exotic matter leads to questions about whether it is actually possible to find a way to distribute the matter in an initial spacetime which lacks a "warp bubble" in such a way that the bubble will be created at a later time. Yet another problem is that, according to Serguei Krasnikov, it would be impossible to generate the bubble without being able to force the exotic matter to move at *locally* FTL speeds, which would require the existence of tachyons. Some methods have been suggested which would avoid the problem of tachyonic motion, but would probably generate a naked singularity at the front of the bubble.

Difficulties

Significant problems with the metric of this form stem from the fact that all known warp drive spacetimes violate various energy conditions. It is true that certain experimentally verified quantum phenomena, such as the Casimir effect, when described in the context of the quantum field theories, lead to stress-energy tensors which also violate the energy conditions and so one might hope that Alcubierre type warp drives could perhaps be physically realized by clever engineering taking advantage of such quantum effects. However, if certain quantum inequalities conjectured by Ford and Roman hold, then the energy requirements for some warp drives may be absurdly gigantic, e.g. the energy equivalent of 10^{67} grams might be required to transport a small spaceship across the Milky Way galaxy. This is orders of magnitude greater than the mass of the universe. Counterarguments to these apparent problems have been offered.

Chris Van Den Broeck, in 1999, has tried to address the potential issues. By contracting the 3+1 dimensional surface area of the 'bubble' being transported by the drive, while at the same time expanding the 3 dimensional volume contained inside, Van Den Broeck was able to reduce the total energy needed to transport small atoms to less than 3 solar masses. Later, by slightly modifying the Van Den Broeck metric, Krasnikov reduced the necessary total amount of negative energy to a few milligrams.

Krasnikov proposed that, if tachyonic matter cannot be found or used, then a solution might be to arrange for masses along the path of the vessel to be set in motion in such a way that the required field was produced. But in this case, the Alcubierre Drive vessel is not able to go dashing around the galaxy at will. It is only able to travel routes which, like a railroad, have first been equipped with the necessary infrastructure. The pilot inside the

bubble is causally disconnected with its walls and cannot carry out any action outside the bubble. Thus, because the pilot cannot place infrastructure ahead of the bubble while "in transit", the bubble cannot be used for the *first* trip to a distant star. In other words, to travel to Vega (which is 25 light-years from the Earth) one first has to arrange everything so that the bubble moving toward Vega with a superluminal velocity would appear and these arrangements will always take more than 25 years.

Coule has argued that schemes such as the one proposed by Alcubierre are not feasible because the matter to be placed on the road beforehand has to be placed at superluminal speed. Thus, according to Coule, an Alcubierre Drive is required in order to build an Alcubierre Drive. Since none have been proven to exist already then the drive is impossible to construct, even if the metric is physically meaningful. Coule argues that an analogous objection will apply to *any* proposed method of constructing an Alcubierre Drive. This assumes that the warp bubble must be constructed entirely through normal space-time.

A paper by José Natário published in 2002 showed that it would be impossible for the ship to send signals to the front of the bubble, meaning that crew members could not control, steer or stop the ship. This assumes that the warp bubble must be controlled entirely through normal space-time.

A more recent paper by Carlos Barceló, Stefano Finazzi, and Stefano Liberati makes use of quantum theory to show that the Alcubierre Drive at FTL velocities is impossible; mostly due to extremely high temperatures caused by Hawking radiation destroying anything inside the bubble at superluminal velocities and leading to instability of the bubble itself. This could be avoided by arranging the warp metric so that all the Hawking radiation is directed outward behind the spacecraft. These problems do not arise if the bubble velocity is kept subluminal, but it is still necessary to provide exotic matter for the drive to work.

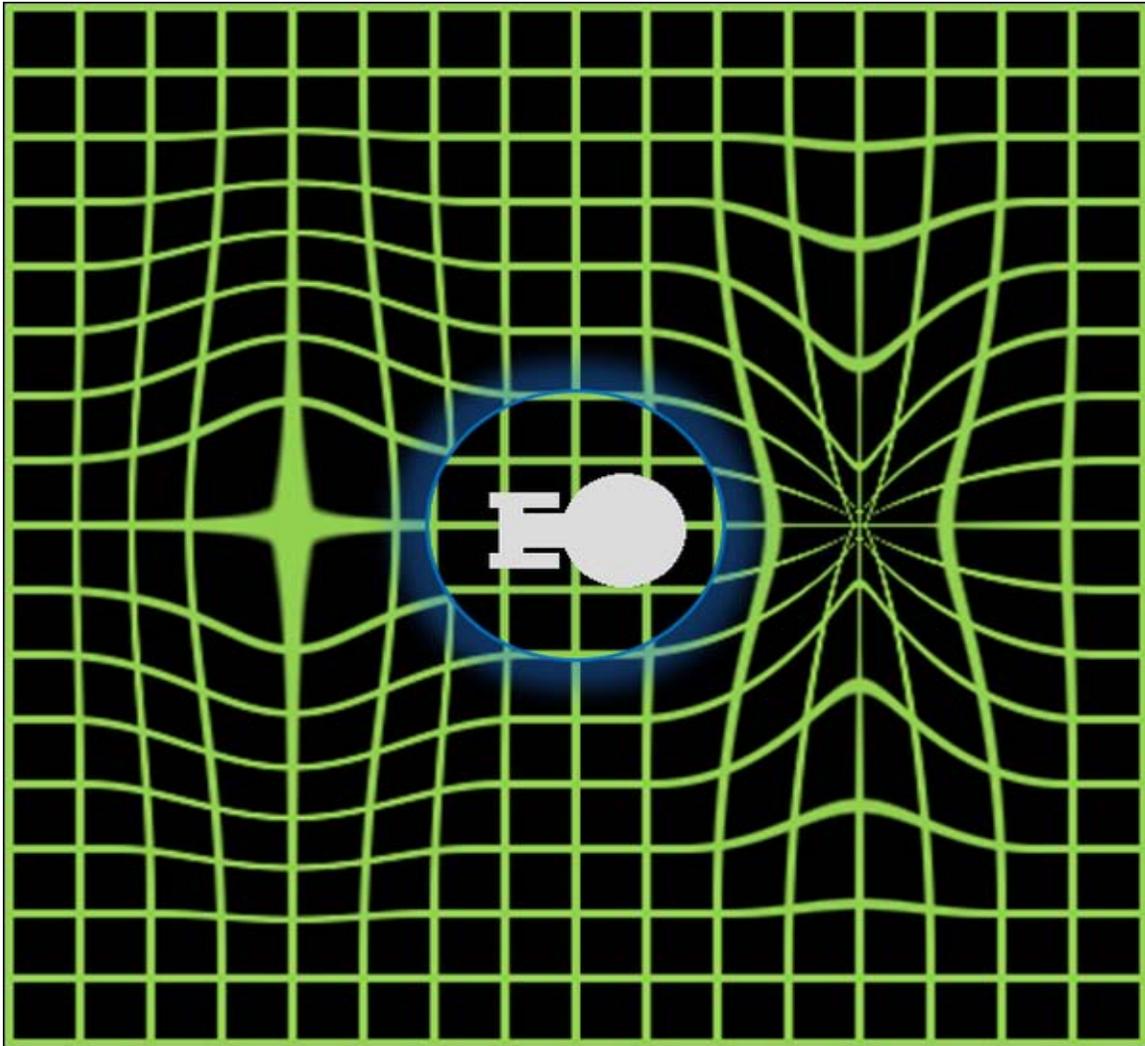
More difficulties emerge in regards to the amount of exotic matter required for such a propulsion. According to Pfenning and Allen Everett of Tufts, a warp bubble traveling at 10 times light-speed must have a wall thickness of no more than 10^{-32} meters. This is only slightly longer than the Planck length, 10^{-35} . A bubble macroscopically large enough to enclose a ship 200 meters across would require a total amount of exotic matter equal to 10 billion times the mass of the observable universe. Of course, straining the exotic matter to an extremely thin band of 10^{-32} meters is considered impractical. Similar constraints apply to Krasnikov's superluminal subway. A modification of Alcubierre's model was recently constructed by Chris van den Broeck of the Catholic University of Louvain in Belgium. It requires much less exotic matter but places the ship in a curved space-time "bottle" whose neck is about 10^{-32} meters. So-called cosmic strings, hypothesized in some cosmological theories, involve very large energy densities in long, narrow lines. But all known physically reasonable cosmic-string models have positive (positive space-time warping effects) energy densities. These results seem to make it rather unlikely that one could construct Alcubierre warp drives using exotic matter generated by quantum effects. It is probable that gravity is the weakest of the natural

forces because it is not confined to normal space-time. Alcubierre's extreme negative energy requirements are based on the assumption that the negative energy should distort space-time by the same inefficient means as all the $E=mc^2$ stored energy in ordinary matter creates gravity. One possible way around this would be to confine gravitons and negative gravitons to normal space-time.

The Alcubierre drive and science fiction

Faster-than-light travel is often used in science fiction to denote a wide variety of imaginary propulsion methods, most of which have nothing to do with the Alcubierre drive or any other physical theory. Some SF works, particularly of the 'hard' genre, have explicitly made use of the Alcubierre theory, such as Stephen Baxter's novel *Ark*.

Warp drive (Star Trek)



A visualization of a warp field. The ship rests in a bubble of normal space.

Warp drive is a faster-than-light (FTL) propulsion system in the setting of many science fiction works, most notably *Star Trek*. A spacecraft equipped with a warp drive may travel at velocities greater than that of light by many orders of magnitude, while circumventing the relativistic problem of time dilation. Some of the other fictions in which warp drive technology is featured include: *Stars!*, *EVE Online*, *Earth and Beyond*, *StarCraft*, *Darkspace*, *Starship Troopers*, *Red Dwarf*, and *Mass Effect*. In contrast to many other fictional FTL technologies, such as a "jump drive" or the Infinite Improbability Drive, the warp drive does not permit instantaneous travel between two points; instead, warp drive technology creates an artificial "bubble" of normal space-time that surrounds the spacecraft (as opposed to entering a separate realm or dimension like hyperspace, such as the "warp drive" which is used in the *Warhammer 40,000* universe). Consequently, spacecraft at warp velocity can continue to interact with objects in normal space.

The idea of warping space as a means of propulsion has enjoyed theoretical study by physicists such as Miguel Alcubierre, who has designed his own hypothetical drive. The propulsion techniques as well that flow from Extended Heim Theory, and which would use drive coils to affect space-time, are also generally in line with the picture of warp drive presented in the various *Star Trek* series as well as the technical publications. However, an approach to FTL travel based on either Alcubierre Drive Theory or Extended Heim Theory which could be facilitated by our present level of technological advancement has yet to be proposed.

The Original Series: establishing a background

Warp drive is one of the fundamental features of the *Star Trek* storyline; in the first pilot episode of *Star Trek: The Original Series*, "The Cage", it is referred to as a "time warp" drive, and it is stated that the "time barrier" has been broken, allowing a group of stranded interstellar travelers to return to Earth far sooner than would have otherwise been possible.



Zefram Cochrane, the inventor of the warp drive, played by James Cromwell in *Star Trek: First Contact*.

The episode "Metamorphosis", also from the original series, establishes a backstory for the invention of warp drive, stating that it was invented by Zefram Cochrane. Cochrane is repeatedly referred to afterwards, but the exact details of the first warp trials were not shown until the second *Star Trek: The Next Generation* movie, *Star Trek: First Contact*. The movie depicts Cochrane as having invented warp drive on Earth in 2063 (two years after the date speculated by the first edition of the *Star Trek Chronology*). By using a matter/antimatter reactor to create plasma, and by sending this plasma through warp coils, he created a warp bubble which he could use to move a craft into subspace and hence exceed the speed of light. This successful first trial led directly to first contact with the Vulcans.

The later prequel series *Star Trek: Enterprise* describes the warp engine technology as a 'Gravimetric Field Displacement Manifold (Commander Tucker's tour, "Cold Front"), and describes the device as being powered by an anti-matter/matter reaction which powers the two separate nacelles (one on each side of the ship) to create a displacement field (the aforementioned "bubble") The episode also firmly establishes that many other civilizations had warp drive before humans. Throughout the series, the viewer is made aware that the Vulcans have more advanced warp drive technology than humans even in the 22nd century. *Enterprise*, set in 2151 onwards, follows the voyages of the first human ship capable of traveling at warp factor 5.2 which under the old warp table formula, is about 140 times the speed of light. In the episode "Broken Bow", Capt. Archer equates warp 4.5 as "...Neptune and back (from Earth) in six minutes."

The Next Generation onwards

Plots involving the *Enterprise* traveling beyond warp 10 were once featured in the original series (such as warp 14.1 in *That Which Survives*), and for *The Next Generation*, it was decided that these would no longer be featured. A new warp scale was drawn up, with warp factor 10 set as an unattainable maximum. This is described in some technical manuals as *Eugene's Limit*, in homage to creator/producer Gene Roddenberry. Normal maximum warp in the original series was warp 8. The warp factors above warp 10 in *TOS*, such as the one above, were slower than warp 10 on the new scale, which reaches an asymptote at warp 10, representing infinite velocity in accordance with the limit imposed by the producers. The much-maligned *Star Trek: Voyager* episode "Threshold" concurred with this: the characters ruled that reaching the velocity of warp 10 was impossible — in spite of this, they went on to achieve the velocity, experiencing a peculiar side effect; they underwent a [reversible] process of hyper-evolution culminating in their transformation into anthropomorphic newts. In this episode, Tom Paris explains that, while traveling at warp 10, he was simultaneously present in every part of the universe. At this velocity, the shuttlecraft Cochrane's sensors are able to collect such enormous amounts of telemetry that the shuttle's storage capacity is completely filled.

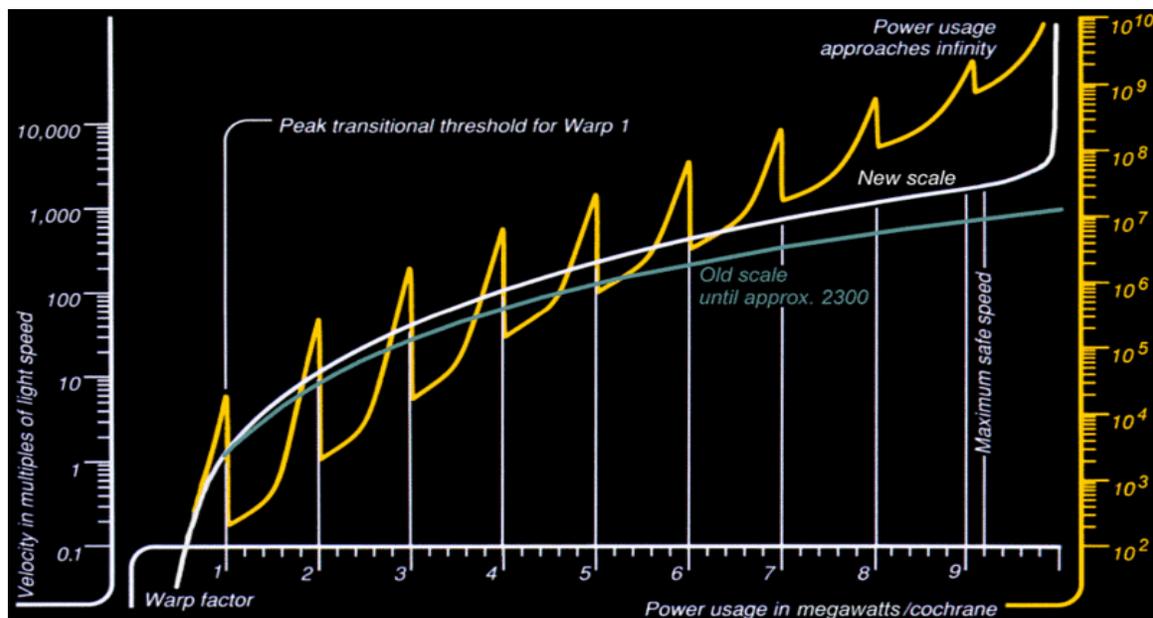
The limit of 10 did not entirely stop warp inflation. By the mid-24th century, the *Enterprise-D* could travel at warp 9.8 at "extreme risk", while normal maximum operating velocity was warp 9.6 and maximum rated cruise was warp 9.2. The Intrepid-class starship *Voyager* has a maximum sustainable cruising velocity of warp 9.975, the

Enterprise-E can go even faster at Warp 9.985. In the alternative future depicted in "All Good Things..." (the final episode of the *Star Trek: TNG*), Federation starships travel at warp 13.

Warp velocities

Warp drive velocity in *Star Trek* is generally expressed in "warp factor" units, which—according to the *Star Trek Technical Manuals*—correspond to the magnitude of the warp field. Achieving warp factor 1 is equivalent to breaking the light barrier, while the actual velocity corresponding to higher factors is determined using an ambiguous formula. Several episodes of the original series placed the *Enterprise* in peril by having it travel at high warp factors; at one point in "That Which Survives" the *Enterprise* traveled at a warp factor of 14.1. In the *Star Trek: The Next Generation* episode "The Most Toys" the crew of *Enterprise-D* discovers that the android Data may have been stolen while on board another ship, *Jovis*. At this point the *Jovis*, which has a maximum warp factor of 3 has had a 23 hour head start which the *Enterprise-D* figures puts her anywhere within .102 light year radius of her last known position. However, the velocity [in present dimensional units] of any given warp factor is rarely the subject of explicit expression, and travel times for specific interstellar distances are not consistent through the various series.

According to the *Star Trek* episode writer's guide for *The Original Series*, warp factors are supposedly converted to multiples of c with the cubic function $v = w^3c$, where w is the warp factor, v is the velocity, and c is the speed of light. Accordingly, "warp 1" is equivalent to the speed of light, "warp 2" is eight times the speed of light, "warp 3" is 27 times the speed of light, etc.



Michael Okuda's new warp scale.

For *Star Trek: The Next Generation* and the subsequent series, Star Trek artist Michael Okuda devised a formula based on the original one but with important differences. For warp 1–9, $s(w) = w^{\frac{10}{3}} c$. In the half-open interval from warp 9 to warp 10, the exponent of w increases toward infinity. Thus, in the Okuda scale, warp velocities approach warp 10 asymptotically. There is no exact formula for this interval because the quoted velocities are based on a hand-drawn curve; what can be said is that at velocities greater than warp 9, the form of the warp function changes because of an increase in the exponent of the warp factor w . Due to the resultant increase in the derivative, even a minor change in the warp factor corresponds to an exponentially larger change in velocity.

Exact velocities were only given in the *Voyager* episode "The 37's" where Tom Paris describes *Voyager's* velocity at warp factor 9.9 (under the new warp table formula) as being about 4 billion miles per second, which would be over 21,000 times the speed of light.

Transwarp

The term *transwarp* has been used a number of times, referring to an advanced form of warp drive used by the Borg. However, the term also refers to a Starfleet development project in *Star Trek III: The Search for Spock*. Episodes of *The Next Generation* and *Voyager* seem to indicate that transwarp technology involves a wormhole conduit directly *through* subspace as opposed to warping normal space via a manipulation of subspace. However, in the *Voyager* episode "Distant Origin", a species known as the Voth used a transwarp technology that didn't appear to be similar to Borg transwarp, but rather an enhanced warp technology. It would seem more appropriate, therefore, for the term "transwarp" to refer to any propulsion system that can be considered superior in potential velocity to standard warp drive, without implying any *specific* technique correlating to this superior velocity.

Federation experiments

The USS *Excelsior* (NX-2000), under command of Captain Styles, was a Federation test-ship for prototype transwarp technology. It is described in *Star Trek III* as allowing a ship to instantaneously travel at any warp velocity, rather than having to progressively increase velocity to the desired magnitude. *Excelsior's* first attempt to enter transwarp failed due to sabotage by Chief Engineer Scott of the *Enterprise*, which prevented the *Excelsior* from pursuing them.

The bridge readouts of *Enterprise-A* at the end of *Star Trek IV: The Voyage Home* (illustrated in the spin-off reference work, *Mr. Scott's Guide to the Enterprise* published in 1987) suggest that the project ultimately succeeded and the USS *Enterprise* was indeed fitted with transwarp. Susan Sackett's memoirs attribute the lack of transwarp in *Star Trek: The Next Generation* to Gene Roddenberry's dislike of the concept.

Borg conduits

It is revealed in the episodes "Descent" and "Endgame" that the Borg have discovered the existence of transwarp conduits — regions in subspace that facilitate travel at velocities up to 20 times those of conventional warp drives. These episodes established that the Borg set up networks of these conduits between important areas in the galaxy. Borg transwarp conduits are activated by an encoded tachyon pulse. When a Borg vessel enters a transwarp conduit, it is subject to extreme gravimetric shear; to compensate, the Borg project a structural integrity field ahead of the vessel. Artificial conduits are linked together with transwarp hubs, of which six were known to exist; in "Endgame" one of these hubs, along with the Unicompex, is destroyed.

Quantum slipstream

Quantum slipstream drive is presumably the standard means of interstellar travel used by Species 116 (of which Arturis was a member) prior to their assimilation by the Borg. In the *Voyager* episode "Hope and Fear", Seven of Nine remarks that the technology involved is not dissimilar to Borg transwarp technology — her point being that both drives involve the traveling vessel becoming immersed in an alternative plane of space-time rather than warping normal space-time.

This method of travel is also highly similar to the method of superluminal travel used on space ships in *Stargate* (referenced as "*Hyperspace*" travel), and Slipstream used in *Andromeda (TV series)*, another space opera created by Gene Roddenberry.

In the books

Some years after *Star Trek: The Original Series (TOS)*, Pocket Books came out with a series of publications based upon the *Enterprise's* encounters during both its first and second five year missions. In "The Wounded Sky" written by Diane Duane, the crew picks up a Hamalki engineer, which invents a new form of the *transwarp drive*. Even though such books are not considered canon, the theories proposed in the book lend to the ideas of warp and transwarp, and further explain the properties of subspace.

According to the aforementioned book, warp drive does indeed create a bubble of space-time around the ship; however, it is explained that the ship is surrounded by a bubble of subspace — another universe where the speed of light is much faster than in ours; furthermore, the alternate universe is *attuned* with our own, such that planetary bodies are in exactly the same place, which simplifies navigation — thus the book leans toward the theories of superstring-manipulation, rather than those of *warping* normal space-time.

The transwarp device invented by the Hamalki uses a different approach to the same idea; in this case, it creates a field around the ship which allows it to enter De Sitter space — a space in which there is infinite energy, zero mass (with exceptions) and no absolute laws of physics. This essentially allows the *Enterprise* to enter De Sitter space and travel millions of times faster than light. In the narrative, the *Enterprise* succeeds in reaching

the Small Magellanic Cloud (200 years away at warp 8), a dwarf galaxy in orbit around the Milky Way galaxy.

Slingshot effect

A curious extension of warp travel which has been shown throughout Star Trek is the "Slingshot Effect". First discovered accidentally in "Tomorrow Is Yesterday" (1967), one of the earlier episodes of the original Star Trek series, it is a method of time travel. Whereas the actual procedure is intentionally obscure, it involved traveling at a high warp velocity (depicted in *Star Trek IV: The Voyage Home* to be over warp 9.8) in the direction of a star, on a precisely calculated "slingshot" path; if successful, the ship is caused to travel to a desired point, past or future. The same technique was used later in the episode "Assignment: Earth" (1968) for historic research — in this episode, the warp factor required for "*time warp*" is given the name "light speed breakaway factor" — the term "*time warp*" being established in *Star Trek IV*. The technique was mentioned as a viable method of time travel in the TNG episode "Time Squared" (1989).

This 'slingshot' effect has been explored in theoretical physics: it is hypothetically possible (though not practical or at all safe) to slingshot oneself 'around' the event horizon of a black hole. The result of such a maneuver would cause time to pass at a faster rate, relative to the ship within the event horizon. Such a journey would, unfortunately, be a 'one-way' trip into the future — the pilot of the craft would not have 'traveled through time' in the classical sense, but would instead have merely 'skipped over' the intervening years. Travel in entropic directions other than forwards remain impossible to ascertain within the rubric of Special Relativity.

Fans of the show and films have noted that the Slingshot involves a star, rather than a black hole, and the most normal consensus from its use concerns the nature of warp travel and warp velocities. A black hole is noteworthy for its singularity and associated event horizon, where not even light possesses escape velocity. Warp-drive and other transluminal vehicles would however be able to escape a black hole event horizon, as they are capable of speeds greater than c . Stars do not possess an event horizon, as their escape velocities are considerably lower than those of black holes. They do however have very great masses. A vessel able to move at transluminal velocities would then be able to take advantage of relativistic physics: interaction with the mass of non-black hole stellar mass at transluminal velocities is very similar to the interaction between a subluminal vessel and a black hole event horizon, in terms of relativistic boundary interactions and equivalence of energy. A warp-ship, then, is able to perform as its own 'event-horizon' when interacting with a stellar mass.

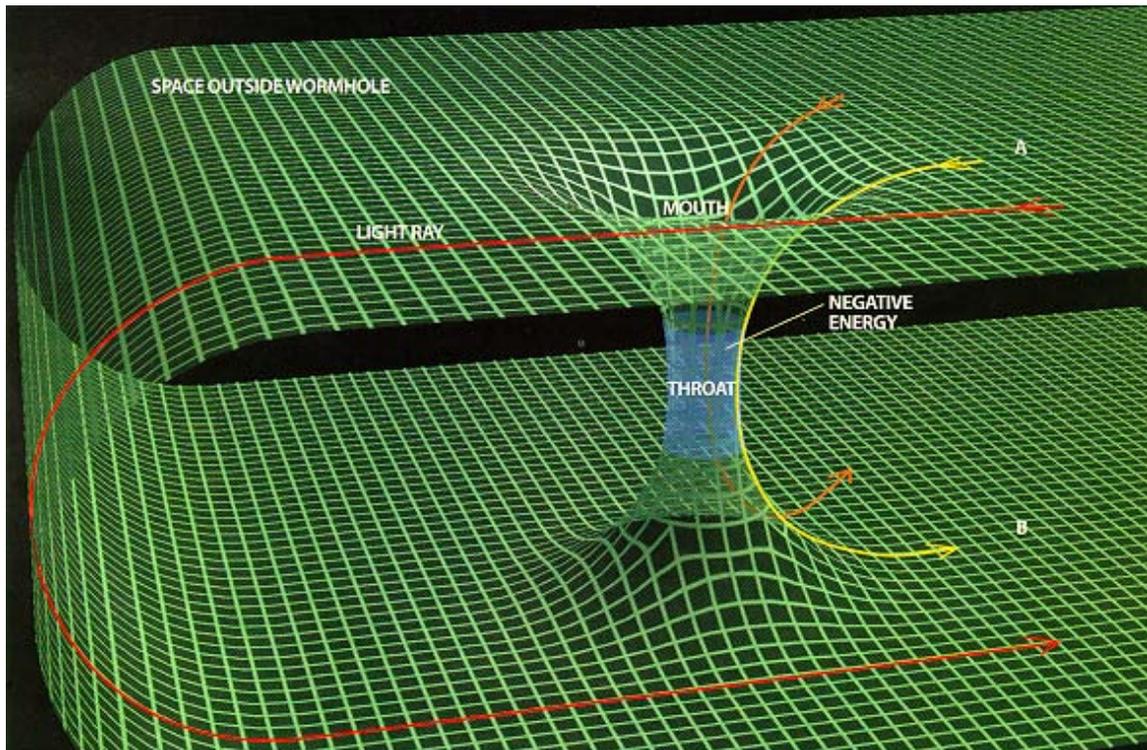
Warp core

A primary component of the warp drive method of propulsion in the Star Trek universe is the "gravimetric field displacement manifold," more commonly referred to as a *warp core*. It is a fictional reactor which taps the energy released in a matter-antimatter

annihilation to provide the energy necessary to power a starship's warp drive, allowing faster-than-light travel. Starship warp cores generally also serve as powerplants for other primary ship systems.

When matter and antimatter come into contact, they *annihilate* — both matter and antimatter are converted directly into enormous quantities of energy, as electromagnetic radiation. In the *Star Trek* universe, fictional "dilithium crystals" are used to regulate this reaction. These crystals are described as being non-reactive to anti-matter when bombarded with high levels of radiation. Usually, the reactants are deuterium, an isotope of hydrogen, and antideuterium (its antimatter counterpart). The reaction chamber is surrounded by powerful magnetic fields to contain the anti-matter. If the containment fields ever fail, the subsequent interaction of the antimatter fuel with the container walls would result in a catastrophic release of energy, with the resultant explosion capable of utterly destroying the ship. Such "warp core breaches" are used as plot devices in many Star

Wormhole



Analogy to a wormhole in a curved 2-D space

In physics, a **wormhole** is a hypothetical topological feature of spacetime that would be, fundamentally, a "shortcut" through spacetime. For a simple visual explanation of a wormhole, consider spacetime visualized as a two-dimensional (2D) surface. If this surface is folded along a third dimension, it allows one to picture a wormhole "bridge". (Please note, though, that this image is merely a visualization displayed to convey an essentially *unvisualisable* structure existing in 4 or more dimensions. The parts of the wormhole could be higher-dimensional analogues for the parts of the curved 2D surface; for example, instead of mouths which are circular holes in a 2D plane, a real wormhole's mouths could be spheres in 3D space.) A wormhole is, in theory, much like a tunnel with two ends each in separate points in spacetime.

There is no observational evidence for wormholes, but on a theoretical level there are valid solutions to the equations of the theory of general relativity which contain wormholes. The first type of wormhole solution discovered was the **Schwarzschild wormhole** which would be present in the Schwarzschild metric describing an eternal black hole, but it was found that this type of wormhole would collapse too quickly for anything to cross from one end to the other. Wormholes which could actually be crossed, known as **traversable wormholes**, would only be possible if exotic matter with negative energy density could be used to stabilize them. (Many physicists such as Stephen Hawking, Kip Thorne, and others believe that the Casimir effect is evidence that negative energy densities are possible in nature). Physicists have also not found any natural process which would be predicted to form a wormhole naturally in the context of general relativity, although the quantum foam hypothesis is sometimes used to suggest that tiny wormholes might appear and disappear spontaneously at the Planck scale. It has also been proposed that if a tiny wormhole held open by a negative-mass cosmic string had appeared around the time of the Big Bang, it could have been inflated to macroscopic size by cosmic inflation.

The American theoretical physicist John Archibald Wheeler coined the term *wormhole* in 1957; however, in 1921, the German mathematician Hermann Weyl already had proposed the wormhole theory, in connection with mass analysis of electromagnetic field energy.

This analysis forces one to consider situations...where there is a net flux of lines of force, through what topologists would call "a handle" of the multiply-connected space, and what physicists might perhaps be excused for more vividly terming a "wormhole".
—John Wheeler in *Annals of Physics*

Definition

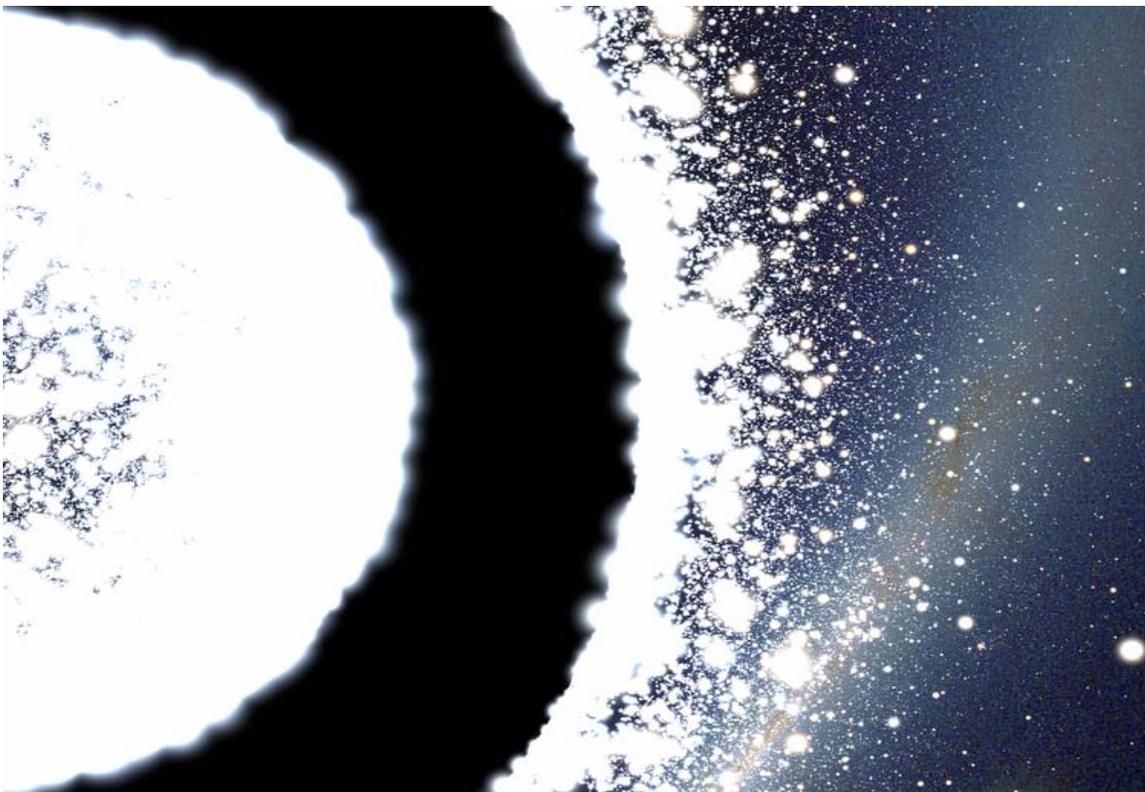
The basic notion of an intra-universe wormhole is that it is a compact region of spacetime whose boundary is topologically trivial but whose interior is not simply connected. Formalizing this idea leads to definitions such as the following, taken from Matt Visser's *Lorentzian Wormholes*.

If a Minkowski spacetime contains a compact region Ω , and if the topology of Ω is of the form $\Omega \sim \mathbb{R} \times \Sigma$, where Σ is a three-manifold of the nontrivial topology, whose boundary has topology of the form $d\Sigma \sim S^2$, and if, furthermore, the hypersurfaces Σ are all spacelike, then the region Ω contains a quasipermanent intra-universe wormhole.

Characterizing inter-universe wormholes is more difficult. For example, one can imagine a 'baby' universe connected to its 'parent' by a narrow 'umbilicus'. One might like to regard the umbilicus as the throat of a wormhole, but the spacetime is simply connected. For this reason wormholes have been defined *geometrically*, as opposed to topologically, as regions of spacetime that constrain the incremental deformation of closed surfaces. For example, in Enrico Rodrigo's *The Physics of Stargates* a wormhole is defined informally as

a region of spacetime containing a "world tube" (the time evolution of a closed surface) that cannot be continuously deformed (shrunk) to a world line [(the time evolution of a point)].

Schwarzschild wormholes



An artist's impression of a wormhole from an observer's perspective, crossing the event horizon of a Schwarzschild wormhole which bridges two different universes. The observer originates from the right, and another universe becomes visible in the center of the wormhole's shadow once the horizon is crossed, the observer seeing light that has

fallen into the black hole interior region from the other universe; however, this other universe is unreachable in the case of a Schwarzschild wormhole, as the bridge always collapses before the observer has time to cross it, and everything that has fallen through the event horizon of either universe is inevitably crushed in the black hole singularity.

Lorentzian wormholes known as **Schwarzschild wormholes** or **Einstein-Rosen bridges** are bridges between areas of space that can be modeled as vacuum solutions to the Einstein field equations, and which are now understood to be intrinsic parts of the maximally extended version of the Schwarzschild metric describing an eternal black hole with no charge and no rotation. Here, "maximally extended" refers to the idea that the spacetime should not have any "edges": for any possible trajectory of a free-falling particle (following a geodesic) in the spacetime, it should be possible to continue this path arbitrarily far into the particle's future or past, unless the trajectory hits a gravitational singularity like the one at the center of the black hole's interior. In order to satisfy this requirement, it turns out that in addition to the black hole interior region which particles enter when they fall through the event horizon from the outside, there must be a separate white hole interior region which allows us to extrapolate the trajectories of particles which an outside observer sees rising up *away* from the event horizon. And just as there are two separate interior regions of the maximally extended spacetime, there are also two separate exterior regions, sometimes called two different "universes", with the second universe allowing us to extrapolate some possible particle trajectories in the two interior regions. This means that the interior black hole region can contain a mix of particles that fell in from either universe (and thus an observer who fell in from one universe might be able to see light that fell in from the other one), and likewise particles from the interior white hole region can escape into either universe. All four regions can be seen in a spacetime diagram which uses Kruskal–Szekeres coordinates, as discussed and illustrated on the page [White Holes and Wormholes](#).

In this spacetime, it is possible to come up with coordinate systems such that if you pick a hypersurface of constant time (a set of points that all have the same time coordinate, such that every point on the surface has a space-like separation, giving what is called a 'space-like surface') and draw an "embedding diagram" depicting the curvature of space at that time, the embedding diagram will look like a tube connecting the two exterior regions, known as an "Einstein-Rosen bridge". For example, the diagrams which show the maximally extended Schwarzschild solution in Kruskal–Szekeres coordinates along with white hypersurfaces of constant time drawn on (time in some other coordinate system besides Kruskal–Szekeres coordinates, since a hypersurface of constant Kruskal–Szekeres time would just look like a horizontal line when drawn in a Kruskal–Szekeres diagram), and the corresponding embedding diagram for that hypersurface. Note that the Schwarzschild metric describes an idealized black hole that exists eternally from the perspective of external observers; a more realistic black hole that forms at some particular time from a collapsing star would require a different metric. When the infalling stellar matter is added to a diagram of a black hole's history, it removes the part of the diagram corresponding to the white hole interior region, along with the part of the diagram corresponding to the other universe.

The Einstein-Rosen bridge was discovered by Albert Einstein and his colleague Nathan Rosen, who first published the result in 1935. However, in 1962 John A. Wheeler and Robert W. Fuller published a paper showing that this type of wormhole is unstable, and that it will pinch off too quickly for light (or any particle moving slower than light) that falls in from one exterior region to make it to the other exterior region.

Before the stability problems of Schwarzschild wormholes were apparent, it was proposed that quasars were white holes forming the ends of wormholes of this type.

While Schwarzschild wormholes are not traversable, their existence inspired Kip Thorne to imagine traversable wormholes created by holding the 'throat' of a Schwarzschild wormhole open with exotic matter (material that has negative mass/energy).

Traversable wormholes



Image of a traversable wormhole which connects the place in front of the physical institutes of Tübingen university with the sand dunes near Boulogne sur Mer in the north of France. The image is calculated with 4D raytracing in a Morris-Thorne wormhole metric, but the gravitational effects on the wavelength of light have not been simulated.

Lorentzian traversable wormholes would allow travel from one part of the universe to another part of that same universe very quickly or would allow travel from one universe to another. The possibility of traversable wormholes in general relativity was first demonstrated by Kip Thorne and his graduate student Mike Morris in a 1988 paper; for this reason, the type of traversable wormhole they proposed, held open by a spherical shell of exotic matter, is referred to as a **Morris-Thorne wormhole**. Later, other types of traversable wormholes were discovered as allowable solutions to the equations of general relativity, including a variety analyzed in a 1989 paper by Matt Visser, in which a path through the wormhole can be made in which the traversing path does not pass through a region of exotic matter. However in the pure Gauss-Bonnet theory (a modification to general relativity involving extra spatial dimensions which is sometimes studied in the context of brane cosmology) exotic matter is not needed in order for wormholes to exist- they can exist even with no matter. A type held open by negative mass cosmic strings was put forth by Visser in collaboration with Cramer *et al.*, in which it was proposed that such wormholes could have been naturally created in the early universe.

Wormholes connect two points in spacetime, which means that they would in principle allow travel in time, as well as in space. In 1988, Morris, Thorne and Yurtsever worked out explicitly how to convert a wormhole traversing space into one traversing time. However, according to general relativity it would not be possible to use a wormhole to travel back to a time earlier than when the wormhole was first converted into a time machine by accelerating one of its two mouths.

Raychaudhuri's theorem and exotic matter

To see why exotic matter is required, consider an incoming light front traveling along geodesics, which then crosses the wormhole and re-expands on the other side. The expansion goes from negative to positive. As the wormhole neck is of finite size, we would not expect caustics to develop, at least within the vicinity of the neck. According to the optical Raychaudhuri's theorem, this requires a violation of the averaged null energy condition. Quantum effects such as the Casimir effect cannot violate the averaged null energy condition in any neighborhood of space with zero curvature, but calculations in semiclassical gravity suggest that quantum effects may be able to violate this condition in curved spacetime. Even if they can, it may be that quantum effects cannot violate a weaker condition known as the "achronal averaged null energy condition", and that this could rule out the possibility of traversable wormholes.

Faster-than-light travel

The impossibility of faster-than-light relative speed only applies locally. Wormholes allow superluminal (faster-than-light) travel by ensuring that the speed of light is not exceeded locally at any time. While traveling through a wormhole, subluminal (slower-than-light) speeds are used. If two points are connected by a wormhole, the time taken to traverse it would be less than the time it would take a light beam to make the journey if it took a path through the space *outside* the wormhole. However, a light beam traveling through the wormhole would always beat the traveler. As an analogy, running around to

the opposite side of a mountain at maximum speed may take longer than walking through a tunnel crossing it.

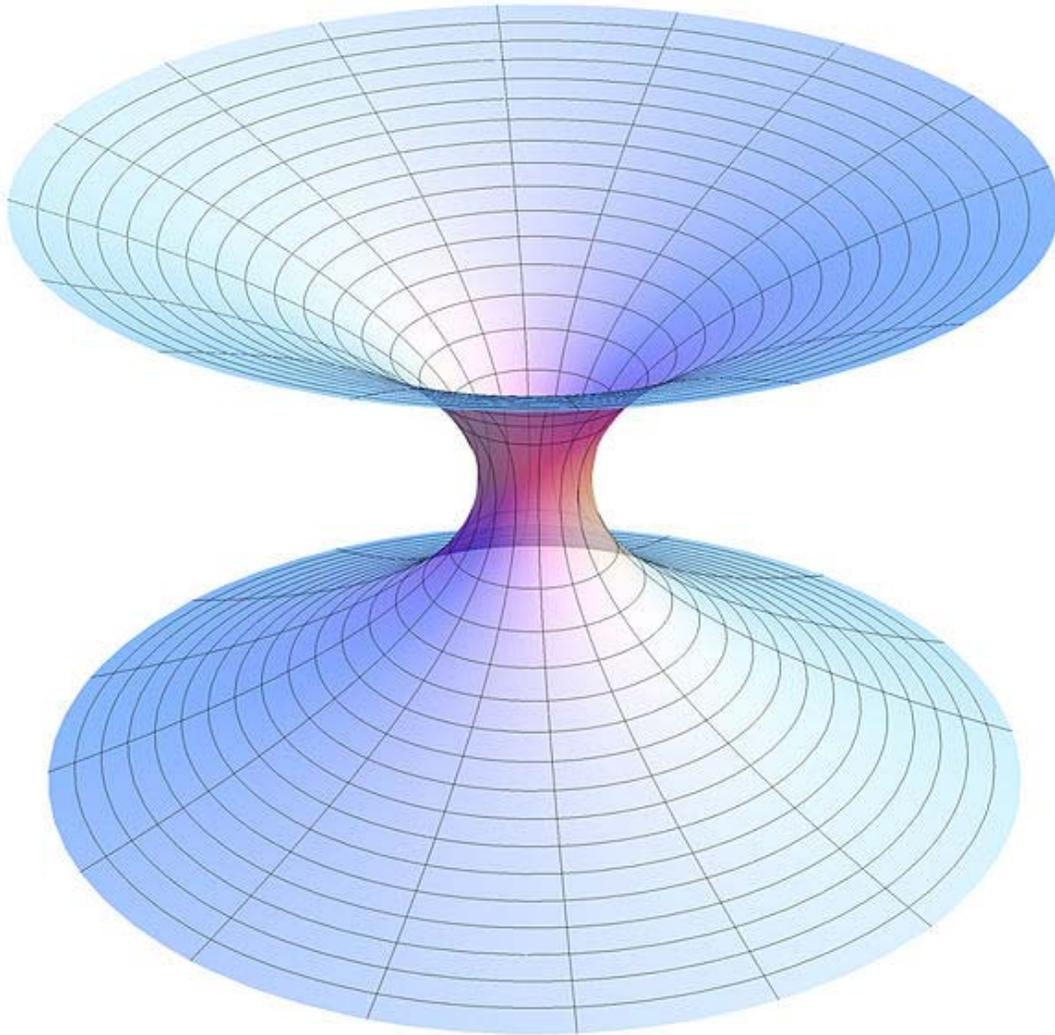
Time travel

The theory of general relativity predicts that if traversable wormholes exist, they could allow time travel. This would be accomplished by accelerating one end of the wormhole to a high velocity relative to the other, and then sometime later bringing it back; relativistic time dilation would result in the accelerated wormhole mouth aging less than the stationary one as seen by an external observer, similar to what is seen in the twin paradox. However, time connects differently through the wormhole than outside it, so that synchronized clocks at each mouth will remain synchronized to someone traveling through the wormhole itself, no matter how the mouths move around. This means that anything which entered the accelerated wormhole mouth would exit the stationary one at a point in time prior to its entry.

For example, consider two clocks at both mouths both showing the date as 2000. After being taken on a trip at relativistic velocities, the accelerated mouth is brought back to the same region as the stationary mouth with the accelerated mouth's clock reading 2005 while the stationary mouth's clock read 2010. A traveler who entered the accelerated mouth at this moment would exit the stationary mouth when its clock also read 2005, in the same region but now five years in the past. Such a configuration of wormholes would allow for a particle's world line to form a closed loop in spacetime, known as a closed timelike curve.

It is thought that it may not be possible to convert a wormhole into a time machine in this manner; the predictions are made in the context of general relativity, but general relativity does not include quantum effects. Some analyses using the semiclassical approach to incorporating quantum effects into general relativity indicate that a feedback loop of virtual particles would circulate through the wormhole with ever-increasing intensity, destroying it before any information could be passed through it, in keeping with the chronology protection conjecture. This has been called into question by the suggestion that radiation would disperse after traveling through the wormhole, therefore preventing infinite accumulation. The debate on this matter is described by Kip S. Thorne in the book *Black Holes and Time Warps*, and a more technical discussion can be found in *The quantum physics of chronology protection* by Matt Visser. There is also the Roman ring, which is a configuration of more than one wormhole. This ring seems to allow a closed time loop with stable wormholes when analyzed using semiclassical gravity, although without a full theory of quantum gravity it is uncertain whether the semiclassical approach is reliable in this case.

Metrics



Embedded diagram of a Schwarzschild wormhole.

Theories of **wormhole metrics** describe the spacetime geometry of a wormhole and serve as theoretical models for time travel. An example of a (traversable) wormhole metric is the following:

$$ds^2 = -c^2 dt^2 + dl^2 + (k^2 + l^2)(d\theta^2 + \sin^2 \theta d\phi^2).$$

One type of non-traversable wormhole metric is the Schwarzschild solution:

$$ds^2 = -c^2 \left(1 - \frac{2GM}{rc^2}\right) dt^2 + \frac{dr^2}{1 - \frac{2GM}{rc^2}} + r^2(d\theta^2 + \sin^2 \theta d\phi^2).$$

Reactionless drive

A **reactionless drive** or **inertial propulsion engine** (also **reactionless thruster**, **reactionless engine**, **bootstrap drive**, and **inertia drive**) is any form of pseudoscientific propulsion not based around expulsion of fuel or reaction mass.

The name comes from Newton's Third Law of Motion, usually expressed as: "For every action, there is an equal and opposite reaction." Such a drive would use a hypothetical form of thrust that does not require any outside force or net momentum exchange to produce linear motion, and therefore necessarily violates the conservation of momentum, a fundamental principle of all current understandings of physics. In addition it can be shown that conservation of energy is violated.

In spite of their physical impossibility, such devices have been often proposed in recent history and are a staple of science fiction.

Physics of reactionless drives

In a sentence: "The underlying problem [with reactionless drives] is that breaking the law of conservation of momentum shatters the entire mathematical framework [of physics]." These devices by their very nature violate the law of conservation of momentum - if a ship with such a drive existed, then any motion of that ship, being unaccompanied by the motion of any other material, would cause the center of gravity of the universe to move with it. Furthermore, the total energy of the universe becomes reference frame dependent - energy can only be conserved in the presence of a reactionless drive in (at most) one reference frame, because in all other reference frames the change in kinetic energy of the ship differs from the power expended by the ship. Given that these two laws - the conservation of momentum and the principle of relativity - are so well established (and thoroughly verified) in physics, any ordinary mechanical system purporting to violate the laws is generally dismissed outright.

Swimming in Spacetime

General relativity allows to swim in curved space without using reaction mass, cf. .

Types

Oscillation thruster

An **oscillation thruster** (also known as a **stiction drive**, **internal drive** or **slip-stick drive**) uses the motion of internal masses to create a net thrust. These thrusters include either vibrational or rotating masses, in which one portion of the cyclical motion is high-speed, and the other low-speed, or alternately high and low impulse. The result is that for some of the motion there is a high force being generated, enough to overcome friction. However on the "return stroke" the force is not high enough, and any motion occurring in

the first portion is not reset. In this way the devices "steal" working mass from their supporting surface, a fact that may not be apparent to casual observation.

Basically, an oscillation thruster works just like walking does, one mass is "thrown" backward, "thrusting" the device forward according to conservation of momentum (like a person taking a step forward), then the mass is more slowly brought forward to its initial position (like the person using their step to pull the rest of their body forward). The thruster is allowed to move forward in the first step because the mass is "thrown" back with large enough force to overcome static friction. The "thruster" doesn't move backward in the second step because static friction provides an outside force that overcomes the step (like the ground does when you're walking).

Although there have been many versions proposed, all oscillation thrusters have the following common components:

- Chassis to support a system of masses,
- Conveyor that moves the masses through an asymmetric cycle,
- Power source for the conveyor.

A crucial feature is that these internal masses go through some sort of cyclic motion where the motion in one direction is quicker than in the return direction.

Inventors of oscillation thrusters extrapolate its behavior to mean that it can work in a vacuum in zero gravity.

One of the most famous proposed reactionless drives was the Dean drive. Although Dean himself gave few indications of how his "reactionless drive" was supposed to work, it appears to be an attempt at an oscillation thruster. Other examples of oscillation thrusters are:

- The Thomson Inertial Engine
- Henry Bull's Impulse Engine of 1935

Gyroscopic Inertial Thrusters

While the general consensus in dogmatic science insists that inertial propulsion is "impossible" one adherent to the concept (David E. Cowlshaw) operated an open internet forum on the subject from 1996 to 2003, and reported numerous proofs of physical testing, and gathered reports from over 20 others also claiming success in the field.

His GIT (Gyroscopic Inertial Thruster) concept reportedly broke the supposed barrier between angular and linear accelerations and momentum, by utilizing a motion profile that operated on the frame with both (angular and linear accelerations).

A variable angular velocity eccentric mass (speeding up and slowing down of an off-center mass circularly in a frame), produces BOTH angular accelerations on the frame

(angular oscillation or the "twist"), AND linear oscillations on the frame (movement toward and away from a rest position in space, or the "hula").

Working models reportedly function by introducing a third motion actor to the well tested and represented variable velocity motion profile.

By introducing inverse in angular direction, but equal in torque force spin changes in the eccentric mass, a means to "rectify" angular accelerations to produce linear spacial displacement was achieved.

By introducing orbital spin enabled eccentric mass accelerations that produce a torque or twisting force on the frame in angular opposition to the angular portion of the variable velocity eccentric mass accelerations, linear displacement in space was achieved by "force rectifying" the angular "twist" accelerations.

This in effect, transfers negatively acting forces on the frame from the linear position changes produced by the eccentric's POINT MASS effects on the frame, into and out of "another dimension" for the negatively acting portion of the cycle.

That extra dimension is the spin axis of the eccentric orbital, storing reverse momentum from the point mass' motion on the negative side of the cycle, then releasing that stored momentum toward the forward directed portion of the cycle.

An easily grasped example is the variable velocity eccentric "dumb hammer" slinger on train tracks. This is a working example of the centrifugal thrust concept that actually works, and has been used repeatedly throughout history, often as a deceptive experimental "proof" (until you lift it off the tracks).

The deceleration toward the rear of the cart is accomplished by generating a torque or twisting force on the earth, rather than by pushing the cart backwards to slow the hammer down. On the opposite side of the cycle, speeding the hammer back up, again it does so by generating a torque through the wheels and rails, rather than pushing linearly backwards on the cart. The "imaginary" centrifugal force then pulls the cart forward.

The GIT style of machines simply replace the torque exchanges with the earth, with a footloose, onboard equivalent set of torque forces, generating the opposing torques of a spin acceleration enabled eccentric mass.

This is linear spacial displacement using a bilateral torque force rectified angular tangential acceleration profile, to produce a bilaterally opposed pairing, resulting in a rectified linear thrust from angular accelerations.

The inventor is no longer publishing his advancements in this field, and his website is no longer active, however the published works, including the reported proofs in retrievable updates are available on a European archive site.

Electrostatic anti-gravity

Electrostatic anti-gravity relies on oddly placed capacitors and a high-voltage source. Claims of electrostatic anti-gravity are explained by the Biefeld–Brown effect, which is distinctly *not* anti-gravity. Believers of this form of "anti-gravity" agree that the Biefeld–Brown effect is in action, but say that it does not account for all the upward force. This area of research has not been fully exhausted, but all verified experiments fail to show any new physics. Supposed "Electrostatic anti-gravity"-machines have been tested in vacuum, even in an episode of the Mythbusters, and either insufficient force or no force at all was produced by the test device able to levitate it, at the undeclared vacuum level that the experiment was performed. In the Mythbusters experiments in vacuum, the lowest unit of force detectable was the device ability to lift its own weight, which was not observed. A company by the name of Gravitec claims to have demonstrated this unaccounted force in an experiment conducted with NASA, but to date, no evidence exists of this claim, and NASA have no record of any such experiment.

Quantum Vacuum

Magnetoelectric materials can be electrically polarized by magnetic fields. The quantum vacuum contains randomly fluctuating magnetic fields. A sufficiently small piece of magnetoelectric material can be placed in the quantum vacuum and then rotated 180 degrees. The random magnetic fields can induce a change in electric polarization in the block of material. Somehow this change causes the combined electric and magnetic fields to push the block in one direction while they (the fields themselves, or more technically, the bosons of which these fields are composed) get pushed in the other direction. The trick doesn't work if the magnetoelectric block is too large but curiously it should work if there's a grid of millions of tiny blocks working together. This mechanism was first suggested in December 2009 and apparently has not yet been tested. The author of the original paper suggested that the mechanism could be used would be powerful enough to reorient satellites if a material with a magnetoelectric constant ten times higher than the strongest such materials known today could be found.

Electromagnetic tethers

At first glance, a device called the electrodynamic tether might appear to constitute a reactionless drive because it does not expel reaction mass. But it is still not reactionless, as electromagnetic fields can carry energy and momentum.

The fundamental scientific problem is one of momentum transfer. If there is no momentum transfer, the postulated device is classified as a "reactionless" drive and labelled a fraud. If there is a mechanism for momentum transfer, then the device is classed as a reaction drive and is therefore by definition not a "reactionless" drive. Tethers do have a mechanism for momentum transfer and although they do not expel reaction mass like a rocket, they transfer momentum and hence cannot be a true reactionless drive.

EmDrive

EmDrive (also **Relativity Drive**) is the name of a spacecraft propulsion system proposed, and reportedly developed, by Roger Shawyer. *New Scientist* ran a cover story on EmDrive in its 8 September 2006 issue. The device is a magnetron with a specially-shaped, fully-enclosed tapering resonator cavity whose area is greater at one end. The inventor claims that the device generates thrust even though no detectable energy leaves the device. The inventor proposes to use it as a spacecraft propulsion system that uses no fuel (other than electricity), and no reaction mass.

On his homepage the inventor claims that independent peer-review is under way, but so far no publication is available.

The device's operation as described seemingly violates several basic laws of physics, notably conservation of momentum, though the inventor insists to the contrary. John Costella, an expert in relativistic electrodynamics describes the EmDrive as a 'fraud'.

Principle of operation

The device exploits an idea first suggested by Allen Cullen in the 1950s, an electrical engineer then at University College London, that involves forces created by reflecting microwaves between opposite walls of a cavity. The idea is to try to design a cavity in such a manner that forces on one side are greater than the other.

The drive comprises a resonant cavity flooded with microwave radiation. The radiation exerts radiation pressure on the walls of the cavity, and normal Newtonian mechanics would of course indicate that, no matter what shape the cavity is, the forces exerted upon it from within must balance to zero.

However, Shawyer claims that relativistic effects cause a cavity shaped like a truncated cone to experience a larger force against the large end than the small end, due to the group velocity of the wave changing as the local diameter of the cavity varies.

The increased confinement of the tapered end of the cone leads to a higher effective propagation constant (phase velocity). It also leads to local reflections which account for the apparent force imbalance when considering only the end walls. However, since it is the phase of the light rather than the actual photons bouncing off the walls, each force acts quasi independently from another—much like in a ring laser gyroscope where the beams act as if having an external frame of reference (which they have, since the speed of light is constant). The same principle applies to the EmDrive.

No microwaves or anything else are allowed to leave the device. Since nothing leaves the drive for propulsive purposes an EmDrive can be classed as a reactionless drive. The principle by which the EmDrive is supposed to operate seems to violate conservation of momentum. However, the emdrive website claims that the device is not reactionless

because the force is created by a "reaction between the end plates of the waveguide and the Electromagnetic wave propagated within it." It is known that the physics equations describing microwaves, Maxwell's equations, conserve momentum, and this would seem to cast doubt on Shawyer's derivation of a thrust effect. In his paper, Shawyer thus takes the following view: any thrust extracted from the device is directly withdrawn from the energy stored in the cavity (due to the Q reflections an average wave encounters when inserted into the cavity, the energy levels quickly build up). In other words: the apparent force on the wider diameter of the cone seems to lessen. The extent to which that happens perfectly matches the amount predicted by the law of conservation of momentum.

Criticism

The EmDrive was the cover story for the 8 September 2006 issue of *New Scientist*. After receiving criticism that no peer-reviewed publications on the subject had been made, Mr. Shawyer submitted a theory paper to *New Scientist* (which is not a peer reviewed scientific journal) Shawyer's paper was almost immediately challenged by Dr. John Costella, a theoretical physicist and electrical engineer who works for the Australian Department of Defence, whose Ph.D. is in relativistic electrodynamics, the field of physics that Mr. Shawyer relies on to support his theory.

Prototypes and tests

In September 2006 *New Scientist* reported that Shawyer had constructed a prototype unit weighing 9 kilograms that consumes 700 watts of power and produces 88 millinewtons of force.

In May 2007 *Eureka* magazine reported that a second unit has been built for demonstration purposes, weighing 100 kilograms, consuming 300 watts for microwave production (and an unspecified amount for ancillary purposes such as cooling) and producing 96.1 millinewtons of force during testing in October 2006. Unlike the prototype unit, which can only be run for short periods before burning out its magnetron, the demonstration unit can be run continuously.

The limiting factor for performance is claimed to be the Q factor of the cavity, as microwave energy lost to heating the cavity reduces the field strength within, so Shawyer is experimenting with a cavity lined in a superconducting material that may produce Q factors sufficient to build a device capable of generating 30 newtons per watt.

These results have neither been reproduced by other scientists or engineers, nor have they been published in a peer-reviewed scientific journal.

***New Scientist* article**

EmDrive was featured on the cover of the 8 September 2006 issue of *New Scientist*, a weekly science magazine. The article portrayed the device as plausible, and emphasized

the arguments of those who held that point of view, although it did quote one engineer as saying "it's a load of bloody rubbish." The article included the following arguments from proponents of the theory:

- With a grant from the UK government's Department of Trade and Industry of £250,000, (actually two grants; one a feasibility study of £45,000 and a second of £81,000 to build a demonstration engine - source SPR Ltd.) a commercial regulatory and support agency, Shawyer has built two prototypes that reportedly produce 16 mN and 300 mN of thrust respectively; each using 1 kW of electrical power. A condition of the funding was independent analysis, which was recently completed by John Spiller who says "The thruster's design is practical and could be adapted fairly easily to work in outer space". Shawyer claims that he has been visited by representatives from China and the US Air Force, but ESA has not yet shown much interest. He estimates that his design could save the aerospace community \$15 billion over the next ten years.
- Engineers in Germany have created superconducting resonators (for use in particle accelerators) with Q values of several billion, which Shawyer claims would equate to a thrust of 30 kN per kilowatt, "enough to lift a large car". Shawyer states that the thrusters work best while stationary relative to their thrust.

New Scientist has drawn great criticism from the scientific community due to the uncritical treatment of EmDrive in its article. Science fiction writer Greg Egan distributed a public letter stating that "a sensationalist bent and a lack of basic knowledge by its writers" was making the magazine's coverage sufficiently unreliable "to constitute a real threat to the public understanding of science". In particular, Egan found himself "gobsmacked by the level of scientific illiteracy" in the magazine's coverage of the EmDrive, where *New Scientist* allowed the publication of "meaningless double-talk" designed to bypass a fatal objection to Shawyer's proposed space drive, namely that it violates the conservation of momentum. Egan urged those reading his letter to write to *New Scientist* and pressure the magazine to raise its standards, instead of "squandering the opportunity that the magazine's circulation and prestige provides" for genuine science education. The letter was endorsed by mathematical physicist John C. Baez and posted on his blog. Egan has also recommended that *New Scientist* publish Costella's refutation of Shawyer's theory paper .

Analysis

Any claim of a reactionless drive is treated with skepticism by the physics community, since reactionless drives violate the well-established principle of the conservation of momentum, which has enormous experimental support. Shawyer claims that his drive does not violate the conservation of momentum.

Since there are no known phenomena that do not conserve energy, any calculation based on standard physical theory that predicts a violation of energy conservation almost certainly is in error. This is a non-controversial and fundamental fact regarding the

mathematical structure of the theories, regardless of whether the theories themselves are or are not correct descriptions of the physical world. Accordingly, the results reported regarding the EmDrive, if true, would demonstrate that existing physical theory (or its *application* in engineering) is incorrect or incomplete.

The EmDrive has been compared to the previous Dean Drive, in that an oscillatory motion is set up so that it has a different effect in each direction of the stroke, in the hope that momentum transfer will differ in each direction, except in this case the oscillations are said to be electromagnetic.

Conservation of momentum is also required and maintained in Maxwell's equations, Newtonian mechanics, Special relativity and quantum mechanics (and their combination, quantum electrodynamics), so this claim cannot be valid unless these well-established physical theories are false or can be otherwise explained in terms within these existing theories.

Shawyer's calculations may be in error. He may have incorrectly identified the forces on the sides of the waveguide. If an error is present, it is most likely that the 'thrust' is eliminated and the drive then cannot accelerate. Despite some criticism, Shawyer has released to the public a video purportedly demonstrating that his device works.

Any dispute will be settled when independent observations are able to conclude whether or not the machine works in the way it is claimed.

Diametric drive

The **diametric drive** was a speculative proposal for an "engine" which would create a non-conservative gravitational field with non-zero curl. It was argued that in such circumstances, the side of the field which creates more force on the spacecraft will accelerate the spacecraft in the direction of the force.

One idea for realizing this concept involved hypothetical particles with negative mass, originally proposed by Robert Forward and Jamie Woodward. If one were to construct a block of negative mass, and then attach it to a normal "positive" mass, the negative mass would fall towards the positive as does any mass toward any other. On the other hand, the negative mass would generate "negative gravity", and thus the positive mass (the spaceship itself generally) would fall *away* from the negative mass. If arranged properly, the distance between the two would not change, while they continued to accelerate forever. It has been argued that stability issues might arise.

Disjunction drive

The "Disjunction Drive": According to a summary of speculative propulsion ideas on NASA's website "This concept entertains the possibility that the source of a field and that which reacts to a field can be separated. By displacing them in space, the reactant is shifted to a point where the field has a slope, thus producing reaction forces between the source and the reactant. Although existing evidence strongly suggests that the source, reactant, and inertial mass properties are inseparable, any future evidence to the contrary would have revolutionary implication to this propulsion application."

Pitch drive and bias drive

One proposed method of achieving a "diametric drive", or possibly a "disjunction drive", which was allegedly studied in the BPP was called the **pitch drive**. This has been described as involving a hypothetical "disjoint field" which, it was claimed, would eliminate the need for the field to be generated on the spacecraft itself.

One specific proposal for such a pitch drive was allegedly called the **bias drive**. According to this proposal, if it were possible to locally alter the value of the gravitational constant G in front of and behind the craft, one could create a bias drive. It might help to point out here that while the gravitational constant is indeed a fundamental physical *constant* in our current gold standard theory of gravitation, general relativity, its best known competitor, the Brans-Dicke theory of gravitation, does in a sense allow for a locally varying gravitational constant, so the notion of a locally varying gravitational constant has been seriously discussed in mainstream physics. It has been claimed that one problem with the concept of a bias drive was that it might create a singularity in the field's gradient located inside the vehicle, but this "objection" appears to be as speculative as the proposal itself.

Differential sail

The **differential sail** was another speculative proposal, which appealed to the zero-point energy field. As the Heisenberg uncertainty principle implies that there is no such thing as an exact amount of energy in an exact location, vacuum fluctuations are known to lead to discernible effects such as the Casimir effect. The differential sail was a speculation that it might be possible to induce differences in the pressure of vacuum fluctuations on either side of sail-like structure -- with the pressure being somehow reduced on the forward surface of the sail, but pushing as normal on the aft surface -- and thus propel a vehicle forward.