Spacecraft Propulsion and Reusable Spaceflight Launch Systems

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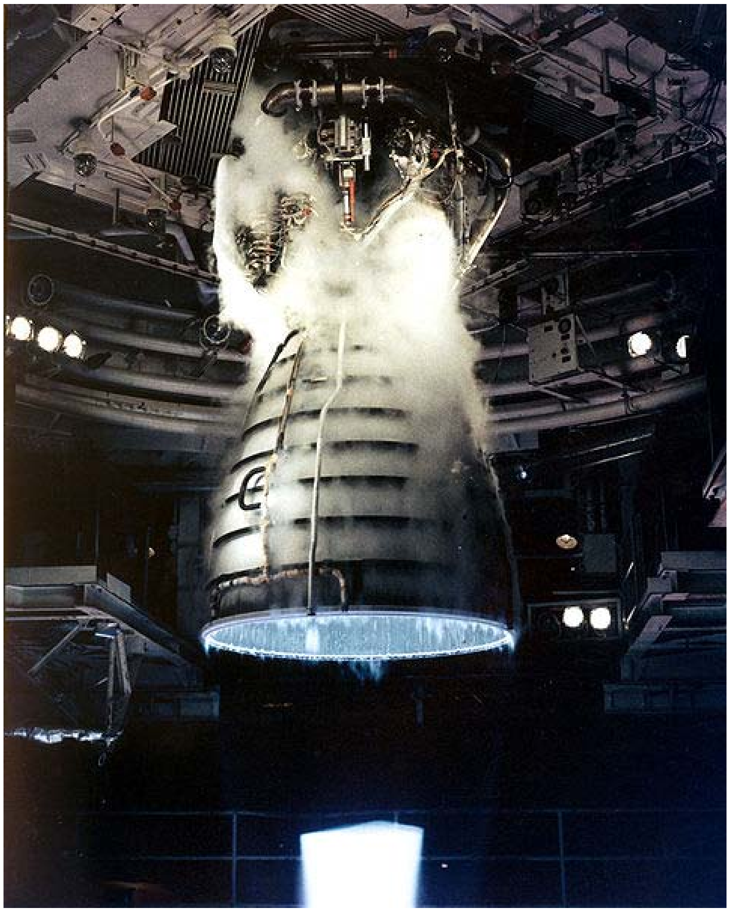
Introduction to Spacecraft Propulsion



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.

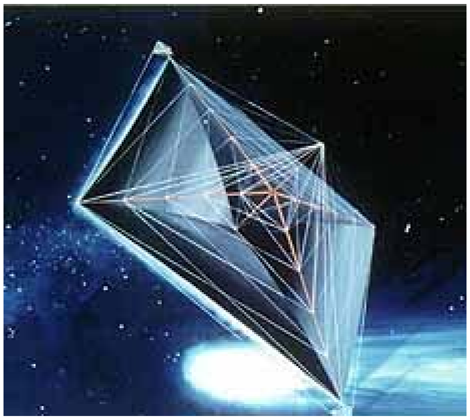
All current spacecraft use chemical rockets (bipropellant or solid-fuel) for launch, though some (such as the Pegasus rocket and SpaceShipOne) have used air-breathing engines on their first stage. Most satellites have simple reliable chemical thrusters (often monopropellant rockets) or resistojet rockets 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/s²), 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/s² ($I_{sp}g_{\text{n}} = v_e$).

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

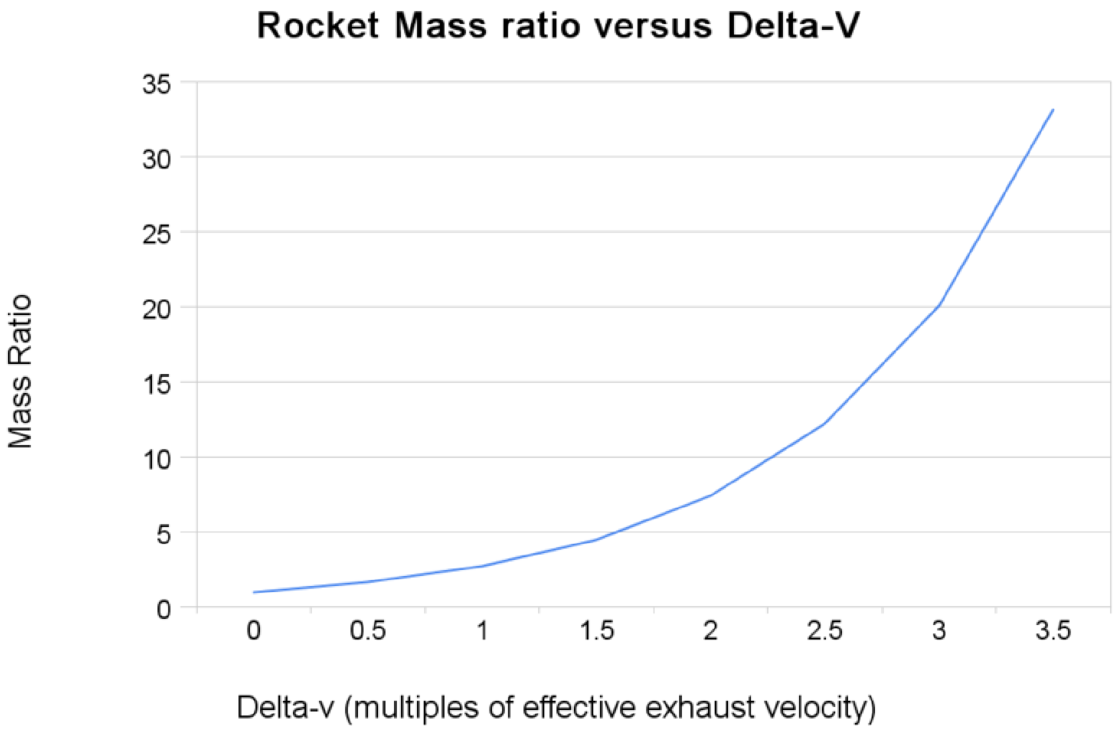
Propulsion methods can be classified based on their means of accelerating the reaction mass. There are also some special methods for launches, planetary arrivals, and landings.

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.

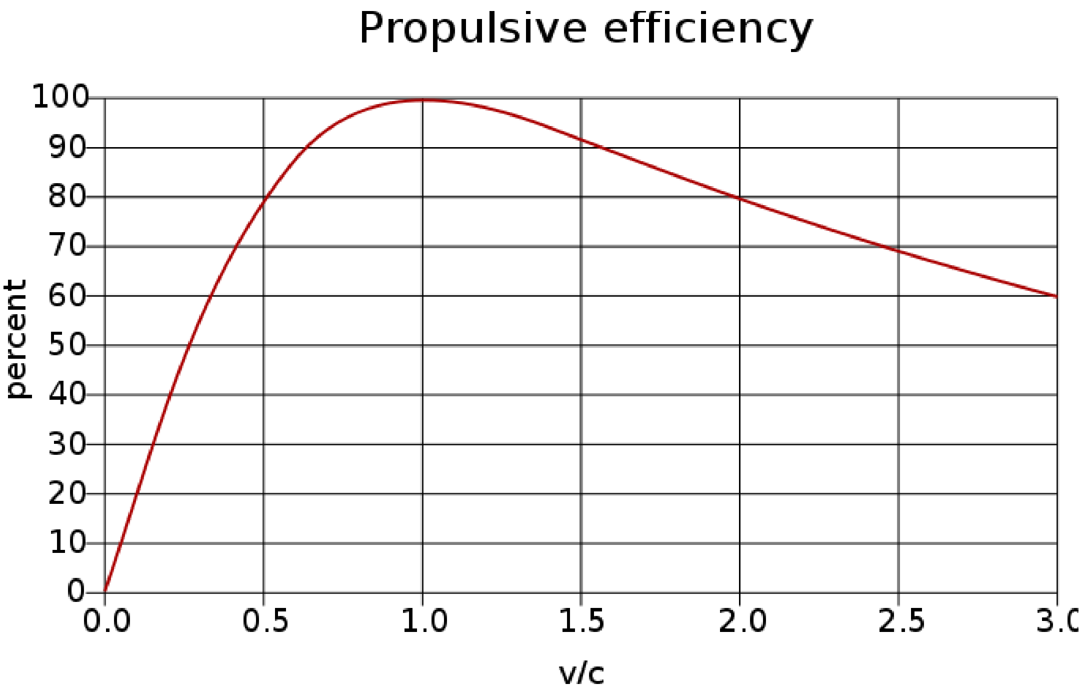
Some effects such as Oberth effect can only be significantly utilised by high thrust engines such as rockets, i.e. engines that can produce a high g-force (thrust per unit mass, equal to delta-v per unit time).

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.



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 ⅔ 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 Δ*v* 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 generator mass/thrust*
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

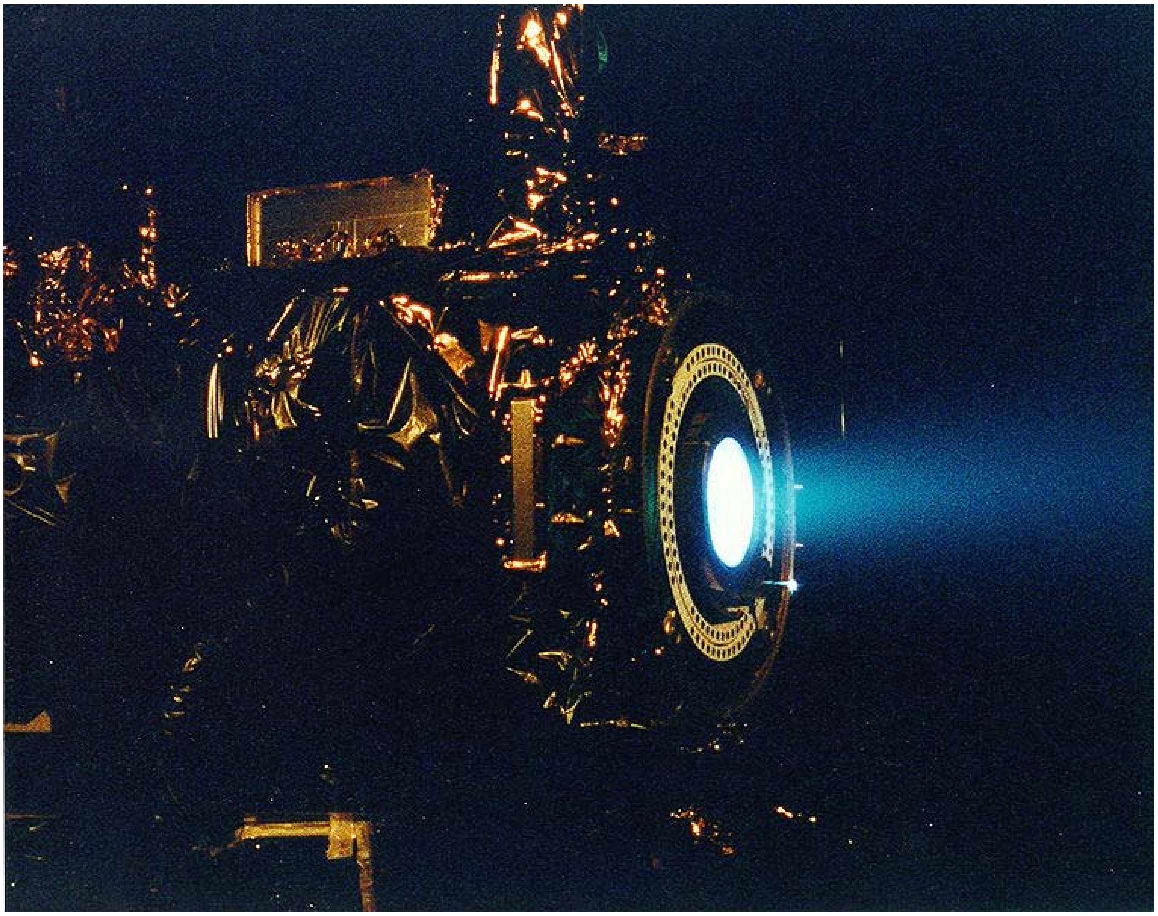
SpaceX's Kestrel engine is tested

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.

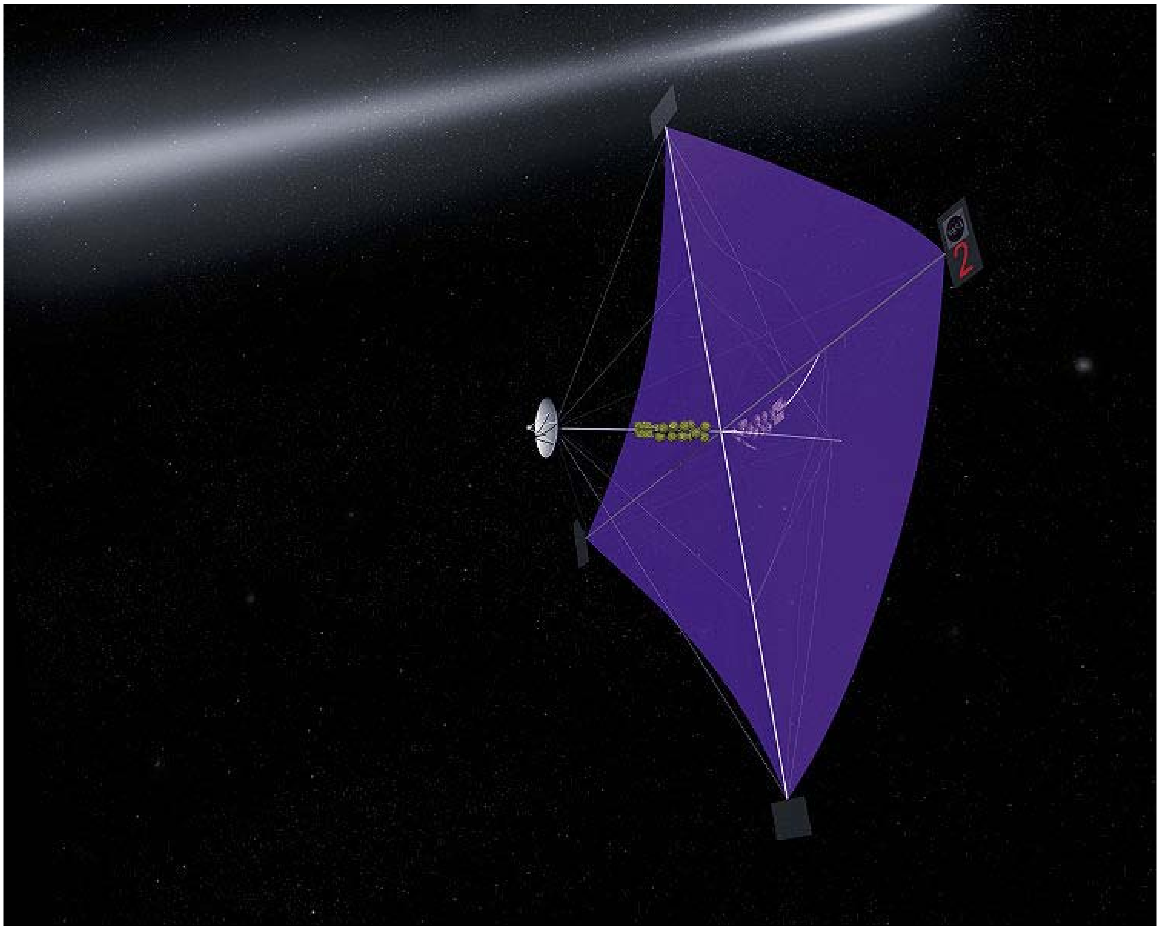
Current nuclear power generators are approximately half the weight of solar panels per watt of energy supplied, at terrestrial distances from the Sun. Chemical power generators are not used due to the far lower total available energy. Beamed power to the spacecraft shows some potential. However, the 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.

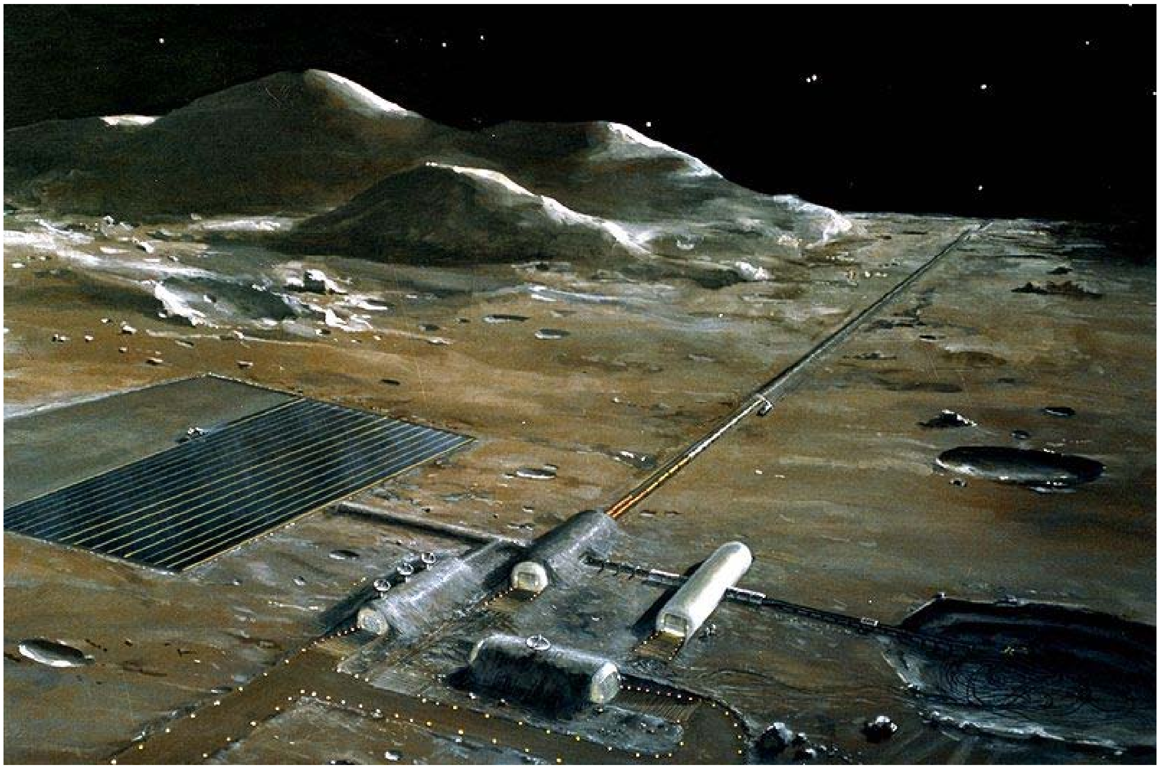
There are several different space drives that need little or no reaction mass to function. A tether propulsion system employs a long cable with a high tensile strength to change a spacecraft's orbit, such as by interaction with a planet's magnetic field or through momentum exchange with another object. 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 airdrag. 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

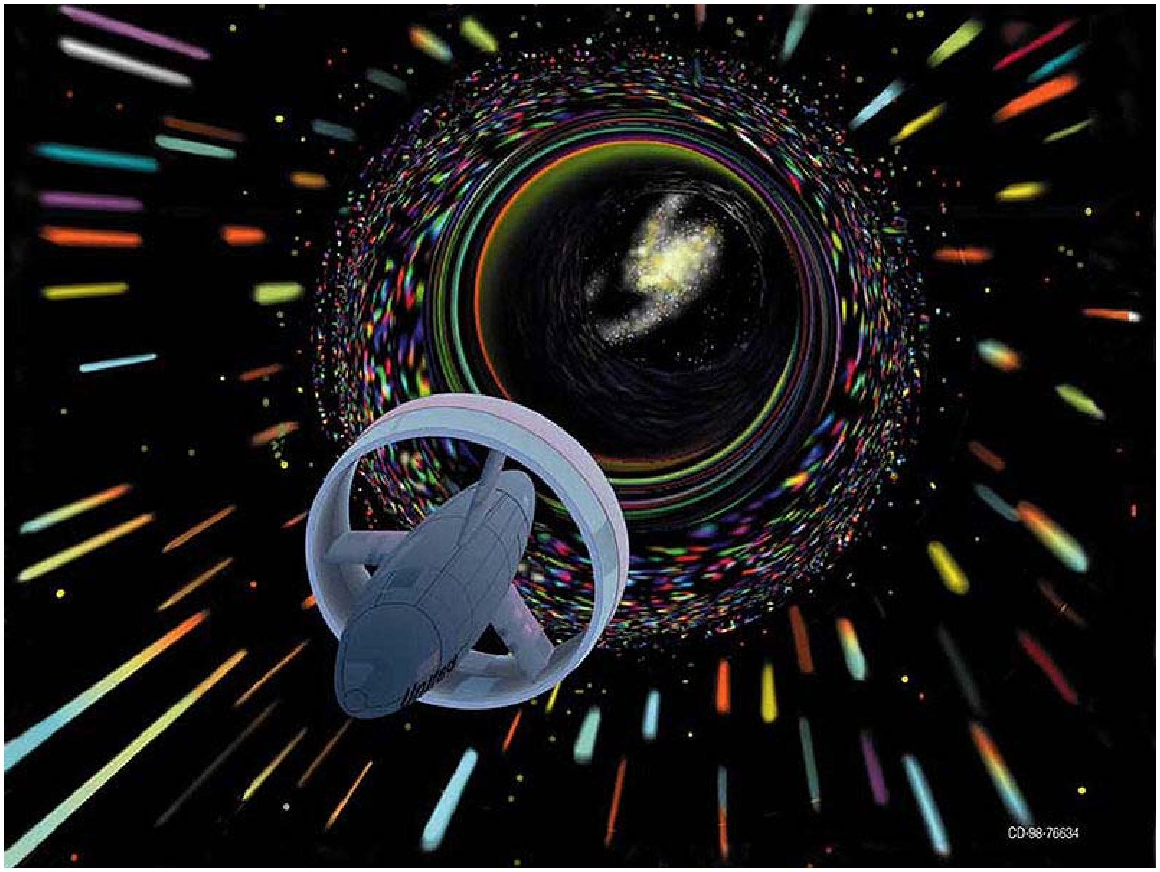
When a vehicle is to enter orbit around its destination planet, or when it is to land, it must adjust its velocity. This can be done using all the methods listed above (provided they can generate a high enough thrust), but there are a few methods that can take advantage of planetary atmospheres and/or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

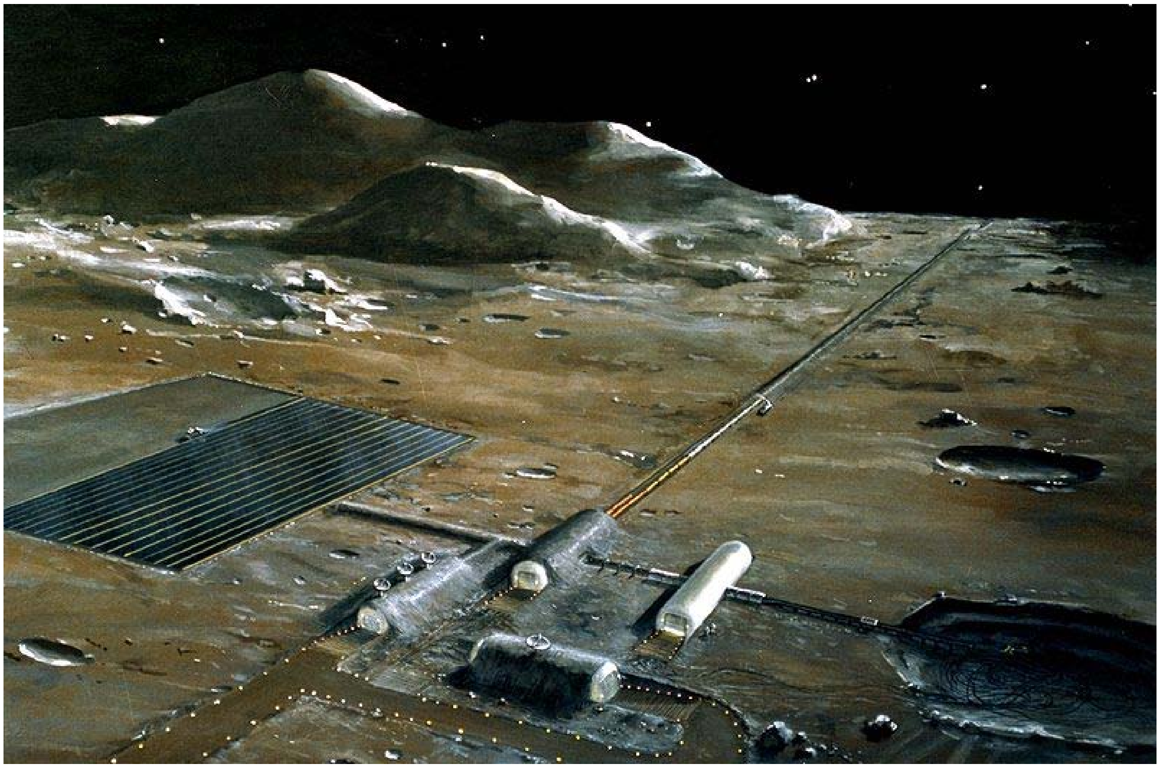
A variety of hypothetical propulsion techniques have been considered that would require entirely new principles of physics to realize and that may not actually be possible. To date, such methods are highly speculative and include:

- Diametric drive
- Pitch drive
- Bias drive
- Disjunction drive
- Alcubierre drive (a form of Warp drive)
- Differential sail
- Wormholes - theoretically possible, but unachieveable 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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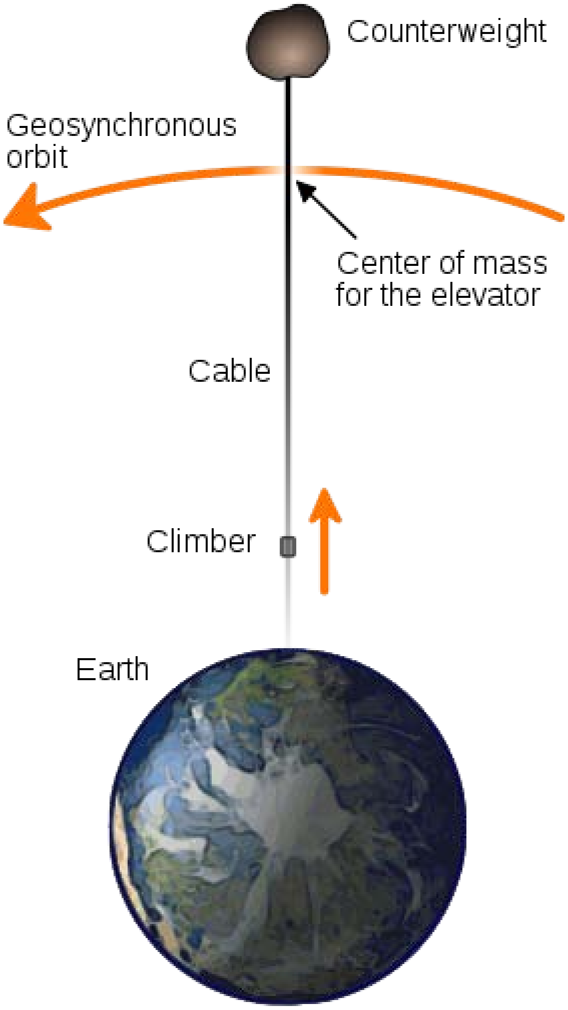
Space elevator



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.

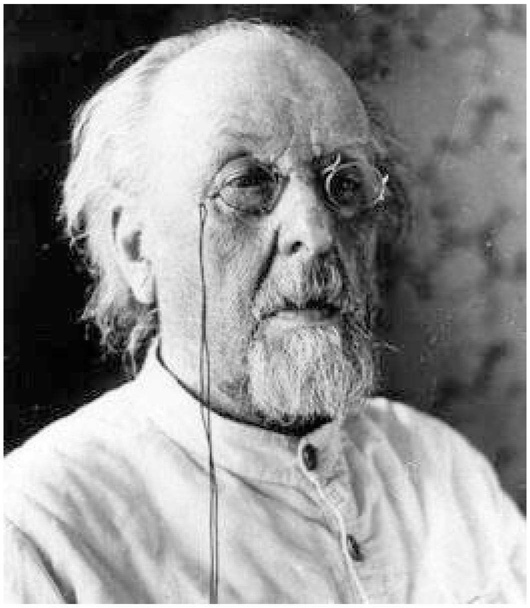
A further issue is that for human riders on an Earth-based elevator, space radiation due to the Van Allen belts would, if unshielded, give a dose well above permitted levels. This would not be an issue for non-living cargo, however.

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).

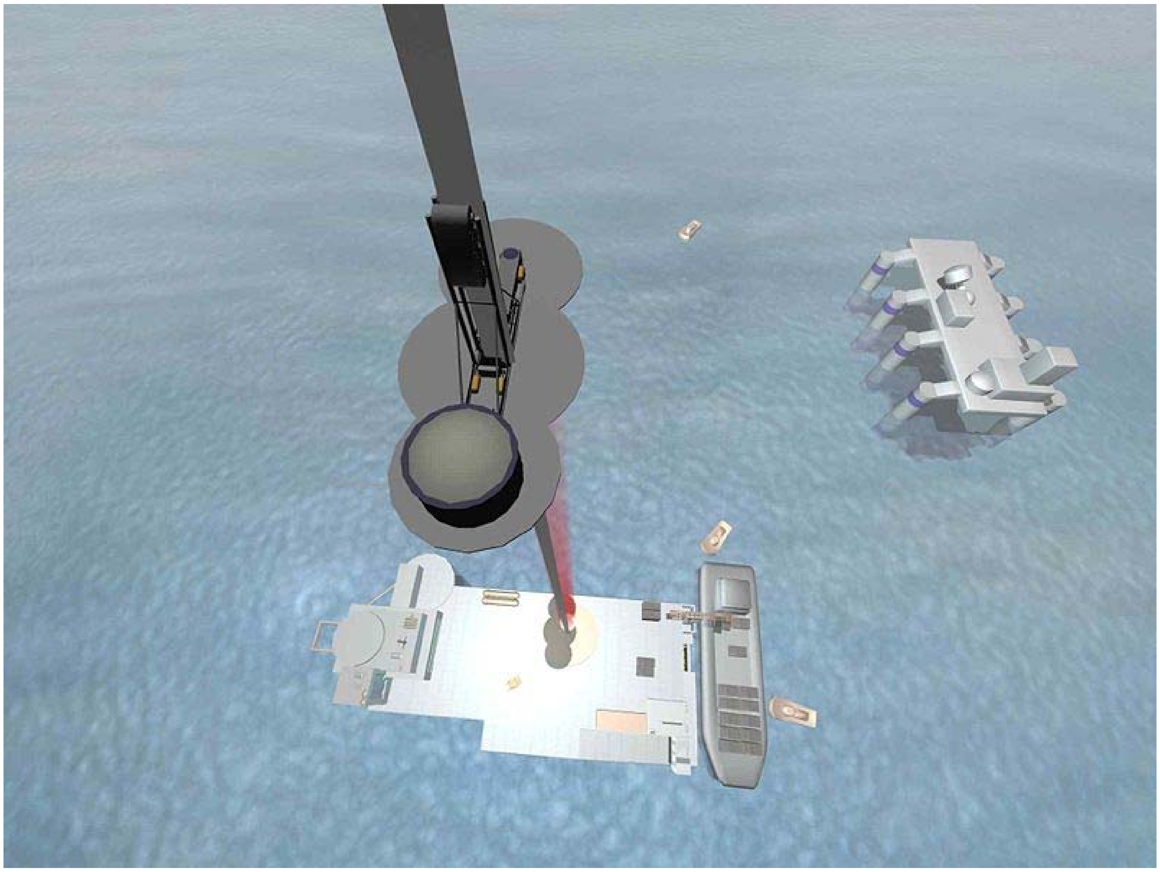
To speed space elevator development, proponents are planning several competitions, similar to the Ansari X Prize, for relevant technologies. Among them are Elevator:2010, which will organize annual competitions for climbers, ribbons and power-beaming systems, the Robolympics Space Elevator Ribbon Climbing 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

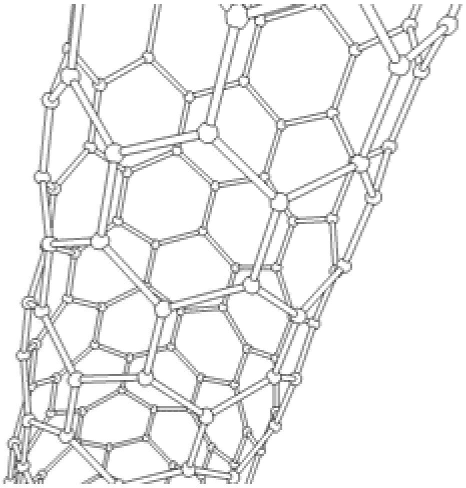
The centrifugal force of earth's rotation is the main principle behind the elevator. As the earth rotates, the centrifugal force tends to align the nanotube in a stretched manner. There are a variety of tether designs. Almost every design includes a base station, a cable, climbers, and a counterweight.

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



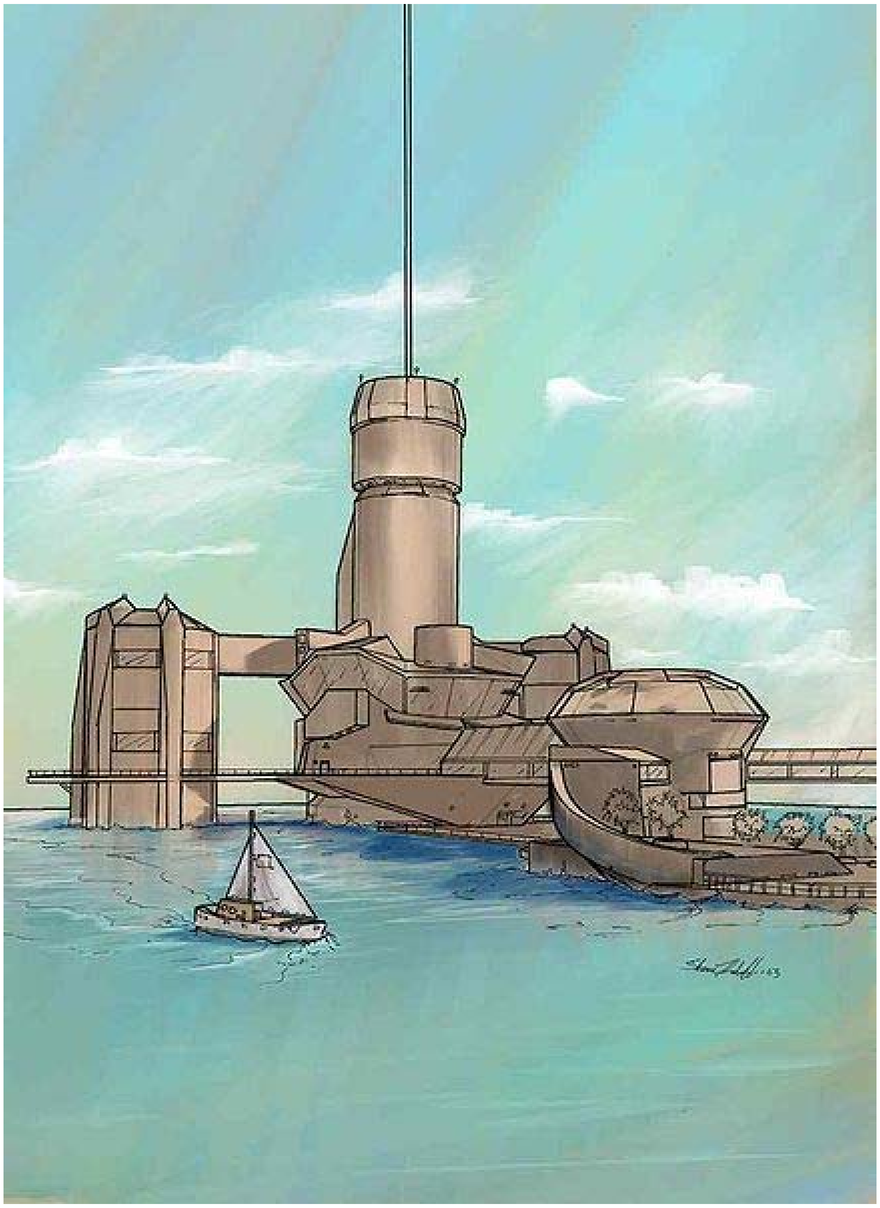
Carbon nanotubes are one of the candidates for a cable material

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.

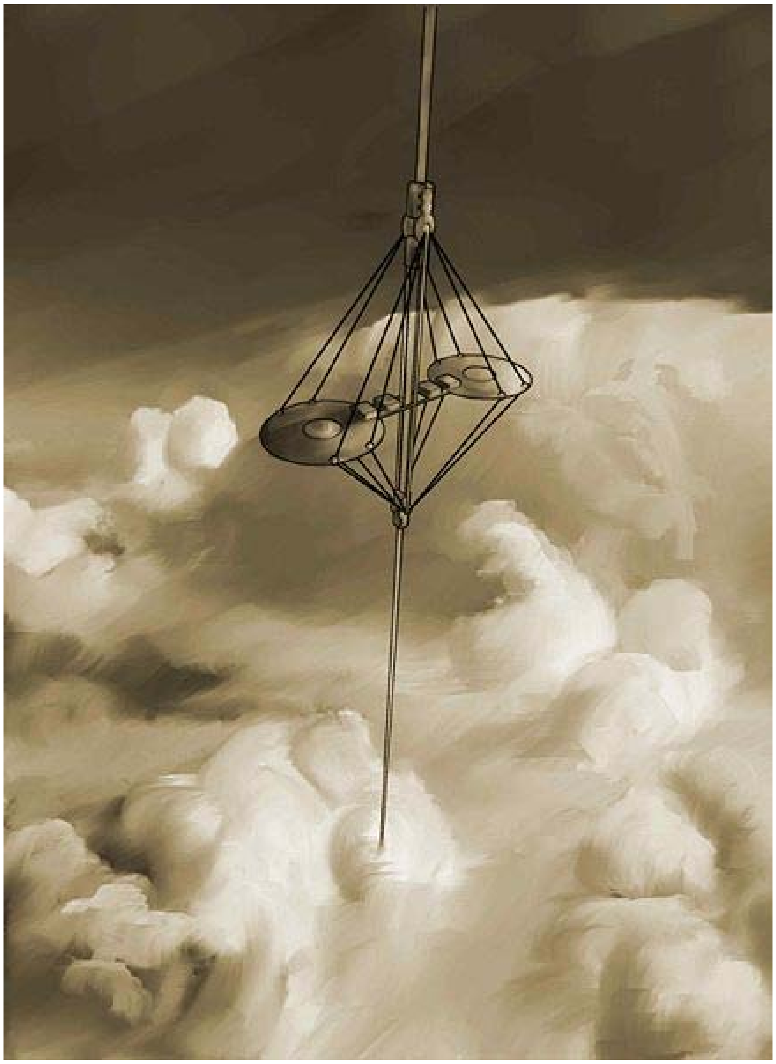
Carbon nanotubes' theoretical tensile strength has been estimated between 140 and 177 GPa (20.3-25.6 million psi) depending on their geometry and its measured tensile strength varies in the range 11–150 GPa (1.6-21.7 million psi), however only on a microscopic scale. The current (2009) technology allows 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/cm^3 (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

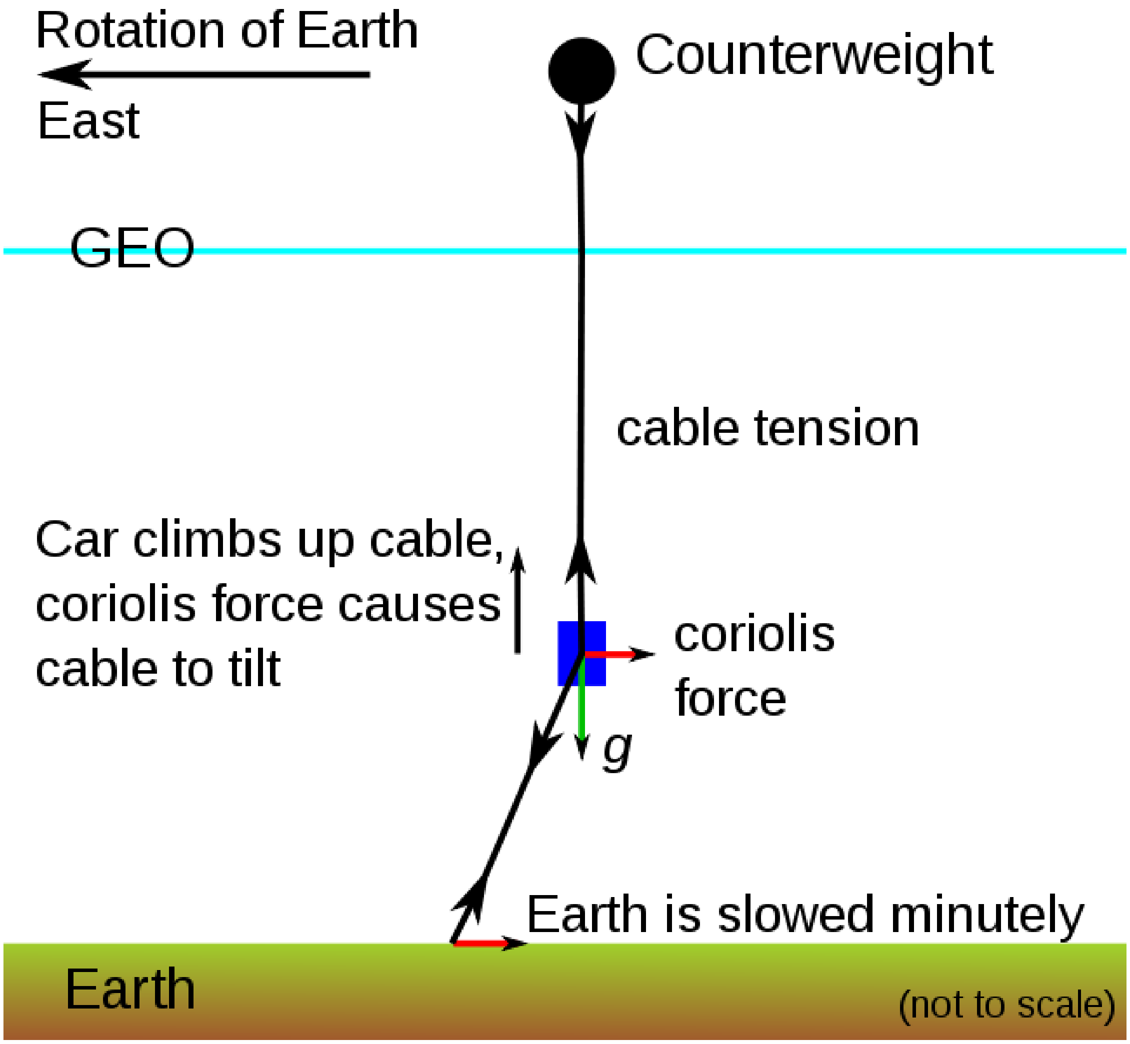


A conceptual drawing of a space elevator climbing through the clouds

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.

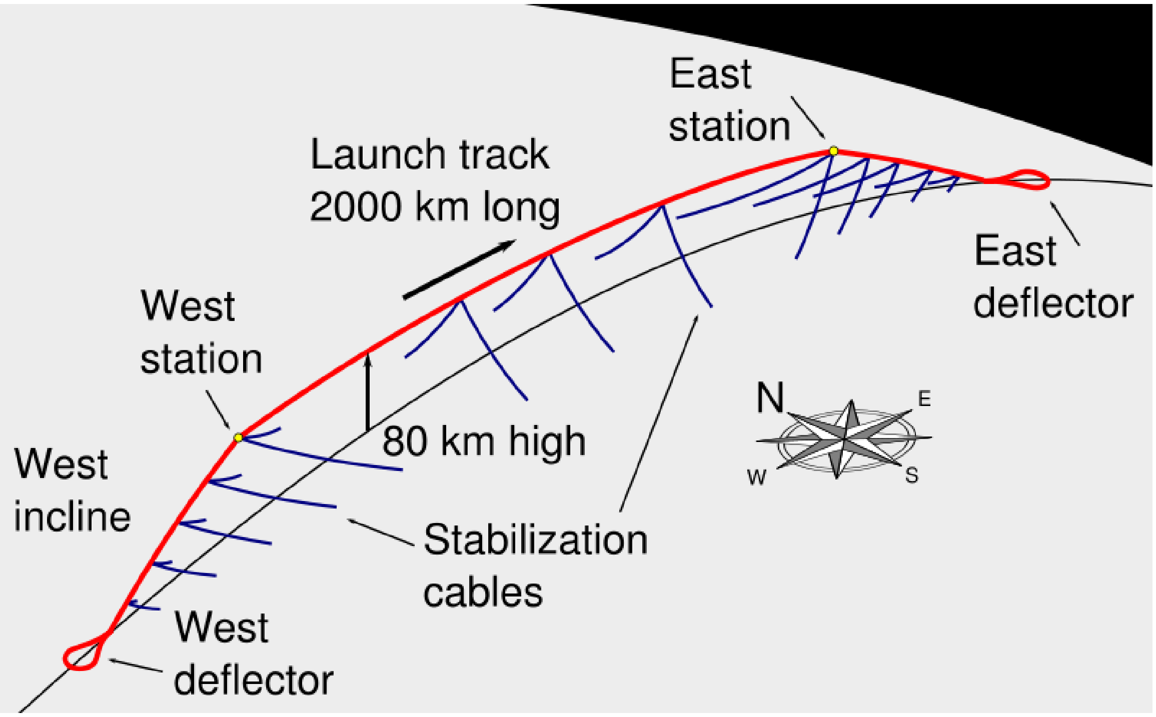
Impacts by space objects such as meteoroids, micrometeorites and orbiting man-made debris, pose a more difficult problem, because the potential of a strand break to cause a failure cascade is, according to Tom Nugent, the Research Director of LiftPort Inc., "A potential show-stopper for construction 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 3*g* acceleration.

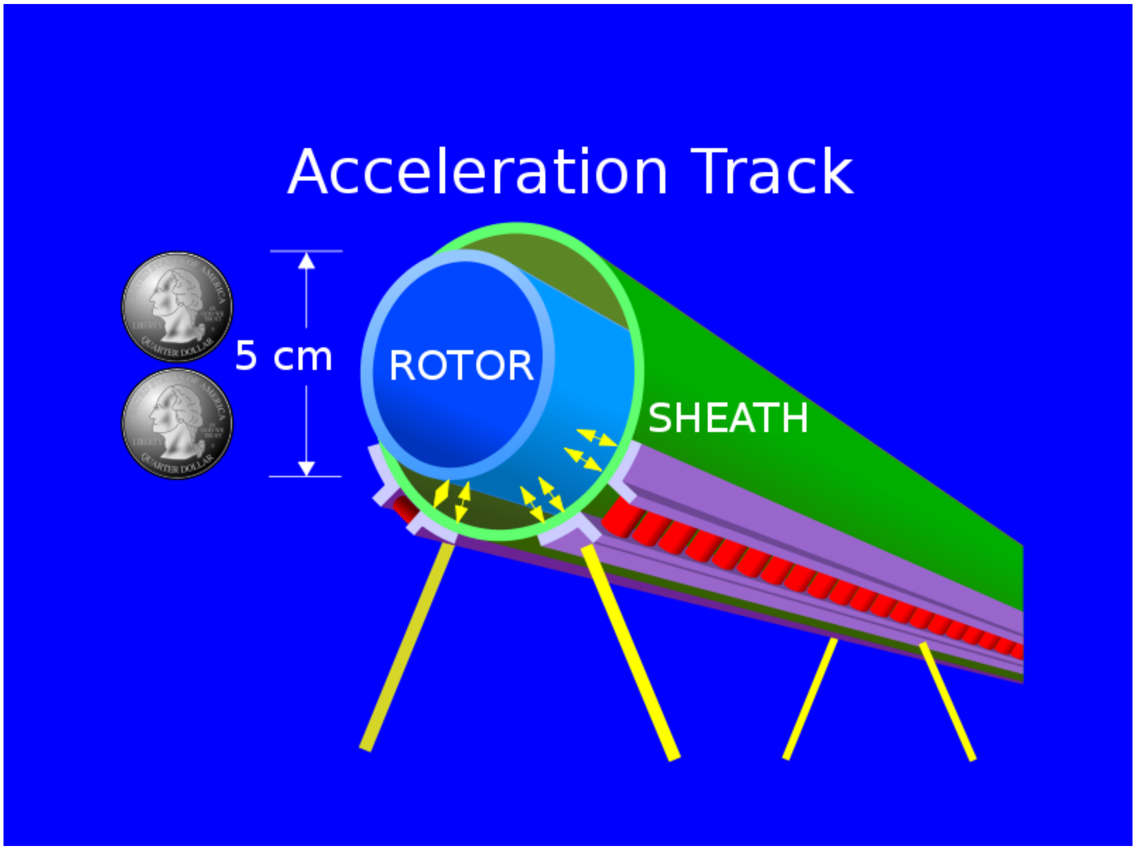
History

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 3*g* (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 3*g* 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 astrodynamic 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

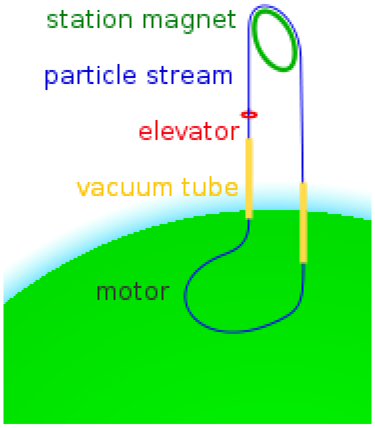
In works by Alexander Bolonkin it is suggested that Lofstrom's project has many non-solved problems and that it is very far from a current technology. For example, the Lofstrom project has expansion joints between 1.5 meter iron plates. Their speeds (under gravitation, friction) can be different and 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.

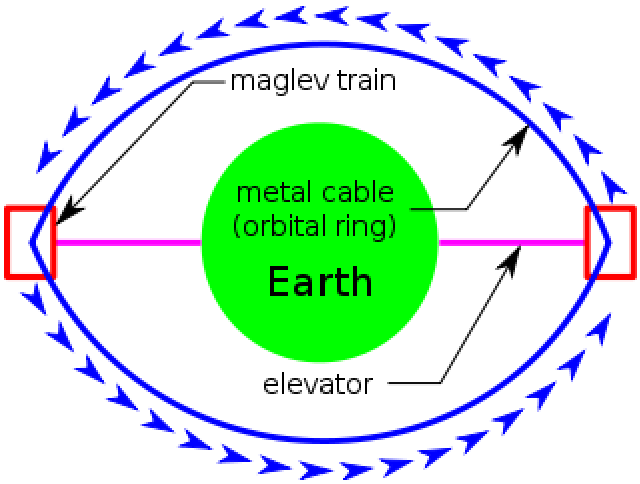
Near-term applications

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 planets 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.

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/refeuling. 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

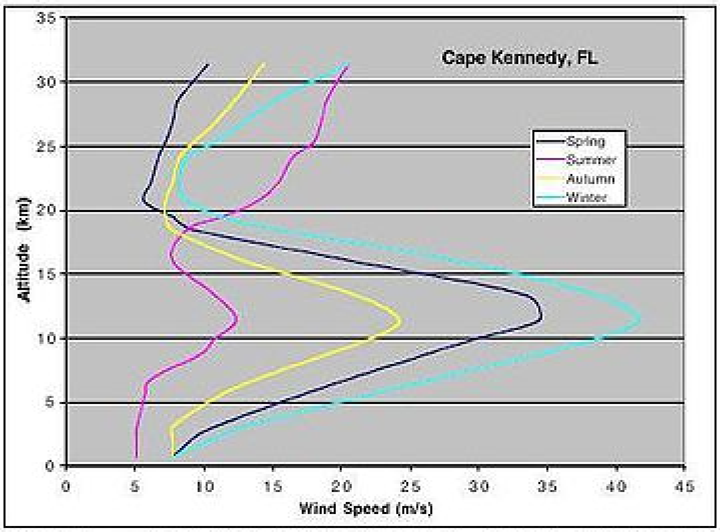


Figure 15 Mean Winds for Cape Kennedy, FL, Throughout the Year [21]

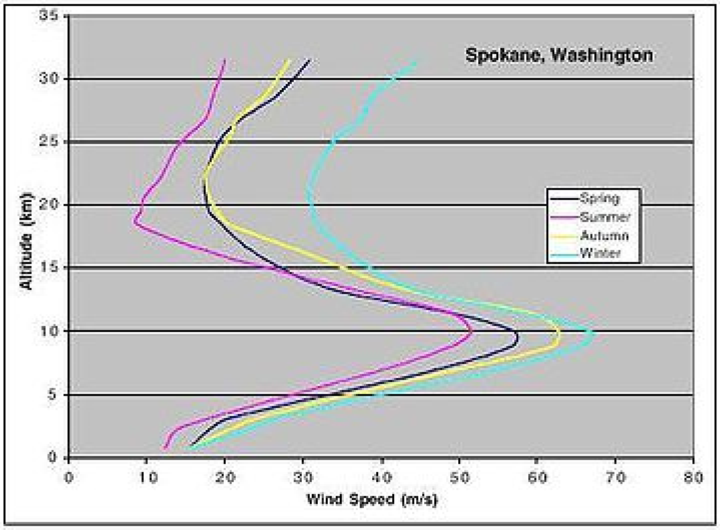


Figure 16 Mean Winds for Albuquerque, NM Throughout the Year [21]

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 Securiy 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:

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

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

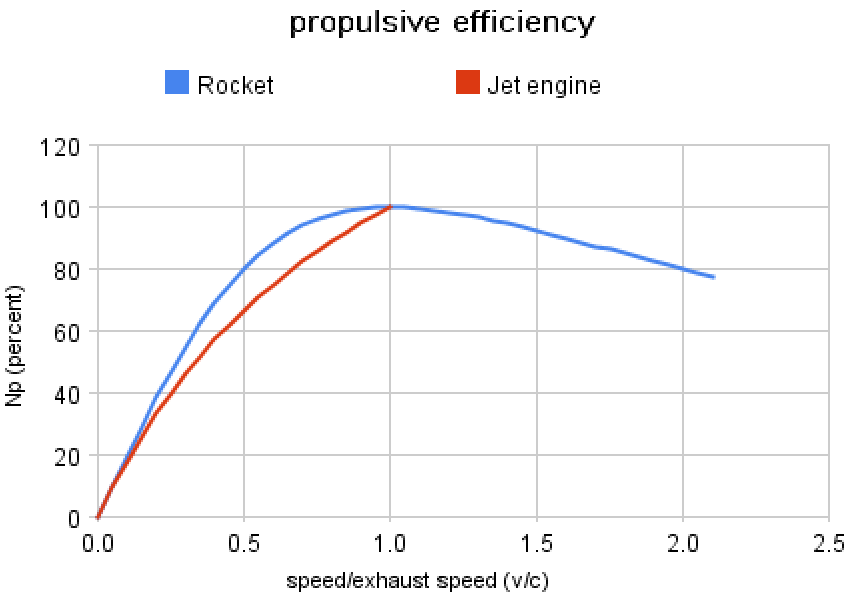
Propulsive efficiency

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 propellent 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 ⅔ 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

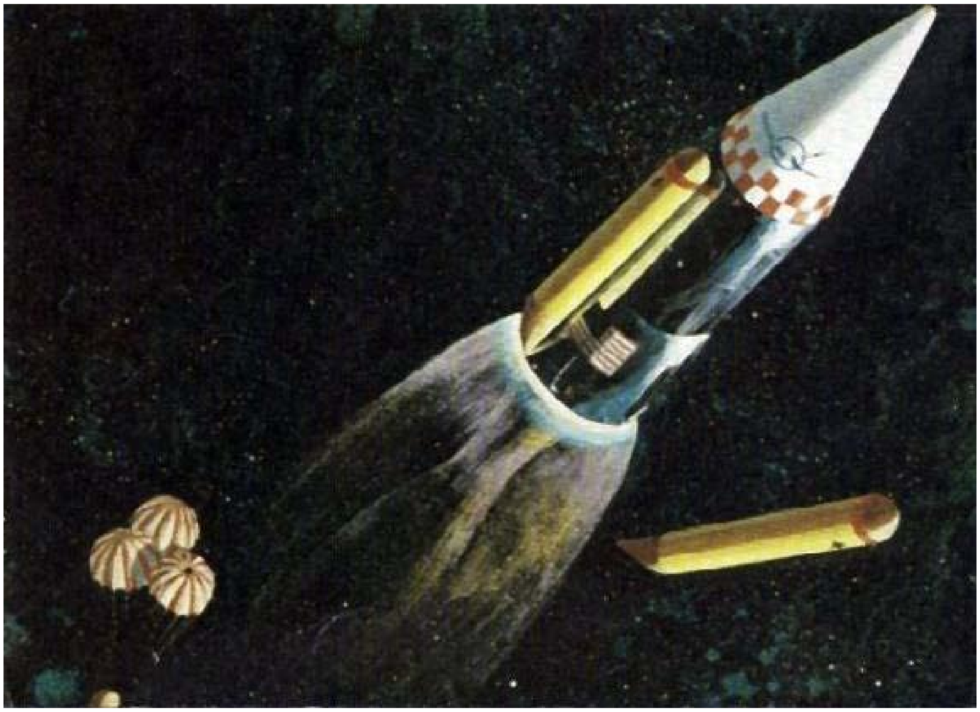
Reusable Launch System

A **reusable launch system** (or **reusable launch vehicle**, RLV) is a launch system which is capable of launching a launch vehicle into space more than once. This contrasts with expendable launch systems, where each launch vehicle is launched once and then discarded.

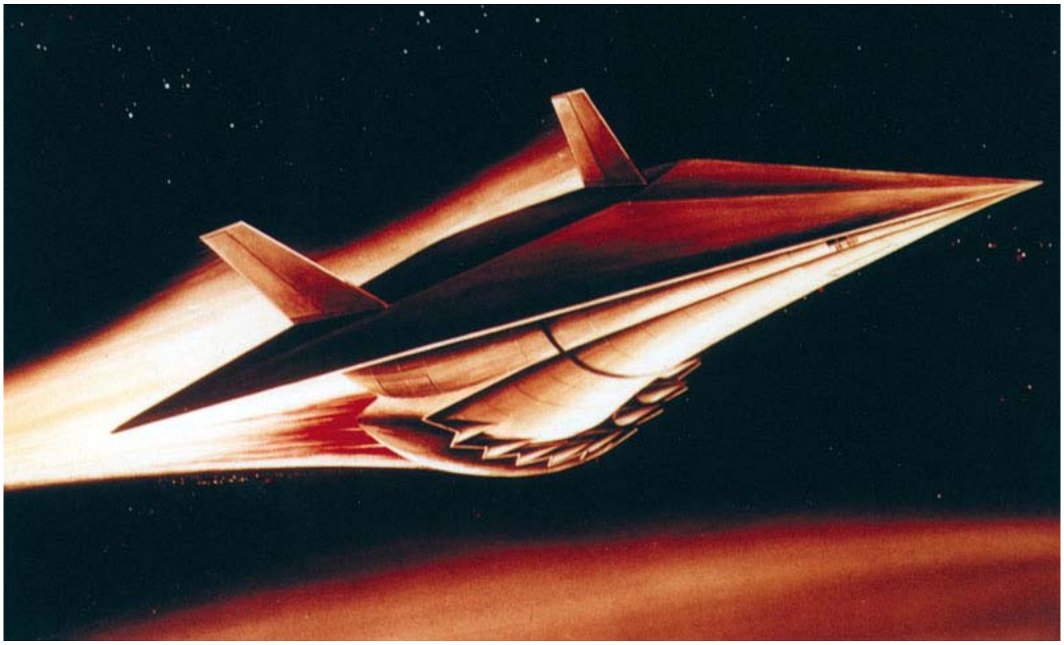
No true orbital reusable launch system is currently in use. The closest example is the partially reusable Space Shuttle. The orbiter, which includes the main engines, and the two solid rocket boosters, are reused after several months of refitting work for each launch. The external fuel drop tank is typically discarded, but it is possible for it be re-used in space for various applications.

Orbital RLVs are thought to provide the possibility of low cost and highly reliable access to space. However, reusability implies weight penalties such as non-ablative reentry shielding and possibly a stronger structure to survive multiple uses, and given the lack of experience with these vehicles, the actual costs and reliability are yet to be seen.

History



ROMBUS



Aerospaceplane 1

As usual, science fiction preceded science fact in this area. In the early 1950s popular science fiction often depicted space launch vehicles as either single-stage reusable rocketships which could launch and land vertically (SSTO VTVL), or single-stage reusable rocketplanes which could launch and land horizontally (SSTO HTHL).

The realities of early engine technology with low specific impulse or insufficient thrust-to-weight ratio to escape our gravity well, compounded by construction materials without adequate performance (strength, stiffness, heat resistance) and low weight seemingly rendered that original single-stage reusable vehicle vision impossible.

However advances in materials and engine technology have rendered this concept potentially feasible.

Before VTVL SSTO designs came the partially reusable multi-stage NEXUS launcher by Krafft Ehricke. The pioneer in the field of VTVL SSTO, Philip Bono, worked at Douglas. Bono proposed several launch vehicles including: ROOST, ROMBUS, Ithacus, Pegasus and SASSTO. Most of his vehicles combined similar innovations to achieve SSTO capability. Bono proposed:

- Plug nozzle engines to retain high specific impulse at all altitudes.
- Base first reentry which allowed the reuse of the engine as a heat shield, lowering required heat shield mass.
- Use of spherical tanks and stubby shape to reduce vehicle structural mass further.
- Use of drop tanks to increase range.
- Use of in-orbit refueling to increase range.

Bono also proposed the use of his vehicles for space launch, rapid intercontinental military transport (Ithacus), rapid intercontinental civilian transport (Pegasus), even Moon and Mars missions (Project Selena, Project Deimos).

In Europe, Dietrich Koelle, inspired by Bono's SASSTO design, proposed his own VTVL vehicle named BETA.

Before HTHL SSTO designs came Eugen Sänger and his Silbervogel ("Silverbird") suborbital skip bomber. HTHL vehicles which can reach orbital velocity are harder to design than VTVL due to their higher vehicle structural weight. This led to several multi-stage prototypes such as a suborbital X-15. Aerospaceplane being one of the first HTHL SSTO concepts. Proposals have been made to make such a vehicle more viable including:

- Rail boost.
- Use of lifting body designs to reduce vehicle structural mass.
- Use of in-flight refueling.

Other launch system configuration designs are possible such as horizontal launch with vertical landing (HTVL) and vertical launch with horizontal landing (VTHL). One of the few HTVL vehicles is the 1960s concept spacecraft Hyperion SSTO, designed by by Philip Bono. X-20 Dyna-Soar is an early example of a VTHL design, while the HL-20 and X-34 are examples from the 1990s. As of February 2010, the VTHL X-37 has completed initial development and flown an initial classified orbital mission of over seven months duration. Currently proposed VTHL manned spaceplanes include the Dream Chaser and Prometheus, both circa 2010 concept spaceplanes proposed to NASA under the CCDev program.

The late 1960s saw the start of the Space Shuttle design process. From an initial multitude of ideas a two-stage reusable VTHL design was pushed forward. That eventually ended up as a reusable orbiter with an expendable drop tank and reusable solid rocket boosters to reduce design expenses.

During the 1970s further VTVL and HTHL SSTO designs were proposed for solar power satellite and military applications. There was a VTVL SSTO study by Boeing. HTHL SSTO designs included the Rockwell Star-Raker and the Boeing HTHL SSTO study. However the focus of all space launch funding in the United States on the Shuttle killed off these prospects. The Soviet Union followed suit with Buran. Others preferred expendables for their lower design risk, and lower design cost.

Eventually the Shuttle was found to be expensive to maintain, even more expensive than an expendable launch system would have been. The cancellation of a Shuttle-Centaur rocket after the loss of Challenger also caused an hiatus that would make it necessary for the United States military to scramble back towards expendables to launch their payloads. Many commercial satellite customers had switched to expendables even before that, due to unresponsiveness to customer concerns by the Shuttle launch system.

In 1986 President Ronald Reagan called for an airbreathing scramjet plane to be built by the year 2000, called NASP/X-30 that would be capable of SSTO. Based on the research project **copper canyon** the project failed due to severe technical issues and was cancelled in 1993.

This research may have inspired the British HOTOL program, which rather than airbreathing to high hypersonic speeds as with NASP, proposed to use a precooler up to Mach 5.5. The program's funding was canceled by the British government when the research identified some technical risks as well as indicating that that particular vehicle architecture would only be able to deliver a relatively small payload size to orbit.

When the Soviet Union imploded in the early nineties, the cost of Buran became untenable. Russia has only used pure expendables for space launch since.

The 1990s saw interest in developing new reusable vehicles. The military Strategic Defense Initiative ("Star Wars") program "Brilliant Pebbles" required low cost, rapid turnaround space launch. From this requirement came the McDonnell Douglas Delta Clipper VTVL SSTO proposal. The DC-X prototype for Delta Clipper demonstrated rapid turnaround time and that automatic computer control of such a vehicle was possible. It also demonstrated it was possible to make a reusable space launch vehicle which did not require a large standing army to maintain like the Shuttle.

In mid-1990, further British research and major reengineering to avoid deficiencies of the HOTOL design led to the far more promising Skylon design, with much greater payload.

From the commercial side, large satellite constellations such as Iridium satellite constellation were proposed which also had low cost space access demands. This fueled a private launch industry, including partially reusable vehicle players, such as Kistler, and reusable vehicle players such as Rotary Rocket.

The end of that decade saw the implosion of the satellite constellation market with the bankruptcy of Iridium. In turn the nascent private launch industry collapsed. The fall of the Soviet Union eventually had political ripples which led to a scaling down of ballistic missile defense, including the demise of the "Brilliant Pebbles" program. The military decided to replace their aging expendable launcher workhorses, evolved from ballistic missile technology, with the EELV program. NASA proposed riskier reusable concepts to replace Shuttle, to be demonstrated under the X-33 and X-34 programs.

The 21st century saw rising costs and teething problems lead to the cancellation of both X-33 and X-34. Then the Space Shuttle Columbia disaster and another grounding of the fleet. The Shuttle design was now over 20 years old and in need of replacement. Meanwhile the military EELV program churned out a new generation of better expendables. The commercial satellite market is depressed due to a glut of cheap expendable rockets and there is a dearth of satellite payloads.

Against this dire backdrop came the Ansari X Prize contest, inspired by the aviation contests made in the early 20th century. Many private companies competed for the Ansari X Prize, the winner being Scaled Composites with their reusable HTHL SpaceShipOne. It won the ten million dollars, by reaching 100 kilometers in altitude twice in a two week period with the equivalent of three people on board, with no more than ten percent of the non-fuel weight of the spacecraft replaced between flights. While SpaceShipOne is suborbital like the X-15, some hope the private sector can eventually develop reusable orbital vehicles given enough incentive. SpaceX is a recent player in the private launch market which has partially reusable vehicles.

Reusability concepts

Single stage

There are two approaches to Single stage to orbit or SSTO. The rocket equation says that an SSTO vehicle needs a high mass ratio. Mass ratio is defined as the mass of the fully fueled vehicle divided by the mass of the vehicle when empty (zero fuel weight, ZFW).

One way to increase the mass ratio is to reduce the mass of the empty vehicle by using very lightweight structures and high efficiency engines. This tends to push up maintenance costs as component reliability can be impaired, and makes reuse more expensive to achieve. The margins are so small with this approach that there is uncertainty whether such a vehicle would be able to carry any payload into orbit. Also, lightweight implies small vehicles, which in turn implies small payloads, increasing the cost per kilogram of the payload.

Two or more stages to orbit

Two stage to orbit requires designing and building two independent vehicles and dealing with the interactions between them at launch. Usually the second stage in launch vehicle is 5-10 times smaller than the first stage, although in **biamese** and **triamese** approaches each vehicle is the same size.

In addition, the first stage needs to be returned to the launch site for it to be reused. This is usually proposed to be done by flying a compromise trajectory that keeps the first stage above or close to the launch site at all times, or by using small airbreathing engines to fly the vehicle back, or by recovering the first stage downrange and returning it some other way (often landing in the sea, and returning it by ship.) Most techniques involve some performance penalty; these can require the first stage to be several times larger for the same payload, although for recovery from downrange these penalties may be small.

The second stage is normally returned after flying one or more orbits and reentering.

Horizontal landing

Scaled Composites SpaceShipOne used horizontal landing after being launched from a carrier airplane

In this case the vehicle requires wings and undercarriage (unless landing at sea). This typically requires about 9-12% of the landing vehicle to be wings; which in turn implies that the takeoff weight is higher and/or the payload smaller.

Concepts such as lifting bodies attempt to deal with the somewhat conflicting issues of reentry, hypersonic and subsonic flight; as does the delta wing shape of the Space Shuttle.

Vertical landing

McDonnell Douglas DC-X used vertical takeoff and vertical landing

Parachutes could be used to land vertically, either at sea, or with the use of small landing rockets, on land (as with Soyuz).

Alternatively rockets could be used to softland the vehicle on the ground from the subsonic speeds reached at low altitude. This typically requires about 10% of the landing weight of the vehicle to be propellant.

A slightly different approach to vertical landing is to use an autogyro or helicopter rotor. This requires perhaps 2-3% of the landing weight for the rotor.

Horizontal takeoff

XCOR Aerospace EZ-Rocket used horizontal takeoff and landing using a standard airport runway

The vehicle needs wings to take off. For reaching orbit, a 'wet wing' would often need to be used where the wing contains propellant. Around 9-12% of the vehicle takeoff weight is perhaps tied up in the wings.

Vertical takeoff

This is the traditional takeoff regime for pure rocket vehicles. Rockets are good for this regime, since they have a very high thrust/weight ratio (~100).

Airbreathing

Airbreathing approaches use the air for propulsion during ascent. The most commonly proposed approach is the scramjet, but turborocket, Liquid Air Cycle Engine (LACE) and precooled jet engines are also proposed to be used.

In all cases the highest speed that airbreathing can reach is far short of orbital speed (about Mach 15 for Scramjets and Mach 5-6 for the other engine designs) and rockets would be used for the remaining 10-20 Mach for orbit.

The thermal situation for airbreathers (particularly scramjets) can be awkward; normal rockets fly steep initial trajectories to avoid drag, whereas scramjets would deliberately fly through relatively thick atmosphere at high speed generating enormous heating of the airframe. The thermal situation for the other airbreathing approaches is much more benign, although is not without its challenges.

Propellant

Hydrogen fuel

Hydrogen is often proposed since it has the highest exhaust velocity. However tankage and pump weights are high due to insulation and low propellant density; and this wipes out much of the advantage.

Still, the 'wet mass' of a hydrogen fuelled stage is lighter than an equivalent dense stage with the same payload and this can permit usage of wings, and is good for second stages.

Dense fuel

Dense fuel is sometimes proposed since, although it implies a heavier vehicle, the specific tankage and pump mass is much improved over hydrogen. Dense fuel is usually suggested for vertical takeoff vehicles, and is compatible with horizontal landing vehicles, since the vehicle is lighter than an equivalent hydrogen vehicle when empty of propellant. Non-cryogenic dense fuels also permit the storage of fuel in wing structures. Projects have been underway to densify existing fuel types through various techniques. These include slush technologies for cryogenics like hydrogen and propane. Another densifying method has been studied that would also increase the specific impulse of fuels. Adding finely powdered carbon, aluminum, titanium, and boron to hydrogen and kerosene have been studied. These additives increase the specific impulse (Isp) but also the density of the fuel. For instance, the French ONERA missile program tested boron with kerosene in gelled slurries, as well as embedded in paraffin, and demonstrated increases in volumetric specific impulse of between 20-100%.

Tripropellant

Dense fuel is optimal early on in a flight, since the thrust to weight of the engines is better due to higher density; this means the vehicle accelerates more quickly and reaches orbit sooner, reducing gravity losses.

However, for reaching orbital speed, hydrogen is a better fuel, since the high exhaust velocity and hence lower propellant mass reduces the take off weight.

Therefore tripropellant vehicles start off burning with dense fuel and transition to hydrogen. (In a sense the Space Shuttle does this with its combination of solid rockets and main engines, but tripropellant vehicles usually carry their engines to orbit.)

Propellant costs

As with all current launch vehicles propellant costs for a rocket are much lower than the costs of the hardware. However, for reusable vehicles if the vehicles are successful, then the hardware is reused many times and this would bring the costs of the hardware down. In addition, reusable vehicles are frequently heavier and hence less propellant efficient, so the propellant costs could start to multiply up to the point where they become significant.

Launch assistance

Since rocket delta-v has a non linear relationship to mass fraction due to the rocket equation, any small reduction in delta-v gives a relatively large reduction in the required mass fraction; and starting a mission at higher altitude also helps.

Many systems have proposed the use of aircraft to gain some initial velocity and altitude; either by towing, carrying or even simply refueling a vehicle at altitude.

Various other launch assists have been proposed, such as ground based sleds, or maglev systems, high altitude (80 km) maglev systems such as launch loops, to more exotic systems such as tether propulsion systems to catch the vehicle at high altitude, or even Space Elevators.

Reentry heat shields

Robert Zubrin has said that as a rough rule of thumb, 15% of the landed weight of a vehicle needs to be aerobraking reentry shielding.

Reentry heat shields on these vehicles are often proposed to be some sort of ceramic and/or carbon-carbon heat shields, or occasionally metallic heat shields (possibly using water cooling or some sort of relatively exotic rare earth metal.)

Some shields would be single use ablatives and would be discarded after reentry.

A newer Thermal Protection System (TPS) technology was first developed for use in steering fins on ICBM MIRVs. Given the need for such warheads to reenter the atmosphere swiftly and retain hypersonic velocities to sea level, researchers developed what are known as SHARP materials, typically hafnium diboride and zirconium diboride, whose thermal tolerance exceeds 3600 C. SHARP equipped vehicles can fly at Mach 11 at 30 km altitude and Mach 7 at sea level. The sharp-edged geometries permitted with these materials also eliminates plasma shock wave interference in radio communications during reentry. SHARP materials are very robust and would not require constant maintenance, as is the case with technologies like silica tiles, used on the Space Shuttle, which account for over half of that vehicles maintenance costs and turnaround time. The maintenance savings alone are thus a major factor in favor of using these materials for a reusable launch vehicle, whose raison d'etre is high flight rates for economical launch costs.

Weight penalty

The weight of a reusable vehicle is almost invariably higher than an expendable that was made with the same materials, for a given payload.

R&D

The R&D costs of reusable vehicle are expected to be higher, because making a vehicle reusable implies making it robust enough to survive more than one use, which adds to the testing required. Increasing robustness is most easily done by adding weight; but this reduces performance and puts further pressure on the R&D to recoup this in some other way.

These extra costs must be recouped; and this pushes up the average cost of the vehicle.

Maintenance

Reusable launch systems require maintenance, which is often substantial. The Space Shuttle system requires extensive refurbishing between flights, primarily dealing with the silica tile TPS and the high performance LH2/LOX burning main engines. Both systems require a significant amount of detailed inspection, rebuilding and parts replacement between flights, and account for over 75% of the maintenance costs of the Shuttle system. These costs, far in excess of what had been anticipated when the system was constructed, have cut the maximum flight rate of Shuttle to 1/4 of that planned. This has also quadrupled the cost per pound of payload to orbit, making Shuttle economically infeasible in today's launch market for any but the largest payloads, for which there is no competition.

For any RLV technology to be successful, it must learn from the failings of Shuttle and overcome those failings with new technologies in the TPS and propulsion areas.

Manpower & Logistics

The Space Shuttle program requires a standing army of over 9,000 employees to maintain, refurbish, and relaunch the shuttle fleet, irrespective of flight rates. That manpower budget must be divided by the total number of flights per year. The fewer flights means the cost per flight goes up significantly. Streamlining the manpower requirements of any launch system is an essential part of making an RLV economical. Projects that have attempted to develop this ethic include the DC-X Delta Clipper project, as well as the current SpaceX Falcon 1 and Falcon 9 programs.

One issue mitigating against this drive for labor savings is government regulation. Given that NASA and USAF (as well as government programs in other countries) are the primary customers and sources of development capital, government regulatory requirements for oversight, parwork, quality, safety, and other documentation tend to inflate the operational costs of any such system.

Orbital reusable launchers

Currently in use

- Space Shuttle (partially reusable)

Planned

- PlanetSpace Silver Dart (partly reusable spaceplane, based on hypersonic glider design)
- SpaceX Falcon 1 (announced as partially reusable; 28 September 2008 test flight reached orbit, but vehicle recovery not yet demonstrated)
- SpaceX Falcon 9 (announced as partially reusable; maiden flight achieved orbit, 4 June 2010)
- Reaction Engines Skylon (proposed airbreathing SSTO spaceplane)
- Avatar RLV (proposed reusable Indian launch system for small payloads)

Historical

- Soviet Union Energia-Buran system (partially reusable, now cancelled)

Cancelled

- Hopper (proposed reusable European launch system)
- HOTOL British SSTO
- Hyperion SSTO — 1960s concept HTVL spacecraft
- Kliper Russian-European partially reusable spacecraft that was to be launched around 2011 for the first time. It has been reported, however, that Energia is still working on the craft, and the Russian space program plans to review the decision to cancel the Kliper once they produce their now-planned modernized version of the Soyuz spacecraft. Thus, the Russian space program may decide to use it after all, and even so Energia may be able to market it to other space programs if they finish it.
- Phoenix SSTO
- Roton Commercial launch vehicle project, cancelled in 2000 due to lack of funds.

Suborbital reusable launchers

Planned

- ARCASPACE: Orizont
- Armadillo Aerospace: Black Armadillo
- Blue Origin: New Shepard
- Canadian Arrow
- The da Vinci Project: Wild Fire MK VI
- Masten Space Systems: XA 1.0
- Pablo de Leon & Associates: Gauchito
- Rocketplane Limited, Inc.: Rocketplane XP
- Space Adventures: Explorer
- Starchaser Industries: Starchaser V - Thunderstar
- TGV Rockets
- The Spaceship Company: SpaceShipTwo
- Reusable Vehicle Testing project of the Japanese Space Exploration Agency (JAXA)

Historical

- North American X-15
- Scaled Composites: SpaceShipOne

Regulations

In 2006, the US Federal Aviation Administration issued a new regulation regarding commercial reusable launch vehicles, both suborbital and orbital, as Part 431. The text can be found under the US Federal Code at 14 CFR Part 431. The new regulation was made in anticipation of planned commercial reusable launch operations including the American companies listed above. FAA regulations only have jurisdiction within the United States and its territories, and to aircraft and spacecraft registered in the United States.

Chapter 6

Blue Origin New Shepard

The **Blue Origin New Shepard** reusable launch vehicle is a vertical-takeoff, vertical-landing (VTVL) manned rocket which is being developed by Blue Origin, a company owned by Amazon.com founder and businessman Jeff Bezos, as a commercial system for suborbital space tourism. The New Shepard makes reference to the first United States astronaut in space, Alan Shepard.

As of 2006 the launch vehicle was to be assembled at the Blue Origin facility near Seattle, Washington. Also in 2006, Blue Origin started the process to build an aerospace testing and operations center on a portion of the Corn Ranch, a 165,000-acre (668 km^2) land parcel Bezos purchased 40 km north of Van Horn, Texas. Blue Origin Project Manager Rob Meyerson has said that he selected Texas as the launch site particularly because of the state's historical connections to the aerospace industry, although that industry is not located near the planned launch site, and the vehicle will not be manufactured in Texas.

A sub-scale demonstration vehicle made its first flight on November 13, 2006.

Design

Liftoff of a DC-X, the reported design inspiration for the New Shepard

The New Shepard craft is planned to be a vertical take-off/vertical landing (VTOL) system. The *New Shepard* will be controlled entirely by on-board computers, without ground control. It will be powered by high test peroxide (HTP) and RP-1 kerosene.

Mission

The New Shepard is expected to be launched vertically from West Texas and then perform a powered flight for about 110 s and to an altitude of 40 km. The craft's momentum would continue to carry it upward in unpowered flight and would decelerate until culminating at an altitude of about 100 km. After reaching apogee the vehicle would perform a descent and restart its main engines a few tens of seconds before vertical landing, close to its launch site. The total mission duration is planned to be 10 minutes.

The manned variant would feature a separate crew module that could separate close to peak altitude, and the propulsion module would perform a powered landing while the crew module would land under a parachute. The crew module can also separate in case of vehicle malfunction or other emergency using solid propellant separation boosters and perform a parachute landing.

Development schedule

Initial low altitude flight testing (up to 600 m) with subscale prototypes was scheduled for the fourth quarter of 2006. This was later confirmed in a press release by Blue Origin. It could involve up to ten flights. Incremental flight testing to 100 km altitude is planned to be carried between 2007 and 2009 with increasingly larger and more capable prototypes. The full-scale vehicle is expected to be operational for revenue service in 2010, and could fly up to 50 times a year. Clearance from the FAA is needed before test flights begin, and a separate license is needed before commercial operations begin. The company held a public meeting on 15 June 2006 in Van Horn, as part of the public comment opportunity needed to secure FAA permissions. Blue Origin says that once cleared for commercial operation, they would expect to conduct a maximum rate of 52 launches per year. The RLV would carry three or more passengers per operation.

Initial flight test

An initial flight test took place on November 13, 2006 at 6:30 am local time (12:30 UTC); an earlier flight on the 10th being canceled due to winds. This marks the first developmental test flight undertaken by Blue Origin. The flight was by the first prototype vehicle, known as Goddard. The flight to 285 feet (87 m) in altitude was successful. Videos are available on the Blue Origins website and elsewhere.

NASA sRLV program

As of March 2011, Blue Origin has submitted the New Shepard reusable launch vehicle for use as an unmanned rocket for NASA's suborbital reusable launch vehicle (sRLV) solicitation under NASA's Flight Operations Program. Blue Origin projects 100 km (62 mi) altitude in flights of approximately ten minutes duration, while carrying an 11.3 kg (25 lb) research payload.

Website

A simple web site was published in June or 2007 at domain public.blueorigin.com, but was moved to blueorigin.com shortly after the first launch in November of that year.

Chapter 7

Ares I & Ares V

Ares I

Ares I

Artist's impression of Ares I launch

Function	man-rated orbital launch vehicle
Manufacturer	Alliant Techsystems (Stage I) Boeing (Stage II)
Country of origin	United States
Size	
Height	94 meters (308 ft)
Diameter	5.5 meters (18 ft)
Mass	TBC
Stages	2
Capacity	

Payload to LEO	25,400 kg (56,000 lb)
Launch history	
Status	In development
Launch sites	Kennedy Space Center, LC-39B
Total launches	1 (prototype)
Maiden flight	Scheduled for 2014 (Augustine Commission estimates 2017)
First Stage	
Engines	1 Solid
Thrust	TBC
Burn time	~150 seconds
Fuel	Solid
Second Stage	
Engines	1 J-2X
Thrust	1,308 kilonewtons (294,000 lbf)
Burn time	TBC
Fuel	LH2/LOX

Ares I was the crew launch vehicle that was being developed by NASA as part of the Constellation Program. The name "Ares" refers to the Greek deity Ares, who is identified with the Roman god Mars. Ares I was originally known as the "Crew Launch Vehicle" (CLV).

NASA planned to use Ares I to launch *Orion*, the spacecraft intended for NASA human spaceflight missions after the Space Shuttle is retired in 2011. Ares I was to complement the larger, unmanned Ares V, which was the cargo launch vehicle for Constellation. NASA selected the Ares designs for their anticipated overall safety, reliability and cost-effectiveness. However, the Constellation program, including Ares I was canceled in October 2010 by the passage of the 2010 NASA authorization bill. Existing Constellation contracts remain in place until Congress passes a new funding bill for 2011.

Development

Advanced Transportation System Studies

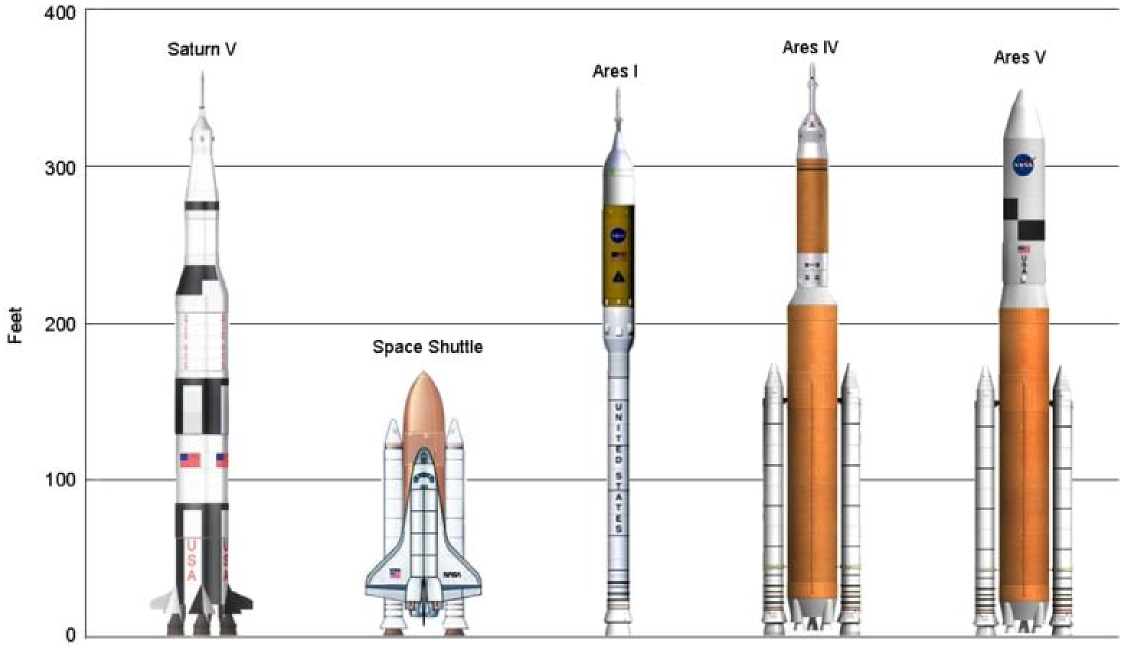
In 1995 Lockheed Martin produced an Advanced Transportation System Studies (ATSS) report for the Marshall Space Flight Center. A section of the ATSS report describes several possible vehicles much like the Ares I design, with liquid rocket second stages stacked above segmented solid rocket booster (SRB) first stages. The variants that were considered included both the J-2S engines and Space Shuttle main engines (SSMEs) for the second stage. The variants also assumed use of the Advanced Solid Rocket Motor (ASRM) as a first stage, but the ASRM was cancelled in 1993 due to significant cost overruns.

Exploration Systems Architecture Study

President George W. Bush had announced the Vision for Space Exploration in January 2004, and NASA under Sean O'Keefe had solicited plans for a Crew Exploration Vehicle from multiple bidders, with the plan for having two competing teams. These plans were discarded by incoming administrator Michael Griffin, and on April 29, 2005, NASA chartered the Exploration Systems Architecture Study to accomplish specific goals:

- determine the "top-level requirements and configurations for crew and cargo launch systems to support the lunar and Mars exploration programs"
- assess the "CEV requirements and plans to enable the CEV to provide crew transport to the ISS"
- "develop a reference lunar exploration architecture concept to support sustained human and robotic lunar exploration operations"
- "identify key technologies required to enable and significantly enhance these reference exploration systems"

A Shuttle-derived launch architecture was selected by NASA for the Ares I. Originally, the vehicle would have used a four-segment solid rocket booster (SRB) for the first stage, and a simplified Space Shuttle main engine (SSME) for the second stage. An unmanned version was to use the five-segment booster, but with the second stage using the single SSME. Shortly after the initial design was approved, additional tests revealed that the Orion spacecraft would be too heavy for the four-segment booster to lift, and in January 2006 NASA announced they would slightly reduce the size of the Orion spacecraft, add a fifth segment to the solid-rocket first stage, and replace the single SSME with the Apollo-derived J-2X motor. While the change from a four-segment first stage to a five-segment version would allow NASA to construct virtually identical motors (albeit with some interchangeable segments), the main reason for the change to the five-segment booster was the move to the J-2X.

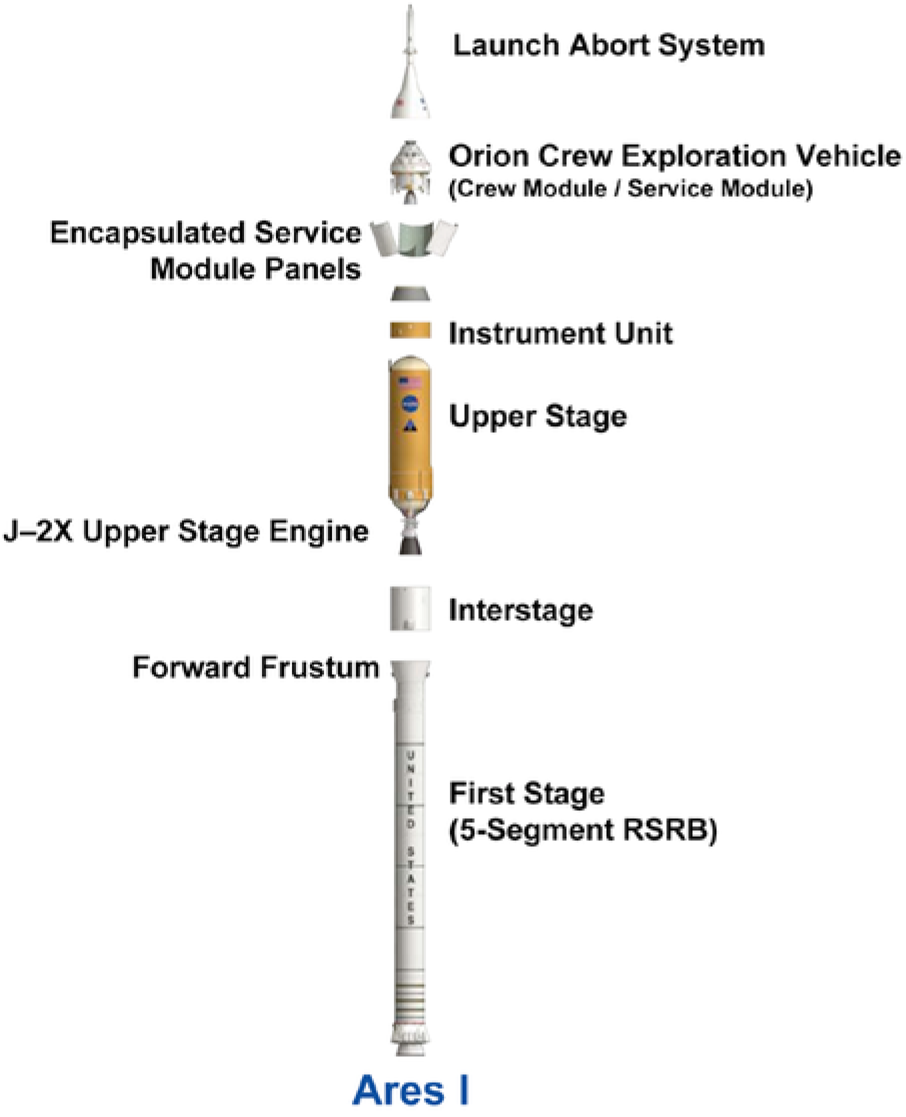


Comparison of the basic size and shape of the Saturn V, Space Shuttle, Ares I, Ares IV, and Ares V

The Exploration Systems Architecture Study concluded that the cost and safety of the Ares was superior to that of either of the Evolved Expendable Launch Vehicle (EELVs). The cost estimates in the study were based on the assumption that new launch pads would be needed for human-rated EELVs. However, the facilities for the current EELVs (LC-37 for Delta IV, LC-41 for Atlas V) are in place and could be modified. The ESAS launch safety estimates for the Ares were based on the Space Shuttle, despite the differences, but included only launches after Challenger, and counted each of the remaining launches as two safe launches of the Ares booster. The safety of the Atlas V and Delta IV was estimated from the failure rates of all Delta II, Atlas-Centaur, and Titan launches since 1992, although they are not similar designs.

In May 2009 the previously withheld appendices to the 2006 ESAS study were leaked, revealing a number of apparent flaws in the study, which gave safety exemptions to the selected Ares I design while using a faulty model which unfairly penalized the EELV-based designs.

Role in Constellation program



Exploded view of the Ares I

Ares I is the crew launch component of the Constellation program. Originally named the "Crew Launch Vehicle" or CLV, the Ares name was chosen from the Greek deity Ares. Unlike the Space Shuttle, where both crew and cargo are launched simultaneously on the same rocket, the plans for Project Constellation outline having two separate launch vehicles, the Ares I and the Ares V, for crew and cargo, respectively. Having two separate launch vehicles will allow for more specialized designs for the different purposes the rockets will fulfill.

The Ares I rocket is specifically being designed to launch the Orion Crew Vehicle. Orion is intended as a crew capsule, similar in design to the Apollo program capsule, to transport astronauts to the International Space Station, the Moon, and eventually Mars. Ares I may also deliver some (limited) resources to orbit, including supplies for the International Space Station or subsequent delivery to the planned lunar base.

Contractor selection

NASA selected Alliant Techsystems, the builder of the Space Shuttle Solid Rocket Boosters, as the prime contractor for the Ares I first stage. NASA announced that Rocketdyne will be the main subcontractor for the J-2X rocket engine on July 16, 2007. NASA selected Boeing to provide and install the avionics for the Ares I rocket on December 12, 2007.

On August 28, 2007 NASA awarded the Ares I Upper Stage manufacturing contract to Boeing. Boeing built the S-IC stage of the Saturn V rocket at Michoud Assembly Facility in the 1960s. The upper stage of Ares I is to be built at the NASA Michoud Assembly Facility, the construction site used for the Space Shuttle's External Tank and the Saturn V's S-IC first stage.

J-2X engines

At approximately US$20-25 million per engine, the Rocketdyne-designed and produced J-2X will cost less than half as much as the more complex Space Shuttle main engine (around $55 million). Unlike the Space Shuttle Main Engine, which was designed to start on the ground, the J-2X was designed from inception to be started in both mid-air and in near-vacuum. This air-start capability was critical, especially in the original J-2 engine used on the Saturn V's S-IVB stage, to propel the Apollo spacecraft to the Moon. The Space Shuttle Main Engine, on the other hand, would require extensive modifications in order to add an air-start capability and to be able to restart in a near-vacuum. Near-vacuum restart capability is needed for the Ares I because it is intended to fly an Earth orbit rendezvous, and because the Orion spacecraft has limited fuel reserves. Due to these design issues, a modified Space Shuttle Main Engine would have to be "pre-fired" in a manner similar to the "Main Engine tests" conducted on the Space Shuttle Main Engines prior to the maiden flights of each NASA orbiter, including the STS-26 return to flight in 1988.

System requirements review

On January 4, 2007, NASA announced that the Ares I had completed its system requirements review, the first such review completed for any manned spacecraft design since the Space Shuttle. This review is the first major milestone in the design process, and is intended to ensure that the Ares I launch system meets all the requirements necessary for the Constellation Program. In addition to the release of the review, NASA also announced that a redesign in the tank hardware was made. Instead of separate LH_2 and LO_2 tanks, separated by an "intertank" like that of the Space Shuttle External Tank, the new LH_2 and LOX tanks will be separated by a common bulkhead like that employed on the Saturn V S-II and S-IVB stages. This provides a significant mass saving and eliminates the need to design a second stage interstage unit that would have to carry the weight of the Orion spacecraft with it.

Analysis and testing

Ares I-X launches from Kennedy Space Center launch pad 39B, 15:30 UTC, October 28, 2009.

In January 2008, NASA Watch revealed that the first stage solid rocket of the *Ares I* could create high vibrations during the first few minutes of ascent. The vibrations are caused by thrust oscillations inside the first stage. NASA officials had identified the potential problem at the Ares I system design review in late October 2007, stating in a press release that they had wanted to solve it by March 2008. NASA admitted that this problem is very severe, rating it four out of five on a risk scale. Still, NASA said they are very confident of solving this problem, referring to a long history of successful problem solving. The mitigation approach developed by the Ares engineering team included active and passive vibration damping, adding an active tuned-mass absorber and a passive "compliance structure" -- essentially a spring-loaded ring that would detune the stack—in the Ares 1 design concept. NASA also pointed out that, since this is a completely new transport system, like the Apollo or Space Shuttle systems were during their development, it is normal for such problems to arise during the development stage. According to NASA, analysis of the data and telemetry from the Ares I-X flight showed that vibrations from thrust oscillation were within the normal range for a Space Shuttle flight.

A study released in July 2009 by the 45th Space Wing of the US Air Force concluded that an abort 30–60 seconds after launch would have a ~100% chance of killing all crew, due to the capsule being engulfed until ground impact by a cloud of 4,000 °F (2,200 °C) solid propellant fragments, which would melt the capsule's nylon parachute material. NASA's study showed the crew capsule would fly beyond the more severe danger.

The Ares I igniter is an advanced version of the flight-proven igniter used on the Space Shuttle's solid rocket boosters. It is approximately 18 inches (46 cm) in diameter and 36 inches (91 cm) long, and takes advantage of upgraded insulation materials that have improved thermal properties to protect the igniter's case from the burning solid propellant. NASA successfully completed test firing of the igniter for the Ares I engines on March 10, 2009 at ATK Launch Systems test facilities near Promontory, Utah. The igniter test generated a flame 200 feet (60 meters) in length, and preliminary data showed the igniter performed as planned. On September 10, 2009, the first Ares I engine was successfully tested in a full-scale, full-duration test firing.

Ares I-X test launch

The Ares I prototype, Ares I-X, successfully completed a test launch on October 28, 2009. The launch pad 39B was damaged more than with a Space Shuttle launch. During descent, one of the three parachutes of the Ares I-X's first stage failed to open, and another opened only partially, causing the booster to splash down harder and suffer structural damage.

Schedule and cost

A concept image of an Ares I launching from Kennedy Space Center launchpad 39B

Ares I mobile launch platform under construction

NASA completed the Ares I system requirements review in January 2007. Project design is to continue through the end of 2009, with development and qualification testing running concurrently through 2012. As of July 2009, flight articles are to begin production towards the end of 2009 for a first launch in June 2011. Since 2006 the first launch of a human has been planned for no later than 2014, which is four years after the planned retirement of the Space Shuttle.

Delays in the Ares I development schedule due to budgetary pressures and unforeseen engineering and technical difficulties have increased the gap between the end of the Space Shuttle program and the first operational flight of Ares I. The total estimated cost to develop the Ares I through 2015 has risen from $28 billion in 2006 to more than $40 billion in 2009.

Originally scheduled for first test flights in 2011, the independent analysis by the Augustine Commission found in late 2009 that due to technical and financial problems Ares I was not likely to have its first crewed launch until 2017-2019 under the current budget, or late 2016 with an unconstrained budget. The Augustine Commission also stated that Ares I and Orion would have an estimated recurring cost of almost $1 billion per flight. However, recent financial analysis has shown that the Ares I would cost $1 billion or more to operate per flight if the Ares I is flown just once a year. If the Ares I system is flown multiple times a year the marginal costs could fall to as low as $138 million per launch. The Ares I marginal cost is a fraction of the Shuttle's marginal costs even when it was flown multiple times per year. By comparison, the cost of launching three astronauts on a manned Russian Soyuz is $153 million.

On February 1, 2010, President Barack Obama announced a proposal to cancel the Constellation program effective with the U.S. 2011 fiscal year budget, but later announced changes to the proposal in a major space policy speech at Kennedy Space Center on April 15, 2010. In October 2010, the NASA authorization bill for 2010 was signed into law which canceled Constellation. But previous legislation keeps Constellation contracts in force until a new funding bill is passed for 2011.

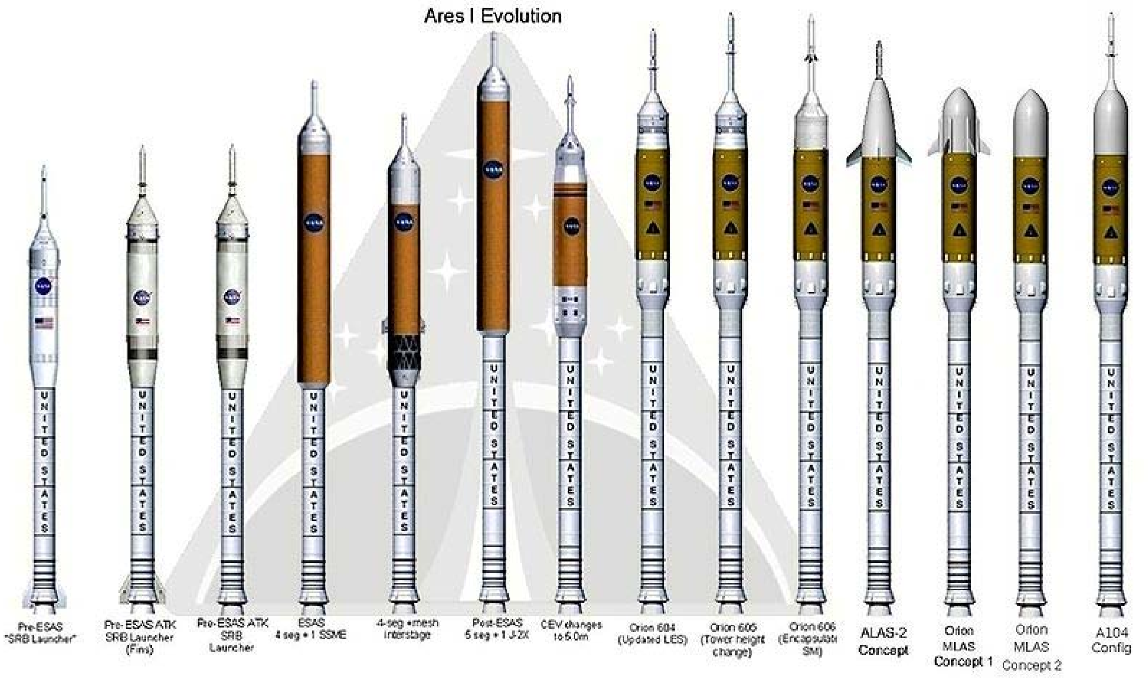
On February 8, 2011 it was reported that Alliant Techsystems and Astrium proposed to use Ares I's first stage with the second stage from the Ariane 5 to form a new rocket named Liberty.

Design

Ares I has a payload capability in the 25-metric-ton (28-short-ton; 25-long-ton) class and is comparable to existing vehicles such as the Delta IV and the Atlas V. The NASA study group that selected what would become the Ares I rated the vehicle as almost twice as safe as an Atlas or Delta IV-derived design. The rocket is making use of an aluminum-lithium alloy which is lower in density but similar in strength compared to other aluminum alloys. The new alloy is produced by Alcoa.

First stage

The first stage is a more powerful and reusable solid fuel rocket derived from the Space Shuttle Solid Rocket Booster (SRB). Compared with the Solid Rocket Booster, which has four segments, the most notable difference is the addition of a fifth segment. This fifth segment will enable the Ares I to produce more thrust. Other changes made to the Solid Rocket Booster are the removal of the Space Shuttle External Tank (ET) attachment points and the replacement of the Solid Rocket Booster nosecone with a new forward adapter that will interface with the liquid-fueled second stage. The adapter will be equipped with solid-fueled separation motors to facilitate the disconnection of the stages during ascent.



Concept image of the evolution of the Ares I design from pre-ESAS to latest developments.

Upper stage

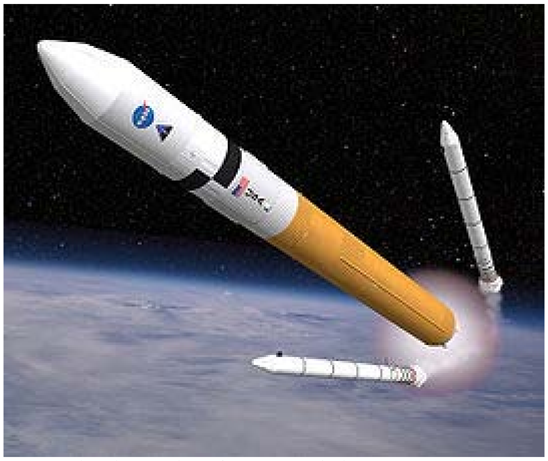
The upper stage, derived from the Shuttle's External Tank (ET) and based on the S-IVB stage of the Saturn V, is to be propelled by a single J-2X rocket engine fueled by liquid hydrogen (LH_2) and liquid oxygen (LOX). The J-2X is derived from the original J-2 engine used during the Apollo program, but with more thrust (~294,000 lbf) and fewer parts than the original engine. On July 16, 2007, NASA awarded Rocketdyne a sole-source contract for the J-2X engines to be used for ground and flight tests. Rocketdyne was the prime contractor for the original J-2 engines used in the Apollo program.

Although its J-2X engine is derived from an established design, the upper stage itself is wholly new. Originally to be based on both the internal and external structure of the ET, the original design called for separate fuel and oxidizer tanks, joined together by an "intertank" structure, and covered with the spray-on foam insulation to keep venting to a minimum. The only new hardware on the original ET-derived second stage would be the thrust assembly for the J-2X engine, new fill/drain/vent disconnects for the fuel and oxidizer, and mounting interfaces for the solid-fueled first stage and the Orion spacecraft.

Using a concept going back to the Apollo program, the "intertank" structure was dropped to decrease mass, and in its place, a common bulkhead, similar to that used on both the S-II and S-IVB stages of the Saturn V, would be used between the tanks. The savings from these changes are being used to increase propellant capacity, which is now 297,900 pounds (135,100 kg). The spray-on foam insulation is the only part of the Shuttle's ET that will be used on this new Saturn-derived upper stage.

Ares V

Ares V



Artist's impression of an Ares V during SRB separation

Function	Cargo Launch Vehicle (unmanned)
Manufacturer	*TBD* (stage I) *TBD* (stage II)
Country of origin	United States
Size	
Height	116 m (381 ft) or 109 m (358 ft)
Diameter	10 m (33 ft) or 8.4 m (28 ft)
Stages	2
Capacity	
Payload to LEO	188,000 kg (410,000 lb)
Payload to TLI	71,100 kg (157,000 lb) or 60,600 kg (134,000 lb)
Launch history	
Status	Canceled
Launch sites	Kennedy Space Center, LC-39A
Total launches	0
Boosters (Stage 0) - 5- or 5.5-segment Shuttle-derived SRB	
№ boosters	2
Engines	1 solid
Thrust	TBC
Burn time	TBC
Fuel	APCP (solid)
First stage	
Engines	5 or 6 RS-68B or 5 SSME
Thrust	TBC
Burn time	TBC

Fuel	LH2/LOX
Second stage - Earth Departure Stage	
Engines	1 or 2 J-2X
Thrust	
Burn time	
Fuel	LH2/LOX

ARES

The **Ares V** (formerly known as the Cargo Launch Vehicle or CaLV) was the planned cargo launch component of the Constellation program, which was to have replaced the Space Shuttle after its retirement in 2011. Ares V and the smaller Ares I were named after Ares, the Greek god of war, which is the equivalent to the Roman god Mars.

Initially, the Ares V would have launched the Earth Departure Stage and Altair lunar lander had NASA returned to the Moon, which was planned for 2019, but would also have served as the principal launcher for missions beyond the Earth-Moon system, including the program's ultimate goal, a manned mission to Mars after 2030. The unmanned Ares V would complement the smaller, and human-rated Ares I rocket for the launching of the 4-6 person Orion spacecraft. Both rockets, deemed safer than the current Space Shuttle, would have utilized technologies developed for the Apollo program, the Shuttle, and the Delta IV EELV programs. However, the Constellation program, including Ares V was canceled in October 2010 by the passage of the 2010 NASA authorization bill.

Development

Early concepts

In the 1997 book *The Case for Mars*, Robert Zubrin discussed a possible future heavy launch vehicle named *Ares*. In the book the rocket would have consisted of the Space Shuttle's External Tank powered by four SSMEs and a second stage powered by an RL-10 engine. One notable difference in the Zubrin *et al.* design is the mounting location of the SSMEs, which were side-mounted on a small flyback craft. This design was meant to allow the Ares to fly using existing Space Shuttle infrastructure.

Constellation

Artist's impression of the Ares V at liftoff

Ares V was to be the cargo launch component of the Constellation program. Unlike the Saturn V and Space Shuttle, where the crew and cargo were launched together on the same rocket, Project Constellation was planned to use two separate launch vehicles, the Ares I and the Ares V, for crew and cargo respectively. This configuration would have allowed the two launch vehicles to be optimized for their respective missions.

Constellation therefore combined the Lunar Orbit Rendezvous used by Apollo with the Earth Orbit Rendezvous mode proposed by Dr. Wernher von Braun (along with the "Direct Ascent" proposal) during the early planning stage of Apollo.

Development of the rocket and its Earth departure stage was led by Marshall Space Flight Center. Ames Research Center was responsible for the Ares V integrated health management system supports in developing its payload shroud. Glenn Research Center led the development of the lunar lander ascent stage as well as Ares V power system, thrust vector control system and payload shroud. Langley Research Center had a lead role on Ares V aerodynamics.

The Augustine Commission concluded that "Under the FY 2010 funding profile, the Committee estimates that Ares V will not be available until the late 2020s". Even if NASA had been given the $3 billion dollar increase and the ISS had been retired in 2015, the committee still believed that the Ares V would not be ready till the mid-2020s.

On February 1, 2010, President Barack Obama announced a proposal to cancel the Constellation program effective with the U.S. 2011 fiscal year budget, but later announced changes to the proposal in a major space policy speech at Kennedy Space Center on April 15, 2010. In October 2010, the NASA authorization bill for 2010 was signed into law, which canceled Constellation. But previous legislation keeps Constellation contracts in force until a new funding bill is passed for 2011.

Further roles

Although the Ares V was a medium to long term project, NASA planned to deploy its lift capability in a range of projects, along the lines of the former Apollo Applications Program.

One proposal was to build an 8 to 16-meter Advanced Technology Large-Aperture Space Telescope to be placed in the Sun/Earth L2 point. It would be a significant increase in dimension and performance over the Hubble Space Telescope and the Ares V vehicle was expected to carry this to its destination in a single launch.

Future Ares V missions could also have served as a cost-effective, mass transport of construction materials for future spacecraft and missions, delivering raw materials for example to a Moon dock positioned as a counterweight to a Moon elevator.

In May 2010 NASA planned flight demonstrations of Ares V hardware along with Ares I hardware after the scheduled upcoming Ares I-X Prime test of the Ares I 5-segment SRB first stage. Several flights were listed as "Heavy Lift" test flights for testing the first stage of the Ares V simultaneously with the Ares I upper stage attached on top of the Ares V first stage. This would save both time and money in avoiding the gap between testing Ares I and Ares V hardware with current limited funding.

Design

Exploded view of the Ares V including Earth Departure Stage. The first stage is shown in white, Second stage in orange-brown, and upper stage checkered.

The Ares V was intended as a heavy-launch vehicle to send large hardware and materials to the Moon, or to send supplies beyond Earth orbit to sustain human presence there. The Ares V was designed to be a three-stage rocket: the first and second stages, which burn together, were to utilize both solid and liquid propulsion with the upper stage providing the necessary propulsion to send the hardware and staples beyond low-Earth orbit and onto a trajectory to the Moon.

Ares V is currently under heavy preliminary design review after the results of the 2009 Augustine Commission. Like the Space Shuttle, the Ares vehicle was to utilize a pair of solid-fueled first stage rocket boosters that burn simultaneously with the liquid-fueled second (core) stage. The solid rocket booster on Ares V was envisioned as an improved version of the current Space Shuttle Solid Rocket Booster, but with five or five and a half segments instead of the current four segments. The liquid-fueled second stage was derived from the Space Shuttle External Tank, and was to use either five or six RS-68B engines attached to the bottom of a new 10 m tank, or five SSMEs attached to the bottom of a stretched version of the Space Shuttle's 8.4 m tank. In either configuration, it was designed to be fueled by liquid oxygen (LOX) and liquid hydrogen (LH2).

The upper stage, derived from the S-IVB upper stage used on the Saturn IB and Saturn V rockets, was nameed the Earth Departure Stage (EDS). Powered by the Apollo-derived J-2X rocket engine, which was also proposed to be used on the liquid-fueled upper stage of the Ares I booster, the EDS was to be used to steer the Altair lunar lander into its initial low-Earth "parking" orbit for later retrieval by the Orion spacecraft, and then would propel both the Altair and Orion to the Moon. The EDS could also have been used to haul large payloads into low-Earth orbit, along with placing large unmanned spacecraft onto trajectories beyond the Earth-Moon system.

The Ares V was designed to have a payload capacity of over 414,000 lb (188 metric tons) to Low Earth orbit (LEO), and 157,000 lb (71 metric tons) to the Moon. Upon completion the Ares V would be the most powerful rocket ever built, lifting more into orbit than even the American Saturn V, the failed Soviet N-1 for the canceled Soviet Moonshot, and the successful Soviet/Russian Energia booster developed for the Buran Shuttle. Besides its lunar role, it could also support a manned Orion expedition to a Near-Earth asteroid, and could boost an 8 to 16-meter successor of the Hubble Space Telescope to the Sun-Earth L_2 point.

Ares V Lite

Ares V Lite was an alternative launch vehicle for NASA's Constellation program suggested by the Augustine Commission. Ares V Lite was a scaled down Ares V. It would use five RS-68 engines and two five-segment SRBs and have a low Earth orbit payload of approximately 140 metric tons (309,000 lb). If chosen, Ares V Lite would replace the Ares V and Ares I launchers. One Ares V Lite version would be a cargo lifter like Ares V and the second version would carry astronauts in the Orion spacecraft.

Chapter 8

Falcon 9

Falcon 9

Falcon 9 launches with first Dragon spacecraft

Function	Orbital launch vehicle
Manufacturer	SpaceX
Country of origin	United States
Cost per launch (2011)	**Normal:** LEO (<80% cap.) $49.9M LEO (>80% cap.) $56.0M GTO (<3,000 kg) $49.9M GTO (>3,000 kg) $56.0M **Heavy:** $95m

Size

Height	54.3 m (178 ft)
Diameter	3.66 m (12.0 ft)
Mass	**Normal:** 333,400 kg (735,000 lb) **Heavy:** 885,000 kg (1,950,000 lb)
Stages	2
Capacity	
Payload to LEO	**Normal:** 10,450 kg (23,000 lb) **Heavy:**32,000 kg (71,000 lb)
Payload to GTO	**Normal:** 4,540 kg (10,000 lb) **Heavy:** 19,500 kg (43,000 lb)
Launch history	
Status	Active
Launch sites	Cape Canaveral SLC-40 Vandenberg SLC-4E Omelek Island
Total launches	2
Successes	2
Failures	0
Maiden flight	**Normal:** June 4, 2010 **Heavy:** none scheduled
Boosters (Falcon 9 Heavy (proposed))	
№ boosters	2
Engines	9 Merlin 1C
Thrust	5,000 kN (1,100,000 lb$_f$)(sl)
Specific impulse	**Sea level:** 255 sec (2.6 kN/kg) **Vacuum:** 304 sec (3.0 kN/kg)
Burn time	Unknown
Fuel	LOX/RP-1
First stage	
Engines	9 Merlin 1C
Thrust	5,000 kN (1,100,000 lb$_f$)(sl)
Specific impulse	**Sea level:** 255 sec (2.6 kN/kg) **Vacuum:** 304 sec (3.0 kN/kg)
Burn time	170 seconds
Fuel	LOX/RP-1
Second stage	
Engines	1 Merlin Vacuum
Thrust	445 kN (100,000 lb$_f$)
Specific impulse	**Vacuum:** 342 sec (3.45 kN/kg)
Burn time	345 seconds
Fuel	LOX/RP-1

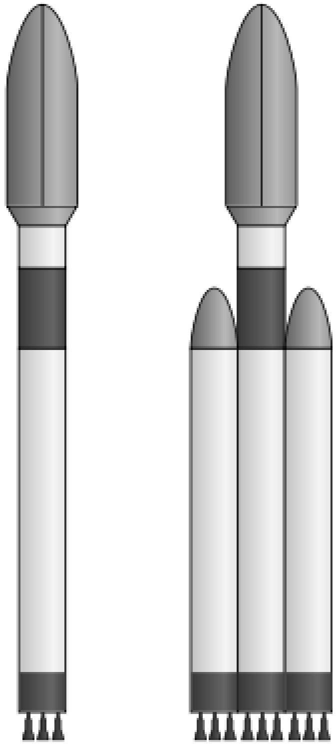
Falcon 9 is a spaceflight launch system that uses rocket engines designed and manufactured by SpaceX. Both stages of the two-stage-to-orbit vehicles use liquid

oxygen (LOX) and rocket-grade kerosene (RP-1) propellants. Multiple variants are planned with payloads of 10,450–26,610 kilograms (23,000–58,700 lb) to low Earth orbit, and 4,450–15,010 kilograms (9,800–33,100 lb) to geostationary transfer orbit, which will place the Falcon 9 design in the medium-lift to heavy-lift range of launch systems.

The first Falcon 9 flight was successfully launched from Cape Canaveral Air Force Station on June 4, 2010 14:45 EDT (19:45 UTC) with a successful orbital insertion, after several delays.

The Falcon 9 is the launch vehicle for the SpaceX Dragon spacecraft. The Falcon 9 and Dragon combination won a Commercial Resupply Services (CRS) contract from NASA to resupply the International Space Station under the Commercial Orbital Transportation Services (COTS) program. The second Falcon 9 launch, and the first launch of the Dragon spacecraft, occurred at 10:43 EST (15:43 UTC) on December 8, 2010 from Cape Canaveral. The launch was successful, with the Dragon spacecraft completing two orbits before splashing down in the Pacific Ocean.

Design



Falcon 9 (left) and Falcon Heavy (right)

The base Falcon 9 is a two stage, LOX/RP-1 powered launch vehicle. Its first stage is powered by nine SpaceX Merlin 1C rocket engines with 556 kN (125,000 lbf) sea-level thrust per engine for a total thrust on liftoff of approximately 5.0 MN (1.1 million lbf). The Falcon 9 first stage uses a pyrophoric mixture of triethylaluminum-triethylborane (TEA-TEB) as a first-stage ignitor.

The proposed Falcon Heavy configuration consists of a standard Falcon 9 with two additional Falcon 9 first stages acting as liquid strap-on boosters, which is conceptually similar to EELV launchers Delta IV Heavy and the future Atlas V HLV, and also to the Russian Angara carrier rocket.

Second stage

The upper stage is powered by a single Merlin engine modified for vacuum operation, with an expansion ratio of 117:1 and a nominal burn time of 345 seconds. For added reliability of restart, the engine has dual redundant pyrophoric igniters (TEA-TEB). SpaceX has expressed hopes that both stages will eventually be reusable.

The interstage, which connects the upper and lower stage for Falcon 9, is a carbon fiber aluminum core composite structure. Stage separation occurs via reusable separation collets and a pneumatic pusher system. The Falcon 9 tank walls and domes are made from aluminum lithium alloy. SpaceX uses an all friction stir welded tank, the highest strength and most reliable welding technique available. The second stage tank of Falcon 9 is simply a shorter version of the first stage tank and uses most of the same tooling, material and manufacturing techniques. This results in significant cost savings in vehicle production.

Reliability

As with the company's smaller Falcon 1 vehicle, Falcon 9's launch sequence includes a hold-down feature that allows full engine ignition and systems check before liftoff. After first stage engine start, the launcher is held down and not released for flight until all propulsion and vehicle systems are confirmed to be operating normally. Similar hold-down systems have been used on other launch vehicles such as the Saturn V and Space Shuttle. An automatic safe shut-down and unloading of propellant occurs if any abnormal conditions are detected.

Like the Saturn V and the unrealized Falcon 5 design, the presence of multiple first stage engines allows for mission completion even if one of the first-stage engines fails mid-flight. This is known as "engine-out capability". Falcon 9 is the first rocket "since the Saturn series from the Apollo program to incorporate engine-out capability"

Falcon 9 has triple redundant flight computers and inertial navigation, with a GPS overlay for additional orbit insertion accuracy.

Reusability

Although the first stage has parachutes and was intended to be recovered to demonstrate (possible future) reuse, to date SpaceX has failed to recover the stages from their initial test launches. The stages are expendable for the initial launches. By flight six, the first stage is intended to be recovered. Although reusability of the second stage is more difficult, SpaceX has intended both stages of the Falcon 9 to be reusable. Musk stated:

"By flight six we think it's highly likely we'll recover the first stage, and when we get it back we'll see what survived through re-entry, and what got fried, and carry on with the process. ... That's just to make the first stage reusable, it'll be even harder with the second stage – which has got to have a full heatshield, it'll have to have deorbit propulsion and communication."

Both stages are covered with a layer of ablative cork, have parachutes to land them gently in the sea and have been marinised by using salt water resistant materials, anodizing and paying attention to the issue of galvanic corrosion.

While many commentators are skeptical of the viability of reusability, Musk has stated that reusability is one of the most important goals, and that if the vehicle does not become reusable, "I will consider us to have failed."

Launch sites

There is one active launch site and two others are planned/proposed:

- Cape Canaveral Air Force Station Launch Complex 40 is an active Falcon 9 launch site.
- SpaceX plans to lease Vandenberg AFB Space Launch Complex 4. Conversion of the site for Falcon 9 is estimated to cost $50 million and the first launch is due in summer 2012. As of June 2010, CEO Elon Musk indicated he is confident that a Vandenberg launch pad can be ready for Iridium satellite launches "within 12 to 18 months".
- SpaceX may upgrade their Omelek Island Falcon 1 launch site for use by the Falcon 9; as of December 2010, their launch manifest gives Omelek (Kwajalein) as a possible site for several Falcon 9 launches, the first as an alternative for the Argentina CONAE mission in 2012.

Launcher versions

Version	Falcon 9	Falcon Heavy
Stage 0		2 boosters with 9 × Merlin 1C engines each
Stage 1	9 × Merlin 1C	9 × Merlin 1C

Stage 2		
Height (max; m)	54.9	54.9
Diameter (m)	3.6 or 5.2	3.6 or 5.2 (large fairing)
Initial thrust (kN)	4,400	15,000
Takeoff weight (tonnes)	333	885
Fairing diameter (Inner; m)		
Payload (LEO; kg)	8,560 (polar orbit from Kwajalein) or 10,450 (launch at Cape Canaveral)	32,000
Payload (GTO; kg)	4,680 (launch at Kwajalein) or 4,540 (launch at Cape Canaveral)	19,500
Price (Mil. USD)	49.9–56 to LEO; 49.9–56 (according to Satellite Mass) to GTO	95
minimal **Price/kg** (LEO; USD)	5,360	
minimal **Price/kg** (GTO; USD)	12,000	
Success ratio (successful/total)	2/2	

Historical data based on circa 2007 specifications may be found in these three sources.

Initial descriptions

At an appearance in May 2004 before the U.S. Senate Committee on Commerce, Science and Transportation, Elon Musk testified, "Long term plans call for development of a heavy lift product and even a super-heavy, if there is customer demand. [...] Ultimately, I believe $500 per pound [of payload delivered to orbit] or less is very achievable."

SpaceX formally announced the Falcon 9 on 2005-09-08, describing it as being a "fully reusable heavy lift launch vehicle." A Falcon 9 medium was described as being capable of launching approximately 21,000 lb (9,500 kg) to low Earth orbit, priced at $27 million per flight ($1286/lb).

Production and testing

As of December 2010, the Falcon 9 production line is manufacturing one new Falcon 9 (and Dragon spacecraft) every three months. In 2012, this will double to one every six weeks.

Production history

On April 12, 2007 SpaceX announced it had completed the primary structure for its first Falcon 9 first-stage tank. The tank was shipped to a SpaceX test facility in Texas for first-stage static firing validation. The first multi-engine test (with two engines connected to the first stage, firing simultaneously) was successfully completed in January 2008, with successive tests leading to the full Falcon 9 complement of nine engines test fired for a full mission length (178 seconds) of the first stage on November 22, 2008.

The original NASA COTS contract called for the first demonstration flight of Falcon in September 2008, and completion of all three demonstration missions by September 2009. February 2008, the plan for the first Falcon 9/Dragon COTS Demo flight was delayed by six months to late in the first quarter of 2009. According to Elon Musk, the complexity of the development work and the regulatory requirements for launching from Cape Canaveral have contributed to the delay. The first COTS demo flight was delayed several additional times, and was eventually scheduled for December 2010.

In October 2009, the first flight-ready first stage had a successful all-engine test fire at the company's test stand in McGregor, TX. In November 2009 Space X conducted the initial second stage test firing lasting forty seconds. This test involved a new test stand and a new flight stage, and succeeded without aborts or recycles. On January 2, 2010, a full-duration (329 seconds) orbit-insertion firing of the Falcon 9 second stage was conducted at the McGregor test site The full stack arrived at the launch site for integration at the beginning of February 2010, and SpaceX initially scheduled a launch date of March 22, 2010, though they estimated anywhere between one and three months for integration and testing.

On February 25, 2010 SpaceX's first flight stack was set vertical at Space Launch Complex 40, Cape Canaveral, and on March 9, SpaceX performed a static fire test, where the first stage was to be fired without taking off. Some fire and smoke were seen at the base of the rocket, leading to speculation of an engine fire. However, all components checked out, but the test executed a nominal abort at T-2 seconds due to a failure in the spin-start system. This system is designed to pump high pressure helium from the launch pad into the first stage turbopumps to get them spinning in preparation for launch. Subsequent review showed that the failure was a valve that didn't receive a command to open. As the problem was with the pad and not with the rocket itself, it didn't occur at the McGregor test site, which didn't have the same valve setup. No damage was sustained by the vehicle or the test pad and the fire and smoke were the result of normal burnoff from the liquid oxygen and fuel mix present in the system prior to launch. All vehicle systems leading up to the abort performed as expected and no additional issues were noted that needed addressing. A subsequent test on March 13 was successful in firing the nine first-stage engines for 3.5 seconds.

The delay of the first flight from March 2010 to June was due to review of the Falcon 9 flight termination system by the Air Force. On June 1, SpaceX announced on their update page that they had completed testing of the FTS and all results were nominal.

The first actual launch attempt, at 1:30pm EDT on Friday, June 4, 2010 (1730 UTC), was aborted shortly after ignition, and the rocket successfully went through a failsafe abort. Ground crews were able to recycle the rocket, and successfully launched it at 2:45pm EDT (1845 UTC) the same day.

Maiden Launch

The Falcon 9 maiden launch occurred on June 4, 2010 and was deemed a success, placing the test payload within 1 percent of the intended orbit. The second stage engine performed a short second burn to demonstrate its multiple firing capability.

The rocket experienced, "a little bit of roll at liftoff" as Ken Bowersox from SpaceX put it. This roll had stopped prior to the craft reaching the top of the tower. The second stage began to slowly roll near the end of its burn which was not expected, and the first stage parachutes failed to open causing it to be damaged upon landing.

The halo from the venting of propellant from the Falcon 9 rocket as it rolled in space could be seen from all of Eastern Australia and some believed it to be a UFO.

Continued development

SpaceX Falcon 9 launch with COTS Demo Flight 1

The next launch attempt for Falcon 9 was COTS Demo Flight 1, with an operational Dragon module. The launch took place on December 8, 2010. The flight placed the Dragon capsule in a roughly 300-kilometer (190 mi) orbit. After two orbits, the capsule re-entered the atmosphere to be recovered off the coast of Mexico. This flight tested the pressure vessel integrity, attitude control using the Draco engines, telemetry, guidance, navigation, control systems, the PICA-X heat shield, and parachutes at speed.

Launches and scheduled launches

Flight N^o	**Date & Time (GMT)**	**Payload**	**Customer**	**Outcome**	**Remarks**
1	4 June 2010, 18:45	Dragon Spacecraft Qualification Unit	SpaceX	Success	1st Successful Flight of Falcon 9 Block 1
2	8 Dec 2010, 15:43	NASA COTS – Demo 1, 2 Cubesats	Commercial Orbital Transportation Services, National Reconnaissance Office	Success	maiden flight of Dragon Capsule; 3 hours, testing of maneuvering thrusters and reentry

Q1 2011	NASA COTS – Demo 2, 2 OG2 satellites	Commercial Orbital Transportation Services, Orbcomm	Scheduled	5 day, approach Space Station
2011	NASA COTS – Demo 3	Commercial Orbital Transportation Services	Scheduled	Dock with Space Station
2011	CASSIOPE	MDA Corp	Scheduled	
2011	NASA Resupply to ISS – Flight 1	NASA Commercial Resupply Services	Scheduled	
2011	NASA Resupply to ISS – Flight 2	NASA Commercial Resupply Services	Scheduled	
2012	DragonLab Mission 1	SpaceX	Scheduled	
2012	Falcon Heavy Demo Flight 1	SpaceX	Scheduled	First Falcon Heavy flight. Rocket with the highest LEO capacity since Saturn V. Most powerful rocket available up to date.
2012	NASA Resupply to ISS – Flight 3	NASA Commercial Resupply Services	Scheduled	
2012	NASA Resupply to ISS – Flight 4	NASA Commercial Resupply Services	Scheduled	
2012	SAOCOM 1A	CONAE	Scheduled	
2012	AMOS-4	Spacecom	Scheduled	
2013	DragonLab Mission 2	SpaceX	Scheduled	
2013	NASA Resupply to ISS – Flight 5	NASA Commercial Resupply Services	Scheduled	
2013	SES-8 communication satellite	SES	Scheduled	First geostationary launch for Falcon

				9. 1Q2013
2013	NASA Resupply to ISS – Flight 6	NASA Commercial Resupply Services	Scheduled	
2013	NASA Resupply to ISS – Flight 7	NASA Commercial Resupply Services	Scheduled	
2013	Unknown	Undisclosed Customer	Scheduled	
2013	SAOCOM 1B	CONAE	Scheduled	
2013	Google Lunar X Prize Moon Mission	Astrobotic Technology	Scheduled (no earlier than December 2013)	deliver a lander, small rover and up to 240 pounds (110 kg) of payload to the surface of the Moon
2014	Space Systems/Loral	Space Systems	Scheduled	
2014	Unknown	Undisclosed Customer	Scheduled	
2014	NASA Resupply to ISS – Flight 8	NASA Commercial Resupply Services	Scheduled	
2014	NASA Resupply to ISS – Flight 9	NASA Commercial Resupply Services	Scheduled	
2014	NASA Resupply to ISS – Flight 10	NASA Commercial Resupply Services	Scheduled	
2014	TBD	Bigelow Aerospace	Scheduled	
2015	NASA Resupply to ISS – Flight 11	NASA Commercial Resupply Services	Scheduled	
2015	NASA Resupply to ISS – Flight 12	NASA Commercial Resupply Services	Scheduled	
2015–2017	Iridium NEXT	Iridium Communications Inc.	Scheduled	up to 10 launches with multiple satellites per launch.

Chapter 9

Kliper

Kliper

Kliper spacecraft

Operator	Roscosmos
Major contractors	NPO Energia
Mission type	Crew Exploration Vehicle
Satellite of	Earth, Moon and Mars.
Launch date	Indefinitely Postponed
Carrier rocket	Soyuz
Launch site	Baikonur Cosmodrome

Kliper (**Клипер**, English: **Clipper**) is a partly reusable manned spacecraft, proposed by RSC Energia.

Designed primarily to replace the Soyuz spacecraft, Kliper has been proposed in two versions: as a pure lifting body design and as spaceplane with small wings. In either case, the craft should be able to glide into the atmosphere at an angle that produces much less stress on the human occupants than the current Soyuz. Kliper has been designed to be able to carry up to six people and to perform ferry services between Earth and the International Space Station.

Development

Announcement of the program

Soyuz TMA-6 spacecraft approaching the International Space Station - the Soyuz spacecraft would have been replaced by Kliper

In February 2004 Nikolai Moiseyev, the deputy director of Russian Federal Space Agency (FSA) told journalists that the Kliper project had been included in the Russian federal space program for 2005-15. At that point he announced that if the program is implemented successfully the first launch may even take place in five years' time. Kliper had been developed since 2000 and reportedly relied heavily on research studies as well as proposals for a small Russian lifting body spacecraft from the 1990s. Externally its design was comparable to the cancelled European minishuttle Hermes or the NASA study X-38. It was planned to be the successor to the veteran spacecraft Soyuz, which has been built in various modifications since 1961.

Early search for support

In 2005 Kliper was displayed in several air shows around Europe and Asia, in order to reach out to international partners who would be interested to co-fund and co-develop the spacecraft. The Russian Space Agency especially looked to Europe as the European Space Agency (ESA) had become its major partner in space activities during the last years. In May 2005 rumours started in the press that Europe would join the Kliper project in a specially funded venture that would be part of the Aurora Programme. These rumours turned out to be correct when both Russian and European space officials announced their cooperation to build Kliper during the Paris Air Show in Le Bourget on June 10, 2005.

Vladimir Taneev, the leading designer of the Kliper system, speculated on the contribution of Europe to the project in the following way:

The European companies will likely contribute avionics, materials, and cabin systems. Many different options are on the table, and in the near future we expect to form Russian-European working groups specialized in different subsystems and fields of design.

The Russian Space Agency as well as ESA announced that they would continue to look for other international partners such as Japan to invest in Kliper. A substantive cooperation with NASA was unlikely, due to the parallel development of America's own next-generation manned launch vehicle, the Crew Exploration Vehicle (CEV).

A further element of this process was made public on October 12, 2005, when various press agencies revealed that JAXA, the Japanese space agency, had been officially approached by Russia to participate in the project. JAXA has made it clear that they are more likely to join the project if ESA does so first, which is in doubt after ESA members rejected a study for Europe's involvement in the Kliper project in December 2005. The addition of Japan would make Kliper a truly multinational project, potentially combining the rugged reliability of Russian launchers with Japanese computer technology. A greater pan-national consensus would have allowed for a lighter funding burden on each participant as well.

Estimated costs

Announcements and speculations following the February 2004 press conference suggested a development budget of 10 billion rubles (approximately US$400 million). However in looking at today's costs for human space travel it was clear that the 10 billion rubles figure was a rather low estimate. In May 2005 The Guardian reported that costs are estimated to be roughly US$3 billion (for development and construction of Kliper until 2015) of which the bulk of 1.8 billion was speculated to come from Europe. Different sources in 2005 have reported that the money needed for the program would be 1.5 billion Euros ($1.8 billion) and on December 12, 2005 an article stated it would be €1 billion (solely in relation to development costs).

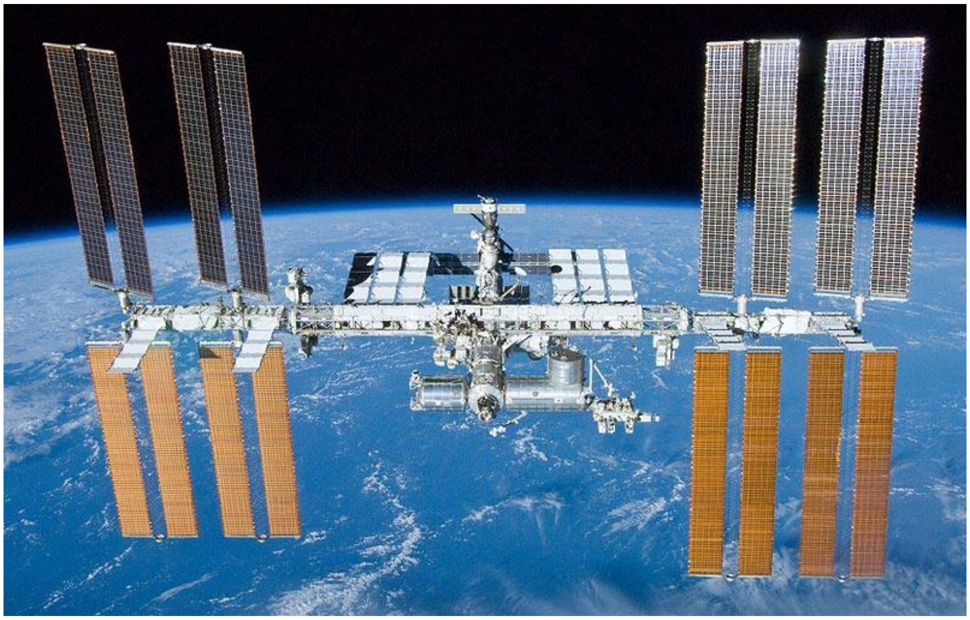
On July 14, 2005 the Russian government approved the national space program for 2006 to 2015 with a budget of 305 billion rubles (ca. $11 billion - the whole budget for the 10-year period will be 425 billion rubles = ca. 15 billion dollars). The budget included the needed funding for the Kliper program. Thus in face of Europe's denial to fund a €50m feasibility study for the Kliper project at the European space summit in December 2005, Russian space officials have announced that Russia would fund Kliper even without any European contribution.

The most recent article on Kliper stated that the project would have incurred 16 billion rubles (~$600 million) in development costs, 11 billion of which will be financed by the government and 5 billion by contractors.

First launch and target for regular flights

In 2004 it was announced that it was likely that Kliper would make its first launch as early as 2010 or 2011 – the same time the Space Shuttle was scheduled to be retired. However, it was reported by BBC News on September 27, 2005, that the first flight tests were not planned until 2011, with the first manned flights in 2012 and the Soyuz being phased out over time until 2014. An article on December 3, 2005 cited the president of the Energia Rocket and Space Corporation Nikolai Sevastyanov that "the first regular lift-off is scheduled for 2012, while a complete transport system will be in place by 2015." After the termination of the Russian Space Agency's tender for a new spacecraft, Energia announced that this would push its Kliper proposal's first flight (if developed at all) back further.

ESA's part in Kliper - Uncertainty over European cooperation



Kliper was planned to be Russia's and even Europe's primary access route to the International Space Station

On September 28, 2005 the BBC reported that Alan Thirkettle, head of ESA's Human Spaceflight Development Department, stated that Kliper would be used: *For future exploration, when we have the objective of going to the Moon, it is important to have* *several possibilities to go there, and within this framework of cooperation to have our own access to orbit around the Moon.* In the same context, Alain Fournier-Sicre, head of the ESA permanent mission in the Russian Federation, also stated that: *The objective is to have a vehicle which is more comfortable than the Soyuz capsule which will be used with pilots and four passengers...It's meant to service the space station and to go between Earth and an orbit around the Moon with six crew members.*

Although there seemed to be a lot of enthusiasm for Kliper within Alan Thirkettle's team at ESA (as outlined in the above paragraph), on December 7, 2005, the European space summit of governmental officials of ESA member states declined to approve a 50-million-euro two-year study focusing on ESA's potential involvement in the Kliper project. In denying funding for the study ESA members stated that, among other factors that seemed unfavourable, under the current Russian proposal Europe would not share control over the design of the program and would be limited to being a small industrial contributor.

Jean-Jacques Dordain, ESA's Director General, put the refusal to fund the study into context: *It is not a question of member states for and member states against. I think the decision could not be taken for reasons that are not linked to Clipper itself. The decision could not be taken because of budgetary restraints.* Dordain concluded that he was convinced that European support for Kliper was vital for ESA's future involvement in space transport and that a favourable decision can be achieved until June 2006. In concluding *We need two transportation systems in the world*, Dordain also outlined shortly after the European Space Summit that the primary requirement of Europe's involvement in the Kliper project was to rely on two separate systems to support the ISS as had been proven vital after the Columbia Space Shuttle disaster in 2003.

Dordain's remarks were echoed by Daniel Sacotte, ESA's director of human spaceflight, microgravity and exploration, in saying simply that *The Russians are not going to finance it, we will finance it from our side*, despite adding a cautionary note that *We needed the support from at least two states out of France, Italy and Germany. We didn't get it.*. What this means in practical terms remains to be seen; however what is clear is that ESA officials are still pushing for Europe's involvement in the Kliper project.

Very negative comments relative to Kliper were brought by the various national delegations at the December meeting, in particular by the French Minister of Research François Goulard. In short, there remain for the time being member states strongly committed to Kliper, and others just as strongly opposed. The long-term view remains uncertain.

In 2006, Jean-Jacques Dordain explained that money allocated to space transportation development, which ESA currently funds in the amount of 300 million for the next 3 years, could be used for Europe's involvement in the project. Given the February 2006 statement that 5 billion rubles (~$200 million) of the development costs will come from "contractors", a limited involvement of ESA in Kliper might have been forthcoming.

Russian Space Agency's tender for Kliper

At the end of 2005, Roskosmos announced that a tender for Kliper would be held in January 2006 between RKK Energia, Khrunichev and Molniya with a selection date of February 3, 2006. However concerns about the bids led to a delay in the process, with a resubmittal deadline of March, 2006 and selection was rescheduled for April 2006. Following further delays, the tender was cancelled on 18 July 2006.

In late July 2006, the Russian Space Agency and the European Space Agency agreed to collaborate on a different project to develop a new spacecraft. They decided to fund a study under a program labelled Crew Space Transportation System (CSTS) which started in September 2006 and evaluate a capsule type concept, derived from Soyuz. While this program is the follow-on project of the RSA's and ESA's collaboration on a new spacevehicle, this program is no longer connected to Energia's winged Kliper design.

RSC Energia continued to pursue the project without Russian government support and announced that it would seek private investment for the craft. News reports in Russia indicated that Kliper was still expected to be ready for Russian Space Agency test flights around the year 2012, as part of Russian spacecraft upgrade program. The project has been officially halted in June 2007, after the major proponent of the project, Nikolai Sevastyanov, was dismissed from the position of the president of RSC Energia. The newly appointed president of RSC Energia, Vitaly Lopota, confirmed that Kliper would not be displayed on the 2007 MAKS aviation and space show. He said that Energia would spend more time on the project analysis, perform additional dynamic modeling, revise the design and appearance and then would come up with new proposals for Roscosmos.

In 2008 Vitaly Lopota shared his vision about new Russian spacecraft. He mentioned two possible options: a space capsule, which better suits missions to the Moon and Mars, and a lifted body design for low Earth orbit missions. According to new plans, instead of Kliper the new PPTS (Rus) will be developed since 2009 to 2017-2018.

Overview

Kliper's design was another attempt to solve the geometric problems of spacecraft. Soyuz has an Orbital Module, a hollow sphere, to be used for eating and hygiene, and an airlock located above the Reentry module (the capsule), with the docking mechanism at the top. In the event of an emergency, it would be lifted away from the rocket along with the reentry module, and the fairing over the spacecraft was designed to successfully split apart either circumferentially just below the reentry module in such an emergency or longitudinally if the flight should be successful. Kliper was designed with the Orbital Module below its reentry module, and the docking mechanism below that. This was made possible by constructing a reentry module broader than the orbital module, so that a pair of rocket nozzles for orbital maneuvering could have been fitted alongside it, as the later Salyut space stations had.

In connection with this new design, Kliper will feature a launch escape system that will enable it to detach from the carrier rocket if an abort of the mission during orbital ascent is required. An abort will be possible during every phase of the launch with the limitation of the first seconds after launch.

Lifting body design

On return from space, Kliper's lifting body design would not only allow a smoother descent into Earth's atmosphere than the capsule design, such as Soyuz; but also permit control. RKK Energia claimed that the craft would be able to land in a predetermined one-square-kilometre area. Artistic impressions showed that the Kliper would have resembled a cylinder topped by a cone. Originally, landing proposals involved both a landing by parachute and as an alternative, in a modified version, a landing on a runway similar to an aircraft, or the Space Shuttle. However, leading designer Vladimir Daneev commented on this issue in June 2005:

We are 99% sure that it will be a spaceship with upturned little wings, enabling the Kliper to land on any class-one military airfield with a runway from three to three and a half kilometres in length.

Kliper, as a vehicle alone, would have been primarily a manned spaceship, carrying six cosmonauts and payloads of up to 700 kilograms (mostly experiments and other equipment used for carrying through experiments in orbit) and was planned to stay in orbit for approximately 15 days independently and for up to 360 days if docked to the International Space Station. This highlighted both the Russian/European and the American change in space transportation philosophy. Rather than focusing on the lifting of cargo and a crew, in the same way as the Space Shuttle or Buran, the Russian space agency adopted a 'people first' philosophy with the aim of 'bolting' extra capabilities for more advanced missions onto Kliper at a later date. Each orbiter was intended to make 25 flights prior to retirement.

Using a space tug

Основные характеристики

Место базирования МБ «Паром»	в составе МКС
Время полета ПКК «Клипер» до стыковки с МБ «Паром»	1 сутки
Время полета связки ПКК «Клипер» - МБ «Паром» до стыковки с МКС	1 сутки
Время полета ПКК «Клипер» в составе МКС	1 год

Kliper utilizing Parom Space Tug

During autumn of 2005 Kliper's design was changed again. In order to fit the Kliper on the planned upgraded version of the Soyuz-2 rocket, labeled the Soyuz-2-3, Kliper would be 'split up' into two spacecraft, the Kliper crew vehicle and Parom, a space tug. Parom would have been a permanent orbital spacecraft awaiting Kliper in orbit, docking with it and then providing orbital manoeuvering and boosting Kliper to higher orbits in order to dock with the International Space Station. The Parom was planned to be indefinitely reusable, refueling itself via the cargo container, space station, or spacecraft that it is attached to.

Final version of Energia's proposal

The version of Kliper presented during the bid in January 2006 differs again from the original design. It showed a lifting body with larger wings, that, according to Energia officials, could be folded around the core crew module and unfold after atmospheric re-entry in order to provide cross-range and better landing accuracy for the spacecraft. The light Kliper version proposed was stripped down to 7 tons and uses the 'split-up'-option with Parom as a spacetug.

Missions

The Kliper program was proposed as the Russian-European counterpart to the American Orion Spacecraft and was therefore designed (similar to the Orion) to be part of a modular system that enabled it to be both a LEO-shuttle type vehicle as well as part of a spacecraft able to go beyond Earth orbit to the Moon and even Mars (there were outline suggestions of lunar applications in September 2005). The modular design would have included the Kliper crew module and - depending on the mission - a mission module or propulsion module. Although far fetched, this corresponds to announcements by the Russian Space Agency that according to a lunar mission study, using the Soyuz, a landing on the Moon could be achieved within the next decade.

Information on Kliper's beyond LEO mission capabilities were expanded further by RSC Energia, with a picture released in December 2005 of what a possible Kliper interplanetary configuration might have looked like. The design was entirely theoretical but made for a view of where RSC Energia saw the Kliper operating, and how it might have done so. This configuration was unlike anything seen so far for a manned space vehicle, with the solar arrays needed for electrical power vastly bigger than the habitable volume at the centre. It was also unclear what the mode of propulsion was. The very large solar array suggested an ion propulsion system might have been contemplated for such a mission, though it might also simply be that there was another reason for such a large array, such as increased power for better telemetry transmission rates over large distances.

Carrier rockets

The present Soyuz rocket would not be able to lift Kliper into low earth orbit, because the spacecraft (the version designed without Parom) was expected to weigh between 13 and 14.5 metric tons (with payload and crew) whereas Soyuz only has a lifting capacity of around 8 metric tons. It was originally planned to heavily enhance the Soyuz rocket - a project that was labelled the Onega rocket or Soyuz-3. Until fall of 2005 it was much more likely that Kliper would have used an Angara-A3 rocket, which was scheduled to make its first launch in 2012 (however the Angara program has been delayed and Angara-A3 may not be developed in light of the funding of the development of Soyuz 2-3) or possibly a Zenit rocket that is built in Ukraine.

At the end of 2005, Kliper's design was changed again (as outlined above) and the most likely solution for a carrier rocket became the Soyuz 2-3, an upgraded Soyuz 2 rocket. This enhanced Soyuz should have been able to launch Kliper into space because of weight reduction resulting in the use of the Parom as a space tug.

With regard to launch sites for Kliper, further information became available as of October 2005, with a planning-stage declaration from Nikolai Moiseev, Deputy Director of the Russian Space Agency that Kliper could have been launched from ESA's Guiana Space Centre in French Guiana. Though this aim had already been suggested, the comment was made in the context of facility upgrades for Kourou that are already under way since 2003 and are expected to be finished in 2007 with the first launch of a Soyuz rocket from French Guiana in 2008. It had been suggested that Kliper could have been launched from both Baikonur and Kourou, by Alan Thirkettle, head of ESA's human spaceflight, microgravity and exploration directorate, in December 2005.

Chapter 10

Lockheed Martin X-33

X-33

Simulated in-flight view of the X-33

Function	Unmanned Re-usable Spaceplane technology demonstrator
Manufacturer	Lockheed Martin
Country of origin	United States
Size	
Height	20 m (69 ft)
Diameter	N/A
Mass	285,000 lb (130,000 kg)
Stages	1
Capacity	
Launch history	
Status	Canceled (2001)
Launch sites	Edwards Air Force Base
Total launches	1
First stage - X-33	
Engines	2 J-2S Linear Aerospikes
Thrust	410,000 lbf (1.82 MN)
Burn time	

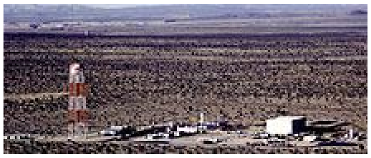
Fuel	LOX/LH2

The **Lockheed Martin X-33** is an unmanned, sub-scale technology demonstrator suborbital spaceplane developed in the 1990s under the U.S. government-funded Space Launch Initiative program. X-33 was a technology demonstrator for the VentureStar orbital spaceplane. The VentureStar was planned to be a next-generation, commercially-operated reusable launch vehicle. The X-33 would flight-test a range of technologies that NASA believed it needed for single-stage-to-orbit reusable launch vehicles (SSTO RLVs), such as metallic thermal protection systems, composite cryogenic fuel tanks for liquid hydrogen, the aerospike engine, autonomous (unmanned) flight control, rapid flight turn-around times through streamlined operations, and its lifting body aerodynamics.

Failures led to the cancellation of the program as a federal program in 2001, but Lockheed Martin has conducted related testing, and has had successes as recently as 2009.

Design and development

Through the use of the lifting body shape, composite liquid fuel tanks, and the aerospike engine, NASA and Lockheed Martin hoped to test fly a craft that would demonstrate the viability of a single-stage-to-orbit (SSTO) design. An SSTO craft would not require external fuel tanks or boosters to reach low-earth orbit. Doing away with the need for "staging" with launch vehicles, such as with the Shuttle and the Apollo rockets, would lead to an inherently more reliable and safer space launch vehicle. While the X-33 would not approach airplane-like safety, the X-33 would attempt to demonstrate that 0.997 reliability, or 3 mishaps out of 1,000 launches, which would be an order of magnitude more reliable than the Space Shuttle system, was achievable. The 15 planned experimental X-33 flights could only begin this statistical evaluation.



X-33 launch facility already completed at Edwards Air Force Base

The unmanned craft would have been launched vertically from a specially designed facility constructed on Edwards Air Force Base, and landed horizontally (VTHL) on a runway at the end of its mission. Initial sub-orbital test flights were planned from Edwards AFB to Dugway Proving Grounds southwest of Salt Lake City, Utah. Once those test flights were completed, further flight tests were to be conducted from Edwards AFB to Malmstrom AFB in Great Falls, Montana, to gather more complete data on aircraft heating and engine performance at higher speeds and altitudes.

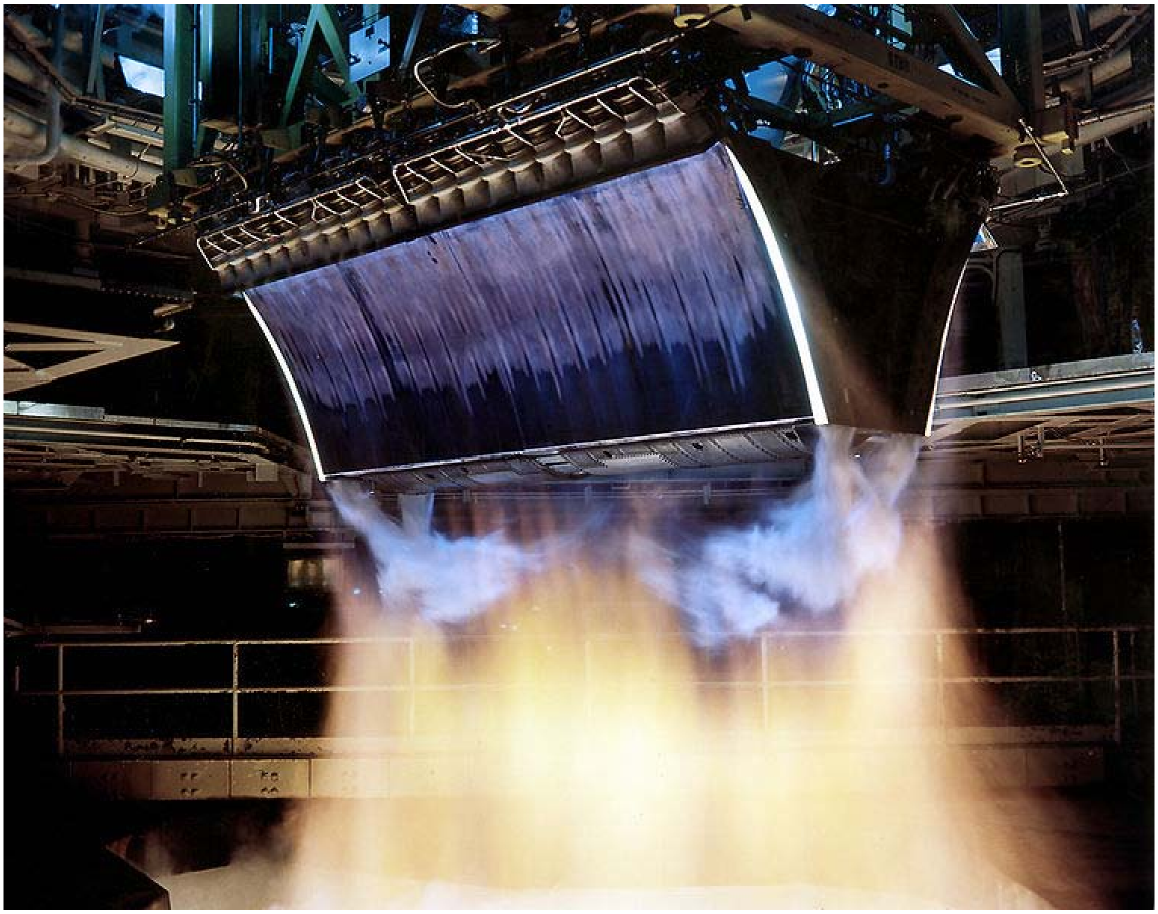
On July 2, 1996, NASA selected Lockheed Martin Skunk Works of Palmdale, California, to design, build, and test the X-33 experimental vehicle for the RLV program. Lockheed Martin's design concept for the X-33 was selected over competing designs from Boeing and McDonnell Douglas. Boeing featured a Space Shuttle-derived design, and McDonnell Douglas featured a design based on its vertical takeoff and landing (VTVL) DC-XA test vehicle.

The X-33 was never intended to fly higher than an altitude of 100 km, nor faster than one-half of orbital velocity. Had any successful tests occurred, extrapolation would have been necessary to apply the results to a proposed orbital vehicle.

Commercial spaceflight

Based on the X-33 experience shared with NASA, Lockheed Martin hoped to make the business case for a full-scale SSTO RLV, called VentureStar, that would be developed and operated through commercial means. The intention was that rather than operate space transport systems as it has with the Space Shuttle, NASA would instead look to private industry to operate the reusable launch vehicle and NASA would purchase launch services from the commercial launch provider. Thus, the X-33 was not only about honing space flight technologies, but also about successfully demonstrating the technology required to make a commercial reusable launch vehicle possible.

The VentureStar was to be the first commercial aircraft to fly into space. The unmanned X-33 was slated to fly 15 suborbital hops to near 75.8 km altitude. It was to be launched upright like a rocket and rather than having a straight flight path it would fly diagonally up for half the flight, reaching extremely high altitudes, and then back down for the rest of the flight. The VentureStar was intended for long inter-continental flights and supposed to be in service by 2012, but this project was never funded or begun.



Aerospike engine test at Stennis Space Center, August 6, 2001

The decision to design and build the X-33 grew out of an internal NASA study titled "Access to Space". Unlike other space transport studies, "Access to Space" was to result in the design and construction of a vehicle.

NASA Cancellation

Construction of the prototype was some 85% assembled with 96% of the parts and the launch facility 100% complete when the program was canceled by NASA in 2001, after a long series of technical difficulties including flight instability and excess weight.

In particular, the composite liquid hydrogen fuel tank failed during testing in November 1999. The tank was constructed of honeycomb composite walls and internal structures to reduce its weight. A lighter tank was needed for the craft to demonstrate necessary technologies for single-stage-to-orbit operations. A hydrogen fueled SSTO craft's mass fraction requires that the weight of the vehicle without fuel be 10% of the fully-fueled weight. This would allow for a vehicle to fly to low earth orbit without the need for the sort of external boosters and fuel tanks used by the Space Shuttle. But, after the composite tank failed on the test stand during fueling and pressure tests, NASA came to the conclusion that the technology of the time was simply not advanced enough for such a design. While the composite tank walls themselves were lighter, the odd hydrogen tank shape resulted in complex joints increasing the total mass of the composite tank to above that of an aluminum-based tank.

NASA had invested $922 million in the project before cancellation and Lockheed Martin a further $357 million. Due to changes in the space launch business—including the challenges faced by companies such as Globalstar, Teledesic, and Iridium and the resulting drop in the number of anticipated commercial satellite launches per year—Lockheed Martin deemed that continuing development of the X-33 privately without government support would not be profitable.

Continued research

After the cancellation in 2001, engineers were able to make a working liquid oxygen tank out of carbon fiber composite.

On September 16, 2004, Northrop Grumman and NASA engineers unveiled a liquid hydrogen tank made of carbon fiber composite material that had demonstrated the ability for repeated fuelings and simulated launch cycles. Northrup Grumman concluded that these successful tests have enabled the development and refinement of new manufacturing processes that will allow the company to build large composite tanks without an autoclave; and design and engineering development of conformal fuel tanks appropriate for use on a single-stage-to-orbit vehicle.

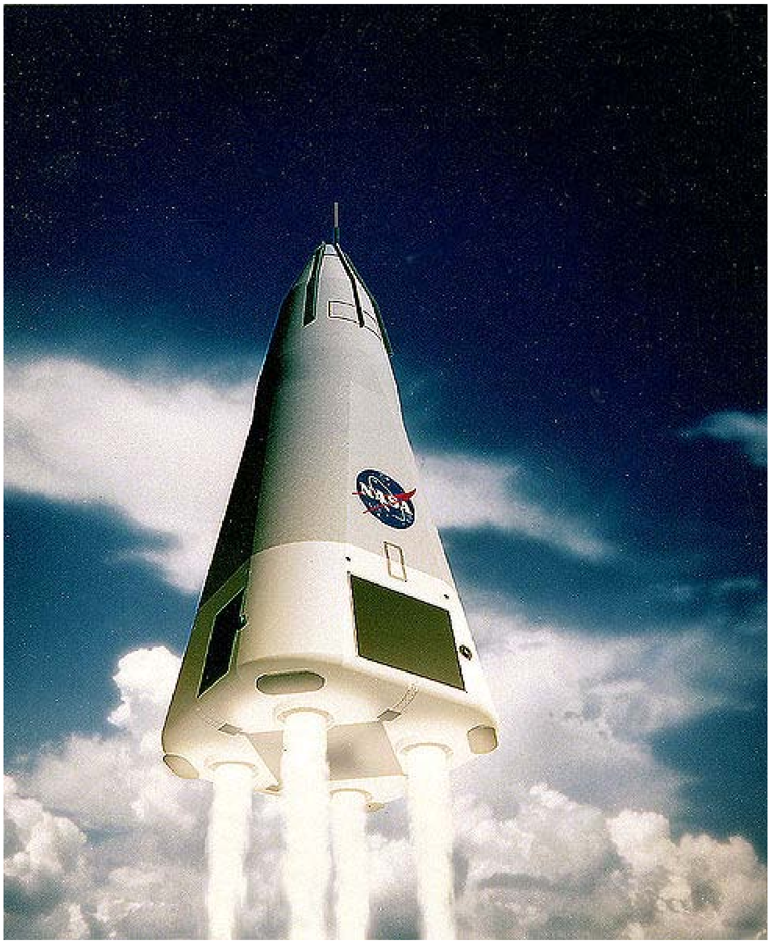
Lockheed Martin has been testing a new and different 1/5 scale rocket described to be similar in capabilities and design, known now simply as a "Space Reusable Launch Vehicle". Two tests were conducted secretly at the Spaceport America in New Mexico. The first on December 19, 2007 was billed as a complete success, while the August 12, 2008 launch ended in an irreparable crash after 12.5 seconds of flight. A third test on October 10, 2009, was another success.

Notable appearances in popular media

In Dan Brown's 2000 novel *Angels & Demons*, CERN, the nuclear physics research laboratory, owns a "Boeing X-33" [*sic*], which is capable of Mach 15, and of flying from Boston to Switzerland in less than an hour. It is also mentioned in his novel *Deception Point*.

Chapter 11

McDonnell Douglas DC-X



McDonnell Douglas DC-XA Reusable Launch Vehicle (RLV) concept

The **DC-X**, short for **Delta Clipper** or **Delta Clipper Experimental**, was an unmanned prototype of a reusable single stage to orbit launch vehicle built by McDonnell Douglas in conjunction with the United States Department of Defense's Strategic Defense Initiative Organization (SDIO) from 1991 to 1993. After that period it was given to NASA, which upgraded the design for improved performance to create the **DC-XA**.

Background

According to writer Jerry Pournelle: "DC-X was conceived in my living room and sold to National Space Council Chairman Dan Quayle by General Graham, Max Hunter and me." According to Max Hunter, however, he had tried hard to convince Lockheed-Martin of the concept's value for several years before he retired. Hunter had written a paper in 1985 entitled "The Opportunity", detailing the concept of a Single-Stage-To-Orbit spacecraft built with low-cost "off-the-shelf" commercial parts and currently-available technology, but Lockheed-Martin was not interested enough to fund such a program themselves.

On February 15, 1989, Pournelle, Graham and Hunter were able to procure a meeting with Vice-President Dan Quayle. They "sold" the idea to SDIO by noting that any space-based weapons system would need to be serviced by a spacecraft that was far more reliable than the Space Shuttle, and offer lower launch costs and have much better turnaround times.

Given the uncertainties of the design, the basic plan was to produce a deliberately simple test vehicle and to "fly a little, break a little" in order to gain experience with fully reusable quick-turnaround spacecraft. As experience was gained with the vehicle, a larger prototype would be built for sub-orbital and orbital tests. Finally a commercially acceptable vehicle would be developed from these prototypes. In keeping with general aircraft terminology, they proposed the small prototype should be called the DC-X, X for "experimental". This would be followed by the "DC-Y", Y referring to pre-run prototypes of otherwise service-ready aircraft. Finally the production version would be known as the "DC-1". The name "Delta Clipper" was chosen deliberately to result in the "DC" acronym, an homage to the famous DC-3 aircraft, which many credit for making passenger air travel affordable.

Design

The DC-X was never designed to achieve orbital altitudes or velocity, but instead to demonstrate the concept of vertical take off and landing. The vertical take off and landing concept was popular in science fiction films from the 1950s (*Rocketship X-M*, *Destination Moon*, and others), but not seen in real world designs. It would take off vertically like standard rockets, but also land vertically with the nose up. This design used attitude control thrusters and retro rockets to control the descent, allowing the craft to begin reentry nose-first, but then roll around and touch down on landing struts at its base. The craft could be refueled where it landed, and take off again from exactly the same position — a trait that allowed unprecedented turnaround times.

In theory a base-first re-entry profile would be easier to arrange. The base of the craft would already need some level of heat protection to survive the engine exhaust, so adding more protection would be easy enough. More importantly, the base of the craft is much larger than the nose area, leading to lower peak temperatures as the heat load is spread out over a larger area. Finally, this profile would not require the spacecraft to "flip around" for landing.

The military role made this infeasible, however. One desired safety requirement for any spacecraft is the ability to "abort once around", that is, to return for a landing after a single orbit. Since a typical low earth orbit takes about 90 to 120 minutes, the Earth will rotate to the east about 20 to 30 degrees in that time; or for a launch from the southern United States, about 1,500 miles (2,400 km). If the spacecraft is launched to the east this does not present a problem, but for the polar orbits required of military spacecraft, when the orbit is complete the spacecraft overflies a point far to the west of the launch site. In order to land back at the launch site, the craft needs to have considerable cross-range maneuverability, something that is difficult to arrange with a large smooth surface. The Delta Clipper design thus used a nose-first re-entry with flat sides on the fuselage and large control flaps to provide the needed cross range capability. Experiments with the control of such a re-entry profile had never been tried, and were a major focus of the project.

Another focus of the DC-X project was minimized maintenance and ground support. To this end, the craft was highly automated and required only three people to man its control center (two for flight operations and one for ground support). In some ways the DC-X project was less about technology research than operations.

Flight testing

The Delta Clipper Advanced

Construction of the DC-X started in 1991 at McDonnell Douglas' Huntington Beach facility. The aeroshell was custom-constructed by Scaled Composites, but the majority of the spacecraft was built from "off the shelf" parts, including the engines and flight control systems.

The DC-X first flew, for 59 seconds, on 18 August 1993. It flew two more flights 11 September and 30 September, when funding ran out as a side effect of the winding down of the SDIO program. Apollo astronaut Pete Conrad was at the ground-based controls for some flights.

Further funding was forthcoming, however, and the test program re-started on 20 June 1994 with a 136 second flight. The next flight, 27 June 1994, suffered an inflight (minor) explosion, but the craft successfully executed an abort and autoland. Testing re-started after this damage was fixed, and three more flights were carried out on 16 May 1995, 12 June, and 7 July. On the last flight a hard landing cracked the aeroshell. By this point funding for the program had already been cut, as a side effect of the winding down of the SDIO program, and there were no funds for the needed repairs.

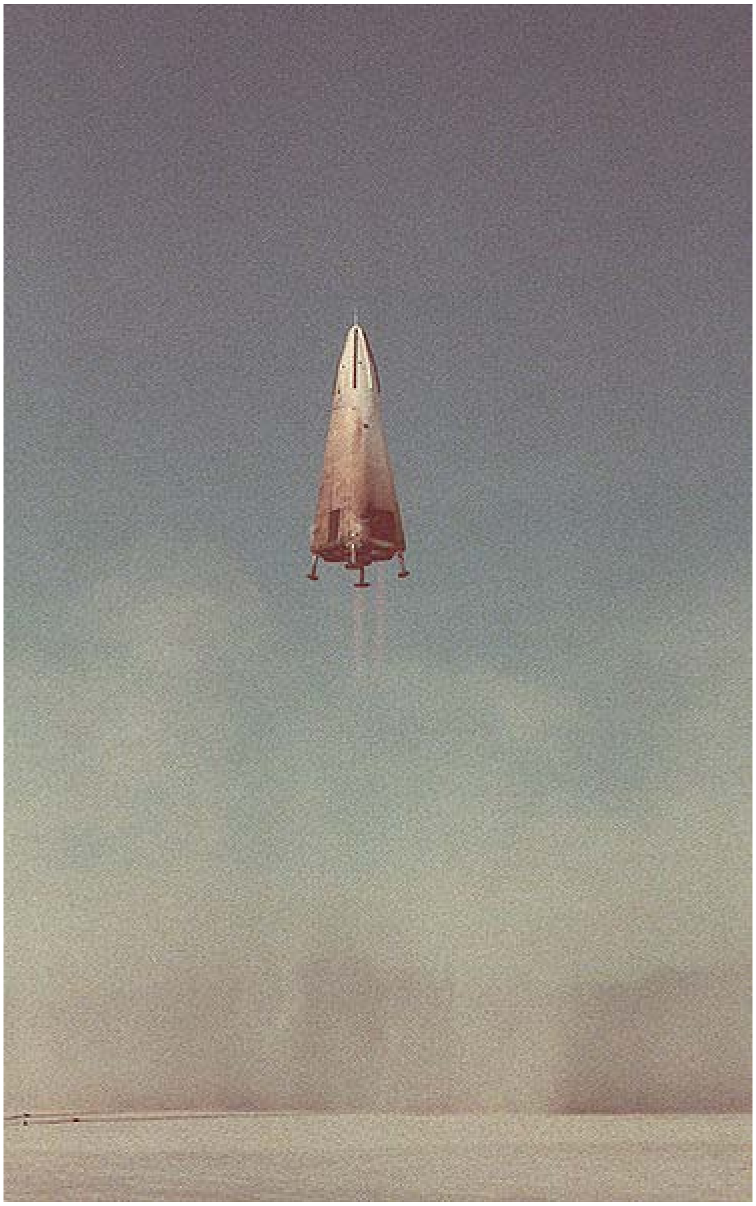
NASA agreed to take on the program at this point. In contrast to the original concept of the DC-X demonstrator, NASA applied a series of major upgrades to test new technologies. In particular, the oxygen tank was replaced by a lightweight (alloy 1460 equivalent of alloy 2219) Al-Li tank from Russia, and the fuel tank by a newer composite design. According to Bob Hartunian (former McDonnell Douglas and Boeing cryo-tank specialist), the Russian-made tank was poor quality, had "16-inch/40.6-cm long weld defects, and there were other issues that, according to U.S. standards, would prevent it from flying."
The control system was likewise improved. The upgraded vehicle was called the **DC-XA**, renamed the **Clipper Advanced**/**Clipper Graham**, and resumed flight in 1996.

The first flight on 18 May 1996 resulted in a minor fire when the deliberate "slow landing" resulted in overheating of the aeroshell. The damage was quickly repaired and the vehicle flew two more times on 7 and 8 June, a 26-hour turnaround. On the second of these flights the vehicle set its altitude and duration records, 3,140 meters and 142 seconds of flight time. Its next flight, on 7 July, proved to be its last. During testing, one of the LOX tanks had been cracked. When a landing strut failed to extend due to a disconnected hydraulic line, the DC-XA fell over and the tank leaked. Normally the structural damage from such a fall would constitute only a setback, but the LOX from the leaking tank fed a fire which severely burned the DC-XA, causing such extensive damage that repairs were impractical.

In a post-accident report, NASA's Brand Commission blamed the accident on a burnt-out field crew who had been operating under on-again/off-again funding and constant threats of outright cancellation. The crew, many of them originally from the SDIO program, were also highly critical of NASA's "chilling" effect on the program, and the masses of paperwork NASA demanded as part of the testing regimen.

NASA had taken on the project grudgingly after having been "shamed" by its very public success under the direction of the SDIO. Its continued success was cause for considerable political in-fighting within NASA due to it competing with their "home grown" Lockheed Martin X-33/VentureStar project. Pete Conrad priced a new DC-X at 50 million dollars, but NASA decided not to rebuild the craft in light of the budget constraints.

Rather, NASA focused development on the Lockheed Martin VentureStar which it felt answered some criticisms of the DC-X; specifically the requirement that many NASA engineers preferred the airplane-like landing of the VentureStar over the vertical landing of the DC-X.



First flight

First landing. The yellow exhaust is due to the low throttle settings, which burns at lower temperatures and is generally "dirty" as a result.

- Height 12 m (39' 4")
- Diameter 4.1 m (13' 5")
- Dry mass: 9,100 kg
- GLOW: 18,900 kg
- Propellants: Liquid oxygen and liquid hydrogen
- Engines: Four RL-10A-5 rocket engines
- Engine thrust: 6,100 kgf
- Reaction controls: four 440 lbf (2,000 N) thrust gaseous oxygen, gaseous hydrogen thrusters

The future of the DC-X

Several engineers who worked on the DC-X have since been hired by Blue Origin, and their Blue Origin New Shepard vehicle is based on the DC-X design. Blue Origin does not require the high cross range capabilities, and therefore uses a base-first re-entry profile. Also, the DC-X provided inspiration for many elements of Armadillo Aerospace's, Masten Space Systems's, and TGV Rockets's spacecraft designs.

Returning the DC-X design to NASA's active research portfolio has been considered for some time now. Some NASA engineers believe that the DC-X could provide a solution for a manned Mars lander. Had a DC-type craft been developed that operated as an SSTO in Earth's gravity well, even if with only a minimum 4-6 crew capacity, variants of it might prove extremely capable for both Mars and Moon missions. Such a variant's basic operation would have to be "reversed"; from taking off and then landing, to landing first then taking off. Yet, if this could be accomplished on Earth, the weaker gravity found at both Mars and the Moon would make for dramatically greater payload capabilities, particularly at the latter destination.

Some proposed design changes include using an oxidizer/fuel combination that does not require the relatively extensive ground support required for the liquid hydrogen and liquid oxygen that DC-X utilized, and adding a fifth leg for increased stability during and after landing. Recently, NASA's Centennial Challenges program has announced a suborbital Lunar Lander Challenge which is a prize for the first team to build a VTVL rocket that has the same delta-v as a vehicle capable of landing on the moon and operate it under competition conditions.

Chapter 12

North American DC-3

The **DC-3** was a proposed space shuttle designed by Maxime Faget at the Manned Spacecraft Center (MSC) in Houston. The design was nominally developed by North American Aviation (NAA), although it was a purely NASA-internal design.

Unlike the eventual Space Shuttle design that emerged, the DC-3 was a fully reusable two-stage-to-orbit design with a smaller payload capacity of about 12,000 lbs and limited maneuverability. Its inherent strengths were good low-speed handling during landing, and a low-risk development that was relatively immune to changes in weight and balance.

Work on the DC-3 program ended when the US Air Force joined the Shuttle program; they demanded a much greater "cross-range" maneuverability than the DC-3 could deliver, and expressed serious concerns about its stability during re-entry. NAA eventually won the Shuttle Orbiter contract, although it was based on a very different design from another team at MSC.

History

Background

In the mid-1960s the US Air Force conducted a series of classified studies on next-generation space transportation systems. Among their many goals, the new launchers were intended to support a continued manned military presence in space, and so needed to dramatically lower the cost of launches and increase launch rates. Selecting from a series of proposals, the Air Force concluded that semi-reusable designs were the best choice from an overall cost basis, and the Lockheed Star Clipper design was one of the most-studied examples. They proposed a development program with an immediate start on a "Class I" vehicle based on expendable boosters, followed by a slower development of a "Class II" semi-reusable design, and perhaps a "Class III" fully-reusable design in the further future. Although is it estimated that the Air Force spent up to $1 billion on the associated studies, only the Class I program that proceeded to development, as the X-20 Dyna-Soar, which was later cancelled.

Not long after the Air Force studies, NASA started studying the post-Project Apollo era. A wide variety of projects were examined, many based on re-using Apollo hardware

(Apollo X, Apollo Applications Program, etc.) Flush with the success of the moon landings, a series of ever-more ambitious projects gained currency, a process that was considerably expanded under the new NASA director, Thomas O. Paine. By about 1970 these had settled on the near-term launching of a 12-man space station in 1975, expanding this to a 50-man "space base" by 1980, a smaller lunar-orbiting station, and then eventually a manned mission to Mars in the 1980s. NASA awarded $2.9-million study contracts for the space stations to North American and McDonnell Douglas in July 1969.

Almost as an afterthought the idea of a small and inexpensive "logistics vehicle" for supporting these missions developed in the late 1960s. George Mueller was handed the task of developing plans for such a system, and held a one-day symposium at NASA headquarters in December 1967 to study various options. Eighty people attended and presented a wide variety of potential designs, many from the earlier Air Force work, from small Dyna-Soar like vehicles primarily carrying crew and launched on existing expendable boosters, to much larger fully-reusable designs.

ILRV

On 30 October 1968 NASA officially began work on what was then known as the "Integrated Launch and Re-entry Vehicle" (ILRV), a name they borrowed from the earlier Air Force studies. The development program was to take place in four phases; Phase A: Advanced Studies; Phase B: Project Definition; Phase C: Vehicle Design; and Phase D: Production and Operations. Four teams were to participate in Phase A; two in Phase B; and then a single prime contractor for Phases C and D. A separate Space Shuttle Main Engine (SSME) competition was to run in parallel.

NASA Houston and Huntsville jointly issued the Request for Proposal (RFP) for eight-month Phase A ILRV studies. The requirements were for 5,000 to 50,000 lb of payload to be delivered into a 500 km altitude orbit. The re-entry vehicle should have a cross range of at least 450 miles, meaning that it could fly to the left or right of its normal orbital path. General Dynamics, Lockheed, McDonnell-Douglas, Martin Marietta, and (the newly named) North American Rockwell were invited to bid. In February 1969 , following study of the RFPs, Martin Marietta's entry was dropped, although they continued work on their own. The other entries were all given additional Phase A funding.

Supported by Paine's ambitious plans, in August 1969 the ILRV program was re-defined to be a "maximum effort" design, and only fully-reusable designs would be accepted. This led to a second series of Phase A studies. The designs that were returned varied widely, meeting a the huge payload range specified in the original RFP. Two basic fuselage designs seemed to be the most common; lifting body designs that offered high cross-range but limited maneuverability after re-entry, and delta-winged designs that reversed these criterion.

DC-3

Faget felt that all of the proposed designs incorporated an unacceptable amount of development risk. Unlike a conventional aircraft, with separate fuselage and wings, the ILRV designs had blended wing-body layouts. This meant that changes in weight and balance, which are almost unavoidable during development, would require changes to the entire orbiter structure to compensate. He also felt that the poor low-speed handling of any of these layouts presented a real danger during landing. Upset by what he felt was a project that seemed to guarantee failure, he started work on his own design, and presented it as the DC-3.

Unlike the other entries, DC-3 was much more conventional in layout, with an almost cylindrical fuselage and low-mounted slightly-swept wings. The design looked considerable more like a cargo aircraft than a spacecraft. Re-entry was accomplished in a 60 degree nose-high attitude that presented the lower surface of the spacecraft to the airflow, using a ballistic blunt-body approach that was similar to the one Faget had successfully pioneered on the Mercury capsule. During re-entry, the wings provided little or no aerodynamic lift. After re-entry, when the spacecraft entered the lower atmosphere, it would pitch over into a conventional flying attitude, ducts would open, and jet engines would start up for landing.

The upside of this design approach was that changes in the weight and balance could be addressed simply by moving the wing or re-shaping it, a common solution that had been used for decades in aircraft design — including the original Douglas DC-3 who's wings were swept rearward for just this reason. The downside was that the spacecraft would have little hypersonic lift, so its ability to maneuver while re-entering would be limited and its cross-range would be about 300 miles. It could make up for some of this with its improved low-speed flying ability, but would still not be able to match the mandated 450 miles.

Although the DC-3 had never been part of the original ILRV plans, Faget's name was so well respected that others at NASA MSC in Houston quickly rallied around him. Other NASA departments all selected their own favorite designs, including recoverable versions of Saturn boosters developed at the Marshall Space Flight Center in Huntsville, lifting-bodies based on the HL-10 that were favored by the Langley Research Center and Dryden Flight Research Center (Edwards), and even a single-stage-to-orbit Aerospaceplane were also proposed. From then on the entire program was beset with in-fighting between the various teams. On 1 June 1969 a report was published that attacked the DC-3 design, followed by several others over the remainder of the year. In spite of this, North American quickly took up the DC-3 design, having learned over the years that the best way to win a NASA contract was to make whatever design Faget favored. They won contract NAS9-9205 to develop the DC-3 in December 1969.

In order to clear the logjam developing between the departments, on 23 January 1970 a meeting was held in Houston to study all of the in-house concepts. Over the next year a number of proposed designs would be dropped, including the entire series of lifting-body-derived vehicles as it proved too difficult to fit cylindrical tanks into the airframe. This left two basic approaches, delta wings and Faget's DC-3 series. Development of the DC-3 continued, with a drop tests of a 1/10 scale model starting on 4 May.

Space Task Group

On 12 February 1969 Richard Nixon formed the Space Task Group under the direction of Vice President Spiro Agnew, giving them the task of selecting missions for a post-Apollo NASA. Agnew quickly became a proponent of NASA's ambitious plans that would culminate in a Mars attempt. The Task Group's final report, delivered on 11 September 1969, outlined three broad plans; the first required funding at $8 to $ 10 billion a year and would fulfill all of NASA's goals, the second would reduce this to $8 billion or less if the manned lunar orbiting station was dropped, and finally the third would require only $5 billion a year and would develop only the space stations and shuttle.

At first Nixon did not comment on the plans. Later he demanded that the program be greatly reduced even from the smallest of the Task Group's proposals, forcing them to select either the space base *or* the shuttle. Discussing the problem, NASA engineers concluded that the development of a shuttle would lower the cost of launching portions of the space station, so it seemed that proceeding with the shuttle might make the future development of the station more likely. However, NASA's estimates of the shuttle development costs were met with great skepticism by the Office of Management and Budget (OMB). Studies by RAND in 1970 showed that there was no benefit to developing a reusable spacecraft when development costs were taken into account. The report concluded that a manned station would be more cheaply supported with expendable boosters.

By this time Paine had left NASA to return to General Electric, and had been replaced by the more pragmatic James Fletcher. Fletcher ordered independent reviews of the shuttle concept; Lockheed was to prepare a report on how the shuttle could reduce payload costs, Aerospace Corporation was to make an independent report on development and operational costs, and Mathematica would later combine these two into a final definitive report. Mathematica's report was extremely positive; it showed that development of a fully-reusable design would lower the per-launch cost, thereby reducing payload costs and driving up demand. However, the report was based on a greatly increased rate of launch; inherent in the math was the fact that lower launch rates would completely upset any advantage. Nevertheless, the report was extremely influential, and made the shuttle program an ongoing topic of discussion in Washington.

Looking to shore up support for the program, Fletcher directed NASA to develop the shuttle to be able to support the Air Force's requirements as well, as initially developed in their "Class III" fully-reusable vehicles. If the shuttle became vital to the Air Force as well as NASA, it would be effectively unkillable. The Air Force's requirements were based about a projected series of large spy satellites then under development, which were 60 feet long and weighed 40,000 lbs. They needed to be launched into polar orbits, corresponding to a normal launch from Kennedy Space Center (KSC) of 65,000 lbs (launches to the east receive a free boost from the Earth's natural rotation). The Air Force also demanded a cross-range capability of 1,500 miles.

End of DC-3

The new Air Force cross-range requirements doomed the DC-3 design.

Spacecraft orbit around the center of the Earth, not the surface. If a spacecraft is launched due East from the equator into a 90 minute low-Earth orbit, it will circle the Earth and return to the spot where it was launched 90 minutes later. During this time, however, the launch site will have moved due to the Earth's rotation. Over the 90 minute period, the Earth will rotate about 1,500 miles, so by the time one full orbit has completed the launch point will be in front of the spacecraft. However, at 17,000 mph the spacecraft will quickly cover this ground, by simply remaining in orbit a few moments longer, it will catch up to the launch point.

At KSC's ~30 degree latitude the picture is similar. Over the same 90 minute orbit KSC will rotate about 1,200 miles. Unlike the due east case, however, the spacecraft will not arrive directly over the launch site, but to its east about 300 miles. A spacecraft wishing to return to its launch site will need about 300 miles of cross-range maneuverability during re-entry, and the NASA shuttle designs demanded about 450 miles in order to have some working room.

Polar orbits from the Air Force's Vandenberg Air Force Base are another matter entirely. Located slightly north of KSC, the distance it would move over a single orbit would be similar, but critically, the shuttle would be traveling south, not east. This meant that it was not flying toward the launch point as it traveled in its orbit, and when it completed one orbit it would have to make up the entire 1,200 miles during re-entry. These missions required a dramatically improved cross-range capability, set at 1,500 miles to give it a slight excess capability. The ballistic re-entry profile of the DC-3 series simply could not come close to matching this requirement.

On 1 May 1971 the OMB finally released a budget plan, limiting NASA to $3.2 billion per year for the next five years. Given existing project budgets, this limited any spending on the shuttle to about $1 billion a year, far less than required to develop any of the completely-reusable designs. Based on these constraints, NASA returned to a Class II-like vehicle with external tankage, which led to the MSC-020 design. Later that year all straight-wing designs were officially abandoned, although Faget's team continued to work on them for some time in spite of this.

Description

The DC-3 was a two-stage vehicle with a large booster and smaller shuttle of overall similar design. Both were similar to "jumbo jets" in layout in general terms, with their large cylindrical fuselage containing fuel tanks instead of passengers or cargo. The bottom of the fuselage was flattened for re-entry aerodynamics, with a slight upward curve as you approached the nose in early models. The wings were low-mounted, in-line with the bottom of the fuselage, with a 14 degree rearward sweep on the front and no sweep on the back. The general layout of the wing planform was similar to the original DC-3. The empennage was a conventional three-surface unit, although in the original MSC-001 design the delta-shaped horizontal stabilizer was located at the bottom of the fuselage and served double-duty in protecting the rear-mounted engines during re-entry. Later versions did not generally include this feature, and used more conventional surfaces mid-mounted on the fuselage.

The orbiter carried a crew of two, and had accommodations for up to ten passengers. A cargo area was mounted in the middle of the craft between the liquid hydrogen (LH2) tank behind it, and a combined LH2/liquid oxygen tank in front of it. This arrangement was used in order to center the cargo over the wing, with the heavier oxygen and crew compartment balancing the weight of the engines. The lighter weight hydrogen then filled out the rest of the internal space. The booster had no cargo area, so it used a simpler arrangement of tankage with a single LH2 tank at the rear. The booster normally flew unmanned, but included a two-man cockpit area that was used during ferry flights.

The orbiter was powered by two modified XLR-129 engines with the thrust increased from 250,000 to 300,000 lbf, two 15,000 lbf RL-10 orbital manoeuvring engines, and six Rolls-Royce RB162 jet engines for landing. The booster used eleven of the same XLR-129 engines, and four Pratt & Whitney JT8D for landing. XLR-129s on both the shuttle and booster were fired for take-off. The orbiter was mounted relatively far forward for launch, its tail in-line with the booster's wings. The combined weight at launch would be about 2,030 tons.

Both craft carried just enough JP-4 for landing go-around. Both could also carry increased loads of JP-4 for test flights or ferrying. After launching the orbiter the booster would be too far down-range to easily turn around and return to Kennedy, so the normal mission profile had it coast across the ocean, land automatically, refuel and pick up a crew, and then be flown back to Kennedy on its JT8D engines.

In order to maximize overall performance, the booster released the orbiter at Mach 10 and 45 miles altitude. This required the booster to carry a complete thermal protection system in order to re-enter for landing. Both the orbiter and booster were to be protected with silica tiles similar to those eventually used on the Space Shuttle, a design that had recently been introduced by Lockheed and quickly became a baseline design for all of the shuttle contenders. As a result, both airframes were able to be built out of aluminum, greatly reducing airframe cost.

Lockheed estimated that development and initial production would cost $5.912 billion over a period from 1970 to 1975. A fleet of six orbiters and four boosters would have supported a launch rate of 50 flights per year.