Reusable Spaceflight Launch Systems

Renato Rojas

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Email: info@wtbooks.com

Table of Contents

Chapter 1

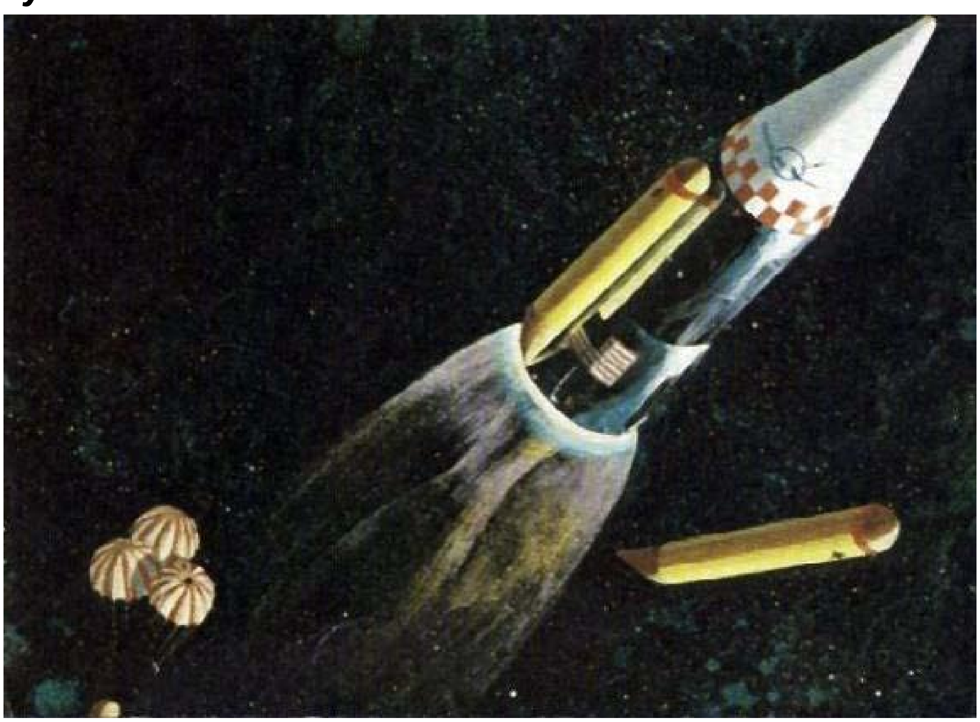
Reusable Launch System

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.

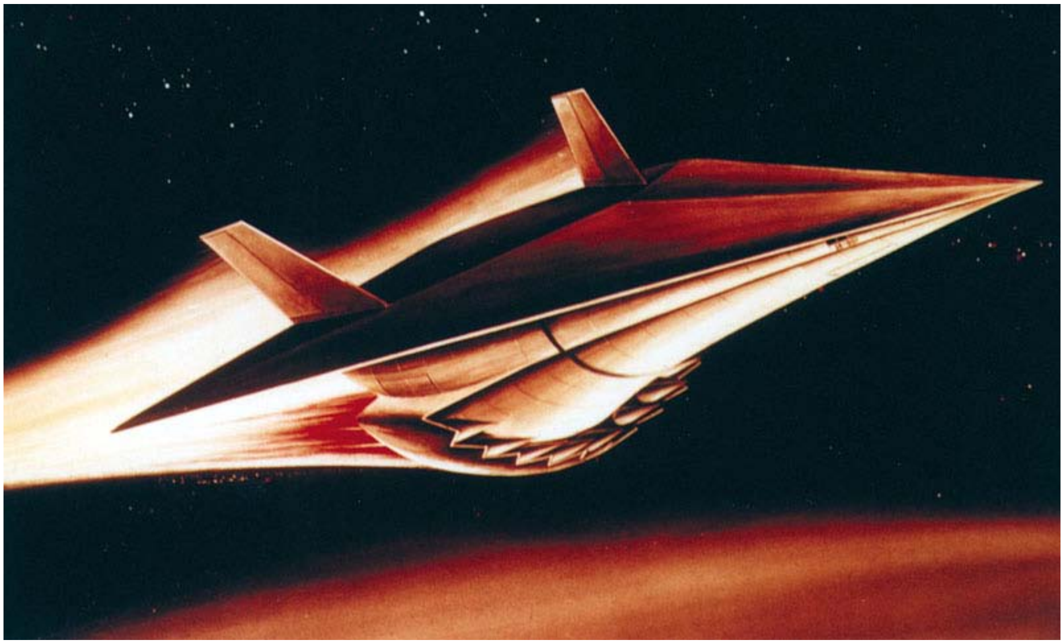
No true orbital reusable launch system is currently in use. The closest example is the partially reusable Space Shuttle. The orbiter, which includes the main engines, and the two solid rocket boosters, are reused after several months of refitting work for each launch. The external fuel drop tank is typically 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 2

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 3

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

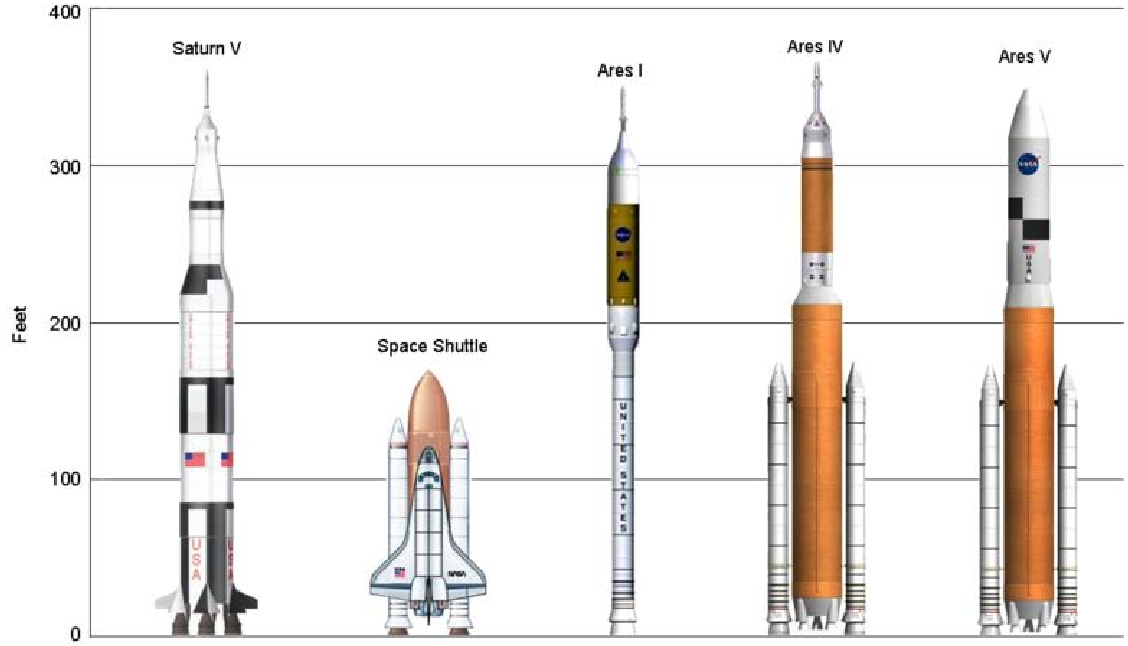
In 1995 Lockheed Martin produced an Advanced Transportation System Studies (ATSS) report for the Marshall Space Flight Center. A section of the ATSS report describes several possible vehicles much like the Ares I design, with liquid rocket second stages stacked above segmented solid rocket booster (SRB) 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.

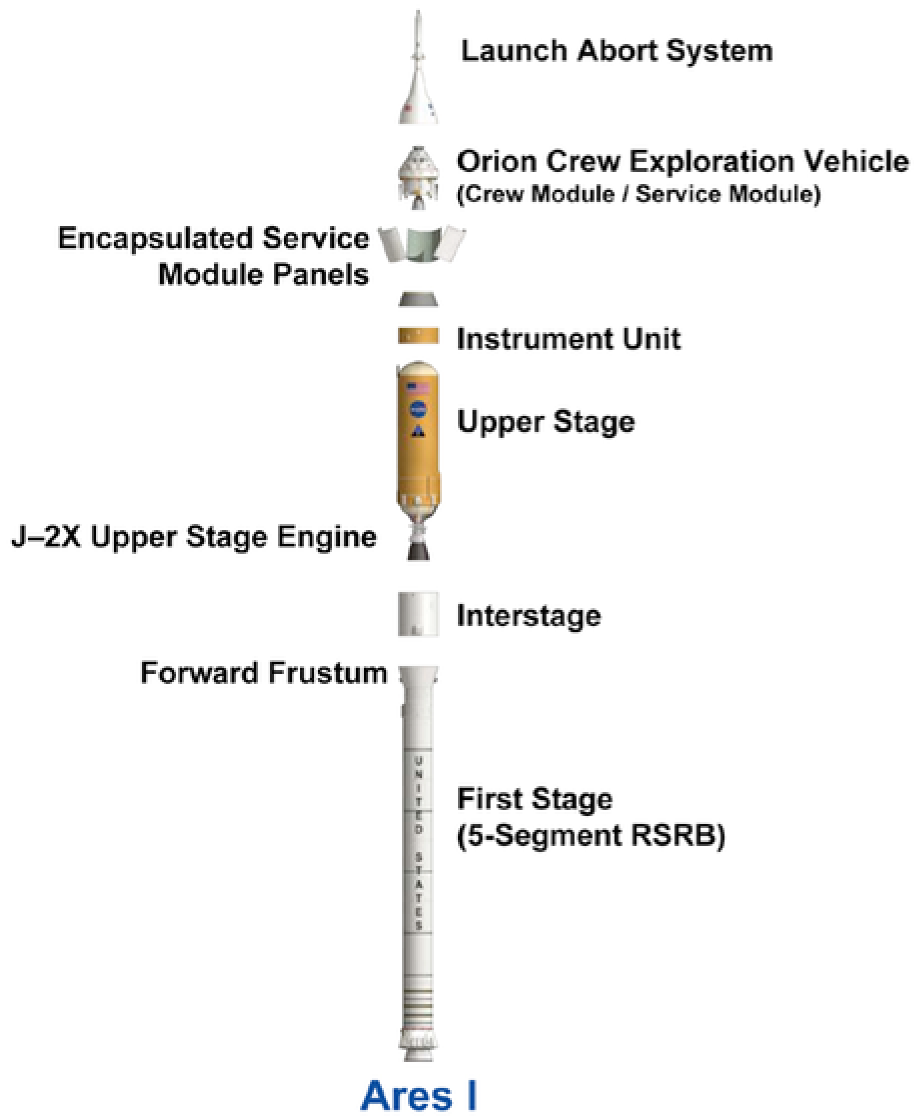


Comparison of the basic size and shape of the Saturn V, Space Shuttle, Ares I, Ares IV, and Ares V

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.

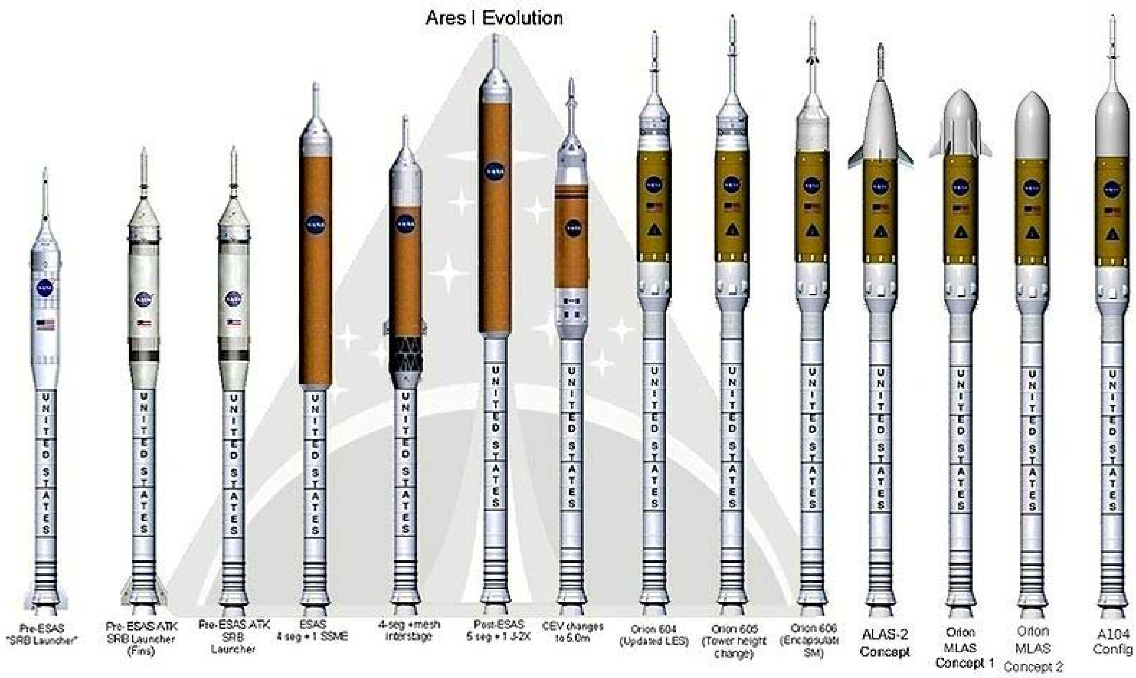
On February 8, 2011 it was reported that Alliant Techsystems and Astrium proposed to use Ares I's first stage with the second stage from the Ariane 5 to form a new rocket named Liberty.

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

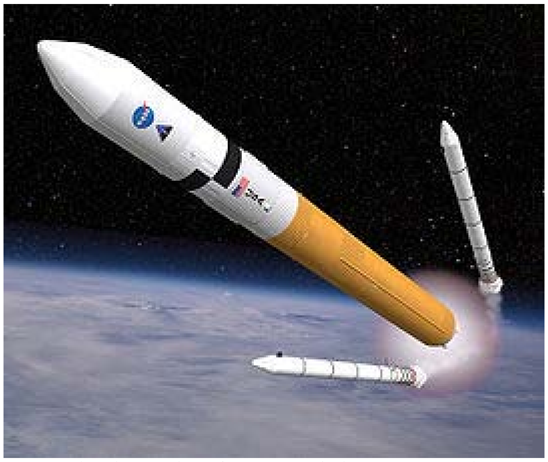
The upper stage, derived from the Shuttle's External Tank (ET) and based on the S-IVB stage of the Saturn V, is to be propelled by a single J-2X rocket engine fueled by liquid hydrogen (LH_2) and liquid oxygen (LOX). The J-2X is derived from the original J-2 engine used during the Apollo program, but 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

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 4

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

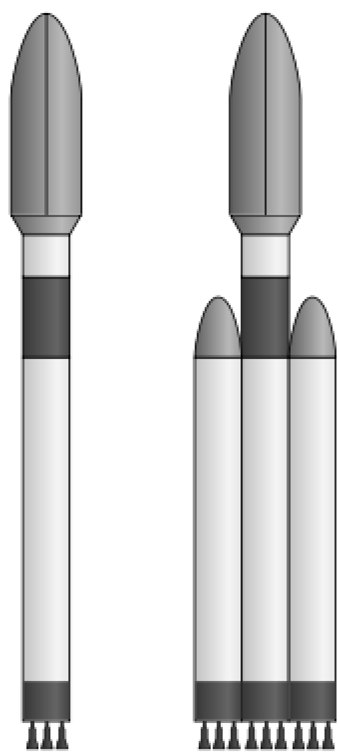
	Heavy: $95m
Size	
Height	54.3 m (178 ft)
Diameter	3.66 m (12.0 ft)
Mass	**Normal:** 333,400 kg (735,000 lb) **Heavy:** 885,000 kg (1,950,000 lb)
Stages	2
Capacity	
Payload to LEO	**Normal:** 10,450 kg (23,000 lb) **Heavy:**32,000 kg (71,000 lb)
Payload to GTO	**Normal:** 4,540 kg (10,000 lb) **Heavy:** 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 Nº	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	Success	maiden flight of Dragon Capsule; 3 hours, testing of maneuvering thrusters and

		Office		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	SES	Scheduled	First geostationary

	satellite			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 5

Kliper

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

Kliper spacecraft

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).

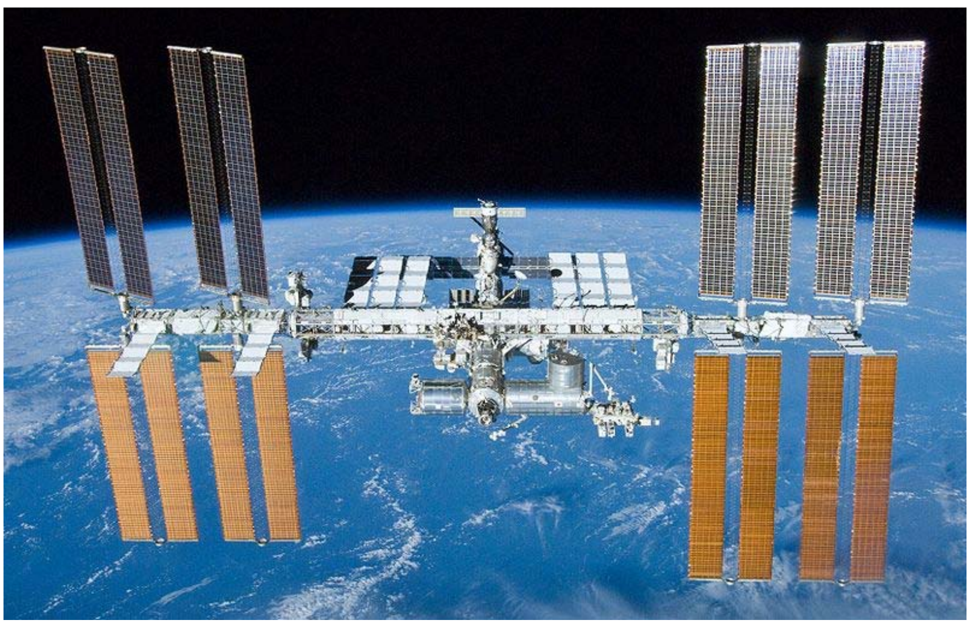
On July 14, 2005 the Russian government approved the national space program for 2006 to 2015 with a budget of 305 billion rubles (ca. $11 billion - the whole budget for the 10-year period will be 425 billion rubles = ca. 15 billion dollars). The budget included the needed funding for the Kliper program. 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

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 6

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

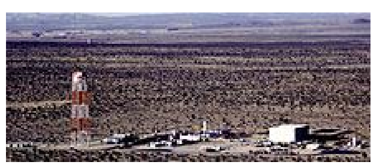
Thrust	410,000 lbf (1.82 MN)
Burn time	
Fuel	LOX/LH2

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.

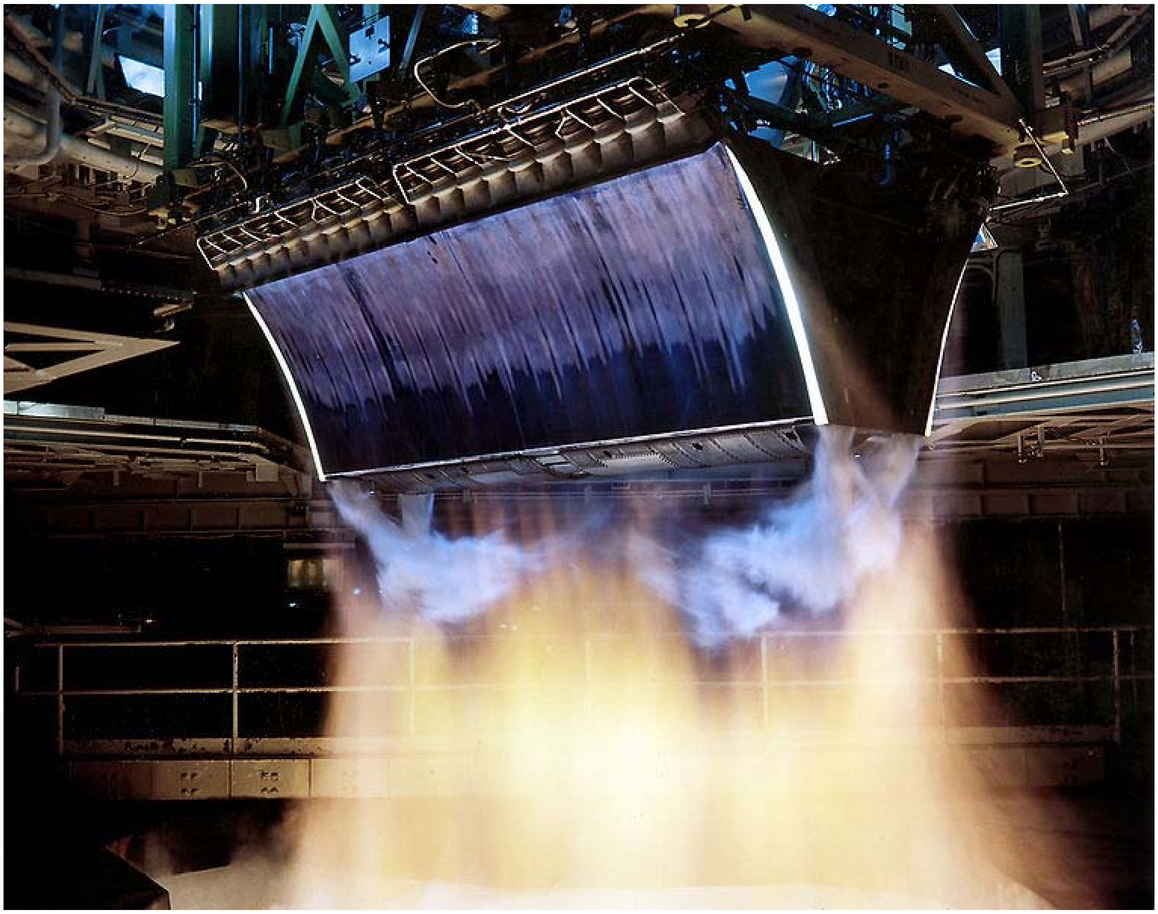
On July 2, 1996, NASA selected Lockheed Martin Skunk Works of Palmdale, California, to design, build, and test the X-33 experimental vehicle for the RLV program. Lockheed Martin's design concept for the X-33 was selected over competing designs from Boeing and McDonnell Douglas. Boeing featured a Space 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.

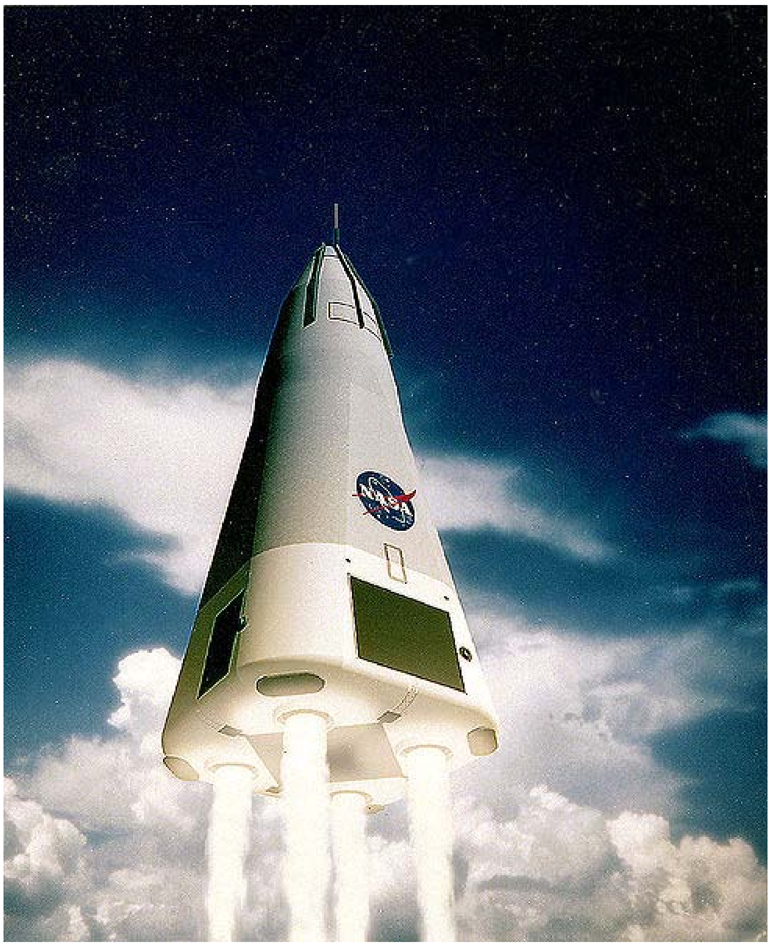
Lockheed Martin has been testing a new and different 1/5 scale rocket described to be similar in capabilities and design, known now simply as a "Space Reusable Launch Vehicle". Two tests were conducted secretly at the Spaceport America in New Mexico. The first on December 19, 2007 was billed as a complete 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 7

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.

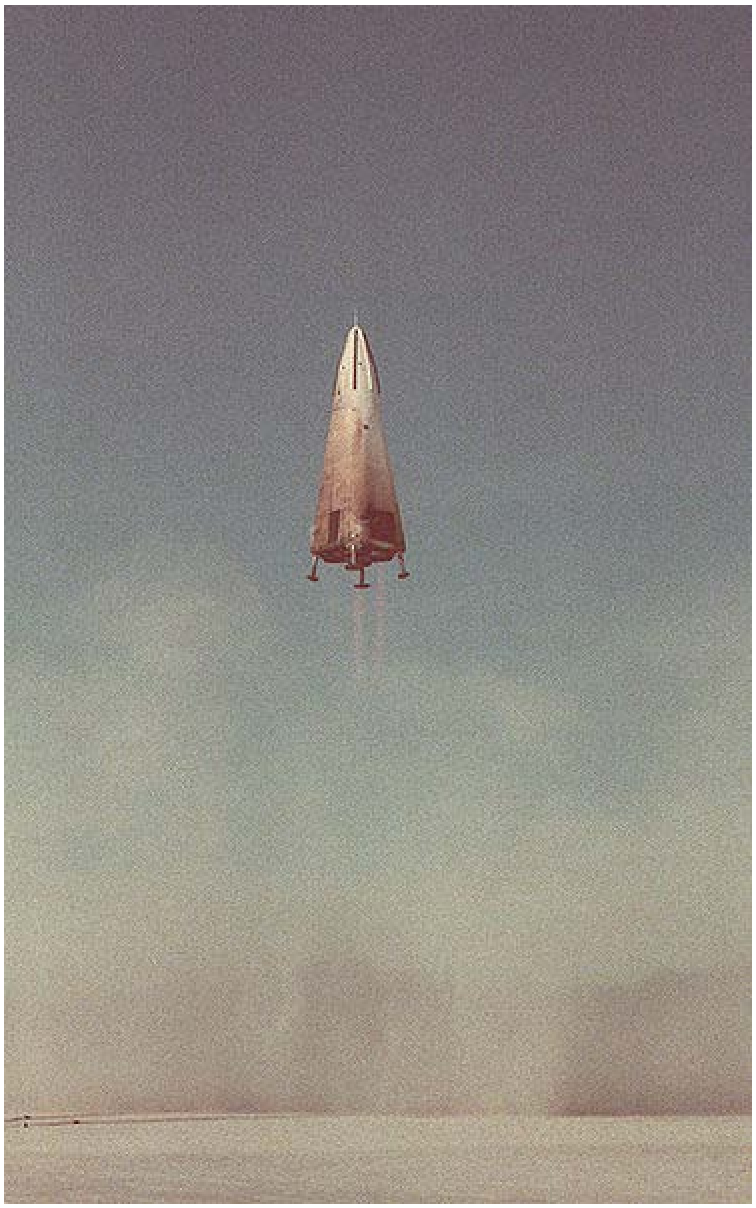
NASA agreed to take on the program at this point. In contrast to the original concept of the DC-X demonstrator, NASA applied a series of major upgrades to test new technologies. In particular, the oxygen tank was replaced by a lightweight (alloy 1460 equivalent of alloy 2219) Al-Li tank from Russia, 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 8

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.

Chapter 9

Reaction Engines Skylon

Skylon

The Skylon vehicle is an aircraft designed to reach orbit.

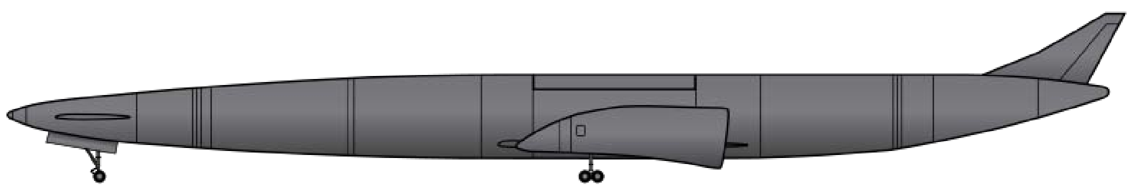
Role	Re-usable Spaceplane
National origin	UK/multinational
Designed by	Reaction Engines Limited
Status	Research and development
Program cost	Projected to be £7.1 billion (~$12 billion est. 2004)
Unit cost	£190 million (projected)
Developed from	**Horizontal Take-Off and Landing** (HOTOL) project

Skylon is a design for an unpiloted spaceplane by the British company, Reaction Engines Limited (REL). It uses a combined-cycle, air-breathing jet engine to reach orbit in a single stage. A fleet of vehicles is envisaged; the design is aiming for re-usability up to 200 times. In paper studies, the costs per kilogram of payload are hoped to be lowered from the current £15,000/kg to £650/kg (as of 2011), including the costs of research and development (R&D), with costs expected to fall much more over time after the initial expenditures have amortised. The cost of the program has been estimated by the developer to be about $12 billion.

The vehicle design is for a hydrogen-powered aircraft that would take off from a conventional runway, and accelerate to Mach 5.4 at 26 km using atmospheric air before switching the engines to use the internal liquid oxygen (LOX) supply to take it to orbit. It would then release its payload, which can weigh up to 12-tonnes, and re-enter the atmosphere. The payload would be carried in a standardised payload container or passenger compartment.

During re-entry the relatively light vehicle would fly back through the atmosphere and land back at the runway, with its skin protected by a ceramic composite. It would then undergo inspection and any necessary maintenance and, if the design goal is achieved, be able to fly again within two days. As of 2010, only a small portion of the funding required to develop and build Skylon has been secured. The research and development work on the SABRE engine design is proceeding under a small European Space Agency (ESA) grant. In January 2011, REL submitted a proposal to the British Government to request additional funding for the Skylon project.

Technology and innovations



The Skylon spaceplane is designed as a two-engine, "tailless" aircraft, which is fitted with a steerable canard.

Structure of the fuselage

The fuselage of Skylon is expected to be carbon fibre space frame; a light and strong structure that supports the weight of the aluminium fuel tanks and to which the ceramic skin is attached. Multiple layers of reflective foil thermal insulation fill the spaces of the frame.

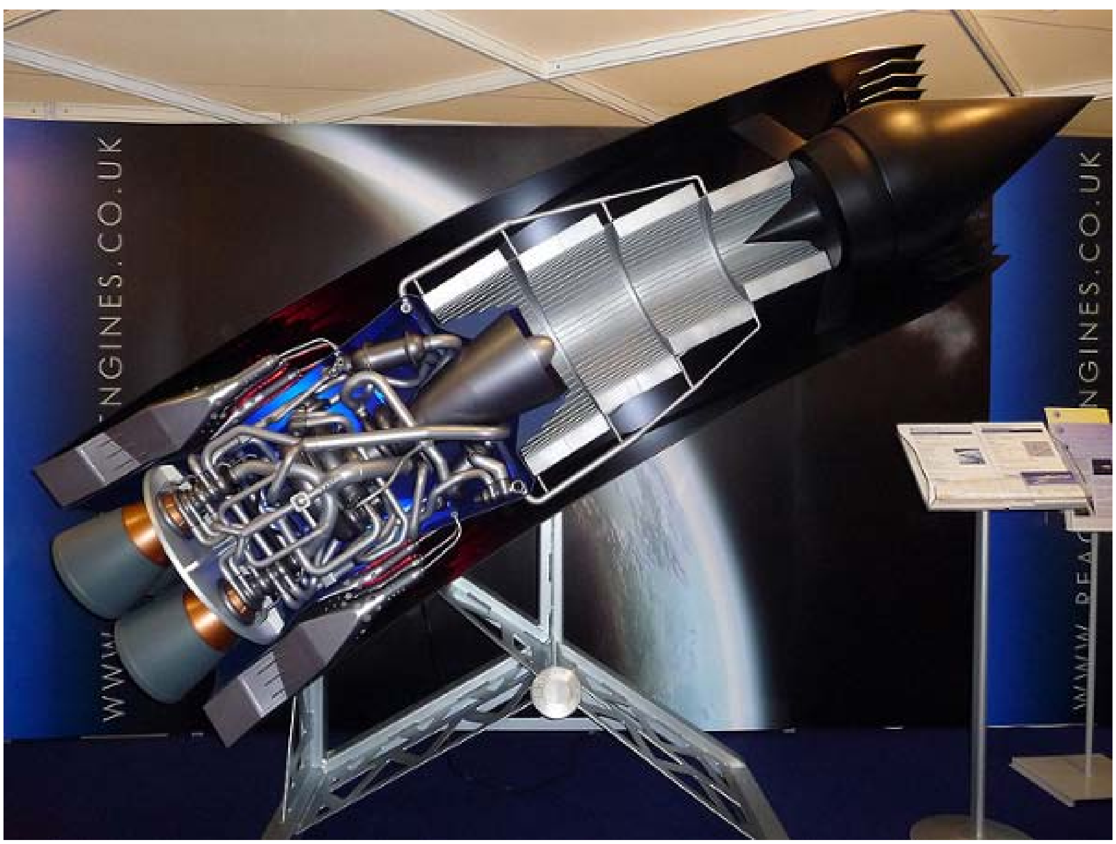
The currently proposed Skylon model C2 will be a physically large vehicle, with a length of 82 metres (269 ft) and a diameter of 6.3 metres (21 ft). Because it will use a low-density liquid hydrogen fuel, a great volume is needed to contain enough energy to reach orbit. The propellant is intended to be kept at low pressure to minimise stress; a vehicle that is both large and light has an advantage during atmospheric reentry compared to other vehicles due to a low ballistic coefficient. Because of the low ballistic coefficient, Skylon would be slowed at higher altitudes where the air is thinner. As a result, the skin of the vehicle would only reach 1100 Kelvin (K). In contrast, the smaller Space Shuttle is heated to 2000 K on its leading edge, and so employs an extremely heat-resistant but extremely fragile silica thermal protection system. The Skylon design need not use such a system, instead opting for using a far thinner yet durable reinforced ceramic skin.

However, due to turbulent flow around the wings during re-entry, some parts of Skylon would need to be actively cooled.

Skylon would employ a highly-loaded tightly spaced wheel assembly, to save weight and also interior space when the wheels are retracted into the fuselage. Because this wheel design distributes the weight of the aircraft and the force of its landing over a smaller area of the runway, it would require a specially strengthened runway. It will possess a retractable undercarriage with high pressure tires and water cooled brakes. If problems were to occur just before a take-off the brakes would be applied to stop the vehicle, the water boiling away to dissipate the heat. Upon a successful take-off, the water would be jettisoned, thus reducing the weight of the undercarriage by many tons. During landing, the empty vehicle would be far lighter, and hence the water would be unneeded. The payload fraction would be significantly greater than normal rockets and the vehicle should be fully reusable (200 times or more).

SABRE Engines

One of the significant features of the Skylon design is the engine, called SABRE. The engines are designed to operate much like a conventional jet engine at up to around Mach 5.5 (1700 m/s), 26 kilometres (16 mi) altitude, beyond which the air inlet closes and the engine operates as a highly efficient rocket to orbital speed.



The Reaction Engines Limited Synergistic Air-Breathing Rocket Engine (SABRE) engine is a key component of the Skylon spaceplane.

The proposed engine for the vehicle is not a scramjet, but a jet engine running combined cycles of a precooled jet engine, rocket engine and ramjet. Originally the key technology for this type of precooled jet engine did not exist as it required a heat exchanger that was ten times lighter than the state of the art. Research conducted since then has achieved the necessary performance.

Operating an air-breathing jet engine at up to Mach 5.5 is difficult. Several previous engines proposed by other designers have been good as jet engines but performed poorly as rockets. This engine design aims to be a good jet engine within the atmosphere, as well as being an excellent rocket engine outside. The problem with operating at Mach 5.5 has been that the air coming into the engine heats up as it is compressed into the engine, which can cause the engine to overheat. Attempts to avoid these issues typically make the engine much heavier (scramjets/ramjets) or greatly reduce the thrust (conventional turbojets/ramjets). In either case the end result is an engine that has a poor thrust to weight ratio at high speeds, resulting in an engine that is too heavy to assist much in reaching orbit.

The SABRE engine design aims to avoid this by using some of the liquid hydrogen fuel to cool the air at the inlet. The air is then used for combustion much like in a conventional jet. Because the air is cooled at all speeds, the jet can be built of light alloys and the weight is roughly halved. Additionally, more fuel can be burnt at high speed. Beyond Mach 5.5, the air would still be unusably hot despite the cooling, so the air inlet closes and the engine relies solely on on-board liquid oxygen and hydrogen fuel as in a normal rocket.

Because the engine uses the atmosphere as reaction mass at low altitude, it will have a high specific impulse (around 2,800 seconds), and burn about one fifth of the propellant that would have been required by a conventional rocket. Therefore, it would be able to take off with much less total propellant than conventional systems. This, in turn, means that it doesn't need as much lift or thrust, which permits smaller engines, and allows conventional wings to be used. While in the atmosphere, using wings to counteract gravity drag is more fuel-efficient than simply expelling propellant (as in a rocket), again reducing the total amount of propellant needed.

"Single Stage to Orbit" capability

A vehicle that can fly to orbit without staging is known as single stage to orbit (SSTO). Proponents of SSTO claim that staging causes a number of problems such as being difficult, expensive or even impossible to recover, reuse and reassemble the parts and therefore believe that SSTO designs hold the promise of reducing the cost of space-flight.

The Skylon design aims to take off from its specially strengthened runway, fly into low earth orbit, re-enter the atmosphere, and land back on its runway like a conventional aeroplane, without staging, while being fully reusable.

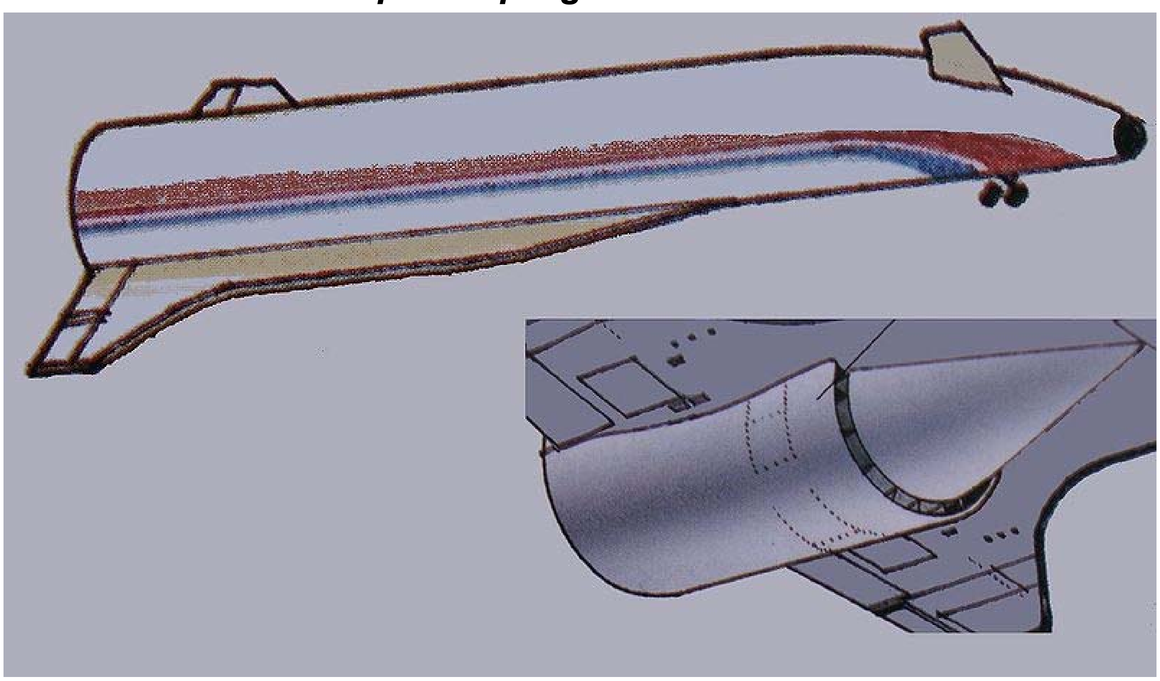
Payload bay

The payload bay of the Skylon C2 design is a cylinder 12.3 metres (40.4 ft) long and 4.6 metres (15 ft) in diameter. It is designed to be comparable with current payload dimensions, and yet able to support the containerization of payloads that Reaction Engines hopes for in the future. To an equatorial orbit, Skylon could deliver 12 tonnes (26,455 lb) to a 300 kilometres (186 mi) height or 10.5 tonnes (23,149 lb) to a 460 kilometres (286 mi) altitude. It could also launch 9.5 tonnes (20,944 lb) to the orbit of the International Space Station, when launching from the equator. Using interchangeable payload containers, Skylon could be fitted to carry satellites or fluid cargo into orbit, or, in a specialised habitation module, up to 30 astronauts in a single launch.

Current project status

As of 2010, the funding required to develop and build the entire craft has not yet been secured, and so current research and development work is focused on the engines, under an ESA grant of €1 million. In January 2011, REL submitted a proposal to the British Government requesting additional funding for the Skylon project.

Research and development programme



The Skylon was developed from the ill-fated British HOTOL project.

Skylon is based upon a previous project of Alan Bond, which was known as HOTOL. The development programme of HOTOL began in 1982, a time when space technology was moving towards reusable launch systems such as the American Space Shuttle. In conjunction with British Aerospace and Rolls Royce, a design emerged that proved highly promising, so much so that the British Government donated £2 million to further their work. However, in 1988, the Conservative government withdrew funding, and the development programme was terminated. Following this major setback, Alan Bond decided to set up his own company, Reaction Engines Limited, with the hope of continuing development with private funding.

After having secured funding, the design of the craft was revisited, undergoing a rigorous redesign throughout much of the 1990s. In the last decade, Reaction Engines has been working with the University of Bristol to develop the engines vital to the success of Skylon. The STRICT/STERN engines produced by this programme were deemed a great success. The next stage of development is to construct a full-sized working prototype of the SABRE Engine.

The differences between Skylon and its predecessor are numerous. For example, HOTOL was to have been launched from a rocket sled (to save weight), whereas Skylon uses a conventional retractable undercarriage. Skylon also uses a different engine design; the SABRE engine is expected to offer higher performance. Another issue that the Skylon design aims to circumvent was the intrinsically poor stability of HOTOL. The weight of the rear-mounted engine tended to make the HOTOL vehicle flip over mid-flight due to the centre of mass lying behind the centre of drag. Attempts to fix this problem ended up sacrificing much of the potential payload that the HOTOL vehicle could carry, and contributed to the failure of the project. Skylon would solve this by placing the engines at the end of the wings closer to the centre of the vehicle and thus moving the centre of mass forward, ahead of the centre of drag.

The complete Skylon project has a projected R&D cost of over $10 billion and will continue for another 7–10 years. In February 2009, the British National Space Centre (now the UK Space Agency) and ESA announced that they were partially funding work with €1 million Euros ($1.28 million dollars) on Skylon's engine to produce a demonstration engine by 2011.

The Technology Demonstration Programme will last approximately 2.5 years and will benefit from another €1 million from the ESA. This programme will take Reaction Engines Ltd from a Technology Readiness Level (TRL) of 2/3 up to 4/5. The former UK Minister for Science and Innovation in 2009, Lord Drayson, commented on Skylon in a speech: "This is an example of a British company developing world-beating technology with exciting consequences for the future of space."

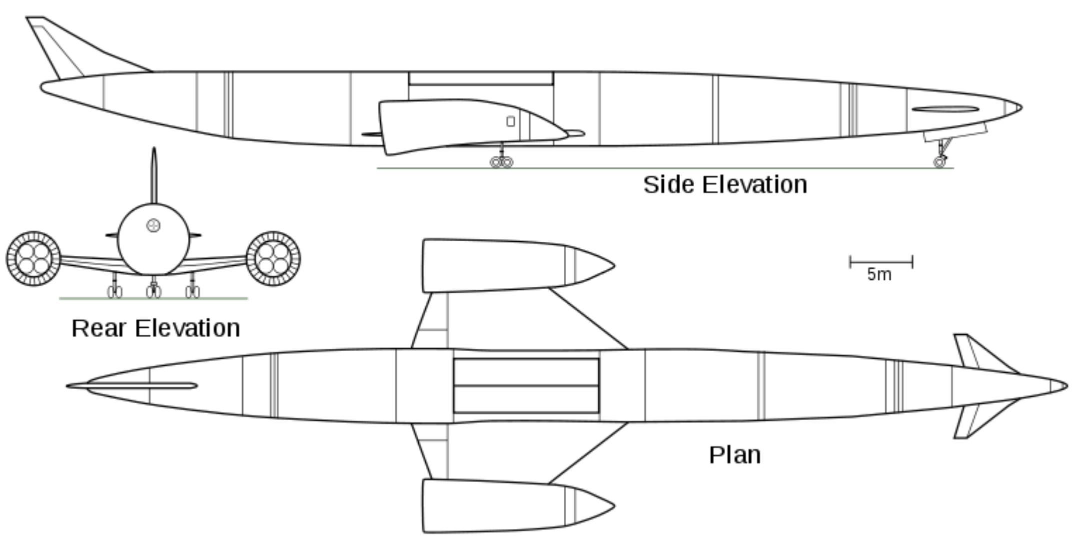
Economics and political will

Once operative, Skylon could potentially lower satellite costs from the current £15,000/kg to £650/kg, according to evidence submitted to the UK parliament by Reaction Engines Ltd. However, funding and support from the British government has not been easy to establish.

Request for funding from the British government was undertaken in 2000, with a proposal that could have offered a large potential return on investment. The request was not taken up at that time. Subsequent discussions with the British National Space Centre led to agreement in 2009 on a co-funding agreement between BNSC, ESA and REL to continue technology development for the SABRE engine. Testing of the SABRE engine will commence in June 2011 with the start of Phase 3 in the Skylon development programme. Pre-orders are expected in the 2011–2013 time frame coinciding with the formation of the manufacturing consortium. According to David Willetts, the UK Minister of State for Universities and Science:

"The European Space Agency is funding proof of concept work for Skylon from UK contributions. This work is focusing on demonstrating the viability of the advanced British engine technology that would underpin the project. Initial work will be completed in mid 2011 and if the trial is successful, we will work with industry to consider next steps."

Specifications



Skylon C2

Data from the Skylon User Manual

General characteristics

- **Crew:** automated
- **Capacity:** 40
- **Length:** 83.3 m (273 ft)
- **Wingspan:** 25.4 m (82 ft)
- **Height:** ()
- **Empty weight:** 53,000 kg (120,000 lb)

- **Loaded weight:** 345,000 kg (760,000 lb)
- **Powerplant:** 2× SABRE synergistic combined cycle jet engine
  - **Dry thrust:** 2,700 LT; 3,000 ST (2,700 LT; 3,000 ST) each
  - **Thrust with afterburner:** 3,500 LT; 4,000 ST (3,500 LT; 4,000 ST) each

Performance

- **Maximum speed:** orbital
- **Range:** orbital ()
- **Service ceiling:** 26,000 m air breathing, >200 km exoatmospheric (85,000 ft air breathing, >124 mi exoatmospheric)
- **Thrust/weight:** ~1.2 – 3 at burnout (~0.768 atmospheric)SSTO

- Fuselage diameter: 6.75 m (22.15 ft)
- Maximum payload mass: 12,000 kg (26,000 lb)
- Specific impulse: 3560 s (35 kN·s/kg) atmospheric, 450 s (4.4 kN·s/kg) exoatmospheric
- SABRE engine thrust/weight ratio: up to 14 atmospheric

Chapter 10

SpaceShipOne

SpaceShipOne is a retired suborbital air-launched spaceplane that completed the first manned private spaceflight in 2004. That same year, it won the $10 million Ansari X Prize and was immediately retired from active service. Its mothership was named "White Knight". Both craft were developed and flown by Mojave Aerospace Ventures, which was a joint venture between Paul Allen and Scaled Composites, Burt Rutan's aviation company. Allen provided the funding of approximately $25 million.

Rutan has indicated that ideas about the project began as early as 1994 and the full-time development cycle time to the 2004 accomplishments was about three years. SpaceShipOne's first official spaceflight, known as flight 15P, was piloted by Mike Melvill. A few days before that flight, the Mojave Air and Space Port was licensed as the USA's first commercial spaceport. A few hours after that flight, Melvill became the first licensed U.S. commercial astronaut. The overall project name was "Tier One" which has evolved into Virgin Galactic Tier 1b with a goal of taking a successor ship's first passengers into space within the next few years.

Development and winning the X Prize

(L to R) Marion Blakely (FAA), Mike Melvill; Richard Branson, Burt Rutan, Brian Binnie, and Paul Allen reflect on a mission accomplished (October 4, 2004)

SpaceShipOne was developed by Mojave Aerospace Ventures (a joint venture between Paul Allen and Scaled Composites, Burt Rutan's aviation company, in their Tier One program), without government funding. On June 21, 2004, it made the first privately funded human spaceflight. On October 4, it won the $10 million Ansari X Prize, by reaching 100 kilometers in altitude twice in a two-week period with the equivalent of three people on board and with no more than ten percent of the non-fuel weight of the spacecraft replaced between flights. Development costs were estimated to be $25 million, funded completely by Paul Allen.

During its test programme, SpaceShipOne set a number of important "firsts", including first privately funded aircraft to exceed Mach 2 and Mach 3, first privately funded manned spacecraft to exceed 100km altitude, and first privately funded reusable manned spacecraft.

SpaceShipOne is an experimental air-launched rocket-powered aircraft with suborbital flight capability that uses a hybrid rocket motor. The design features a unique "feathering" atmospheric reentry system where the rear half of the wing and the twin tail booms folded upward along a hinge running the length of the wing; this increased drag while remaining stable. The achievements of SpaceShipOne are more comparable to the X-15 than orbiting spacecraft like the Space Shuttle. Accelerating a spacecraft to orbital speed requires more than 60 times as much energy as accelerating it to Mach 3.

SpaceShipOne connected to its mother ship White Knight

SpaceShipOne is registered with the FAA as **N328KF**. *N* is the prefix for US-registered aircraft; *328KF* was chosen by Scaled Composites to stand for 328 K (abbreviation for 1000) feet (about 100 kilometers), the officially designated edge of space. The original choice of registry number, **N100KM**, was already taken. N328KF is registered as a glider, reflecting the fact that most of its independent flight is unpowered.

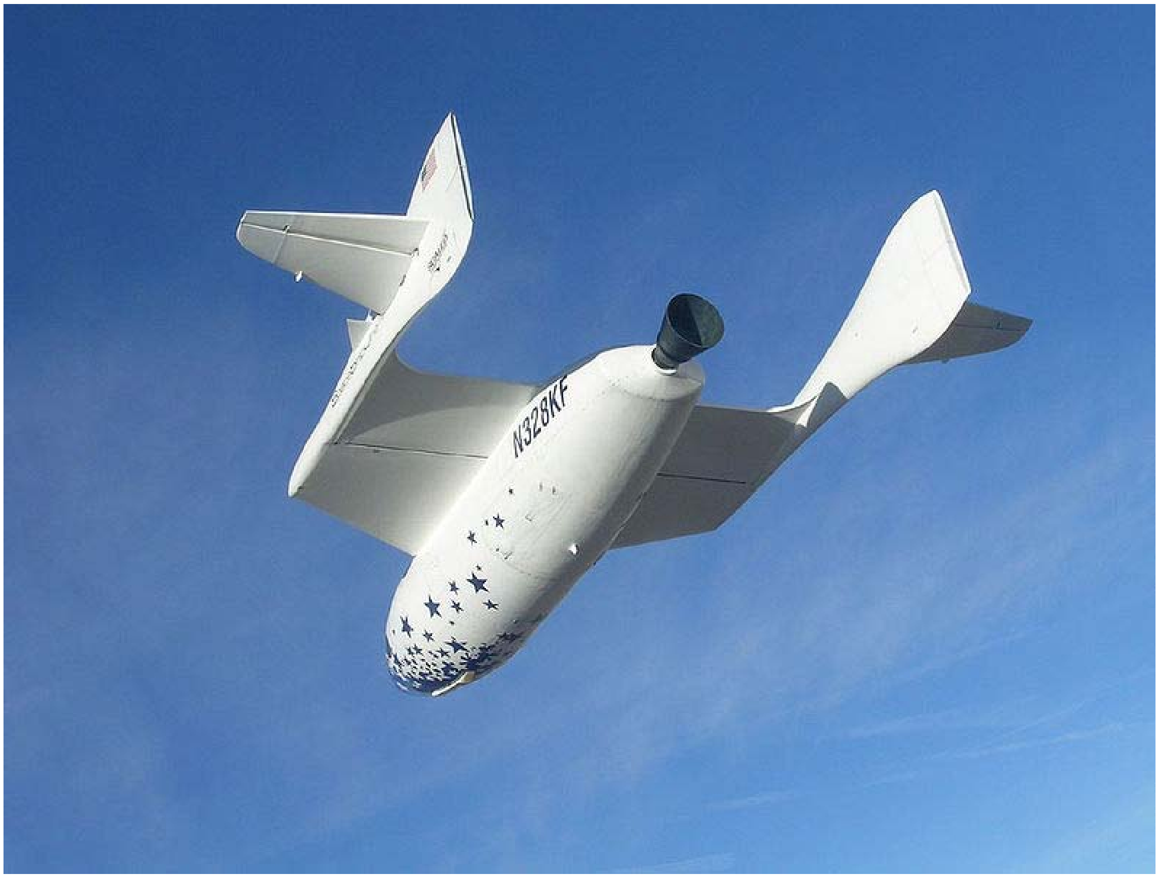
SpaceShipOne's first flight, 01C, was an unmanned captive carry flight test on May 20, 2003. Glide tests followed, starting with flight 03G on August 7, 2003. Its first powered flight, flight 11P, was made on December 17, 2003, the 100th anniversary of the first powered flight.

On April 1, 2004, Scaled Composites received the first license for sub-orbital rocket flights to be issued by the US Office of Commercial Space Transportation. This license permitted the company to conduct powered test flights over the course of one year. On June 17, 2004, Mojave Airport reclassified itself (part-time) as the Mojave Spaceport.

Flight 15P on June 21, 2004, was SpaceShipOne's first spaceflight, and the first privately funded human spaceflight. There were a few control issues, but these were resolved prior to the Ansari X PRIZE flights that followed, with flight 17P on October 4, 2004, winning the prize.

The SpaceShipOne Team was awarded the Space Achievement Award by the Space Foundation in 2005.

Flights



SpaceShipOne in flight.

Cockpit of WhiteKnight in flight, EFIS display edited to look like SpaceShipOne.

All of the flights of SpaceShipOne were from the Mojave Airport Civilian Flight Test Center. Flights were numbered, starting with flight 01 on May 20, 2003. One or two letters are appended to the number to indicate the type of mission. An appended **C** indicates that the flight was a captive carry, **G** indicates an unpowered glide, and **P** indicates a powered flight. If the actual flight differs in category from the intended flight, two letters are appended: the first indicating the intended mission and the second the mission actually performed.

In the table below, the "top speed" reported is the Mach number at burn-out (the end of the rocket burn). This is not an absolute speed.

SpaceShipOne flights

Flight	Date	Top speed	Altitude	Duration	Pilot
01C	May 20, 2003	Mach 0.53	14.63 km	1 h 48 min	unmanned
02C	July 29, 2003		14 km	2 h 06 min	Mike Melvill
03G	August 7, 2003	278 km/h	14.33 km	19 min 00 s	Mike Melvill
04GC	August 27, 2003	370 km/h	14 km	1 h 06 min	Mike Melvill
05G	August 27, 2003	370 km/h	14.69 km	10 min 30 s	Mike Melvill

06G	September 23, 2003	213 km/h	14.26 km	12 min 15 s	Mike Melvill
07G	October 17, 2003	241 km/h	14.08 km	17 min 49 s	Mike Melvill
08G	November 14, 2003	213 km/h	14.42 km	19 min 55 s	Peter Siebold
09G	November 19, 2003	213 km/h	14.72 km	12 min 25 s	Mike Melvill
10G	December 4, 2003	213 km/h	14.75 km	13 min 14 s	Brian Binnie
11P	December 17, 2003	Mach 1.2	20.67 km	18 min 10 s	Brian Binnie
12G	March 11, 2004	232 km/h	14.78 km	18 min 30 s	Peter Siebold
13P	April 8, 2004	Mach 1.6	32.00 km	16 min 27 s	Peter Siebold
14P	May 13, 2004	Mach 2.5	64.43 km	20 min 44 s	Mike Melvill
15P	June 21, 2004	Mach 2.9	100.124 km	24 min 05 s	Mike Melvill
16P	September 29, 2004	Mach 2.92	102.93 km	24 min 11 s	Mike Melvill
17P	October 4, 2004	Mach 3.09	112.014 km	23 min 56 s	Brian Binnie

The flights were accompanied by two chase planes; an Extra 300 owned and flown by Chuck Coleman, and a Beechcraft Starship.

Astronauts

The SpaceShipOne pilots came from a variety of aerospace backgrounds. Mike Melvill is a test pilot, Brian Binnie is a former Navy pilot, and Doug Shane and Peter Siebold are engineers at Scaled Composites. They qualified to fly SpaceShipOne by training on the Tier One flight simulator and in White Knight and other Scaled Composites aircraft.

Specifications

Rear view

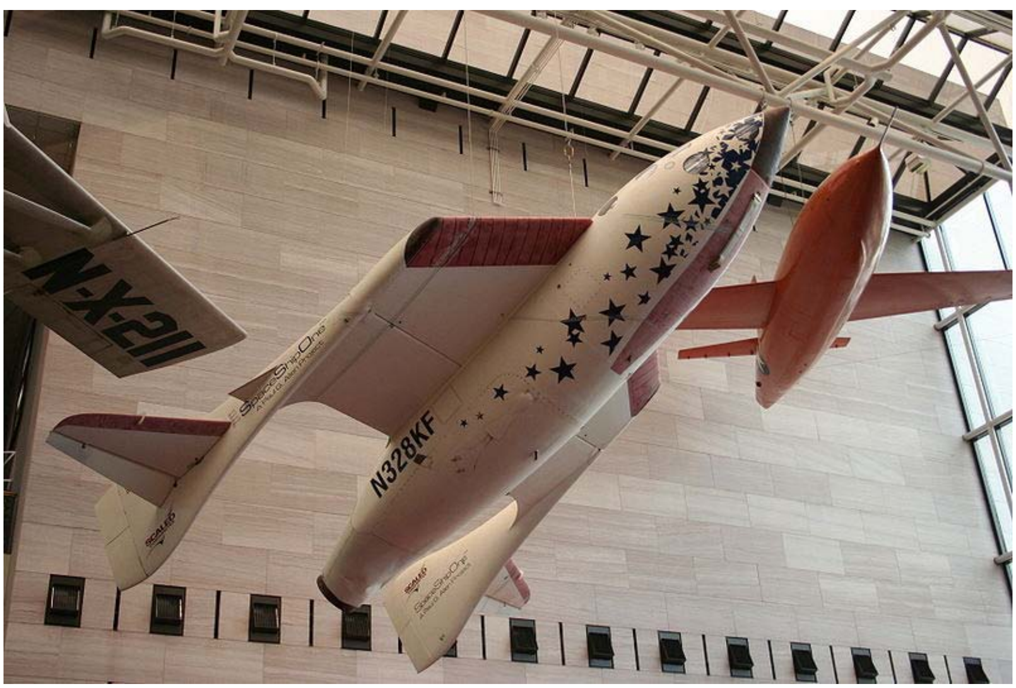
General characteristics

- **Crew:** one, pilot
- **Capacity:** 2 passengers
- **Length:** 16 ft 5 in (8,05 m)
- **Wingspan:** 16 ft 5 in (8,05 m)
- **Height:** ()
- **Wing area:** 161.4 ft² (15 m²)
- **Empty weight:** 2,640 lb (1,200 kg)
- **Loaded weight:** 7,920 lb (3,600 kg)
- **Powerplant:** 1× N2O/HTPB SpaceDev Hybrid rocket motor, 7,500 kgf (74 kN)
- **I_{sp}:** 250 s (2450 Ns/kg)
- **Burn time:** 87 seconds
- **Aspect Ratio:** 1.6

Performance

- **Maximum speed:** Mach 3.09 (2,170 mph, 3,518 km/h)
- **Range:** 35 nm (40 mi, 65 km)
- **Service ceiling:** 367,360 ft (112,000 m)
- **Rate of climb:** 82,000 ft/min (416.6 m/s)
- **Wing loading:** 49.07 lb/ft² (240 kg/m²)
- **Thrust/weight:** 2.08

Retirement



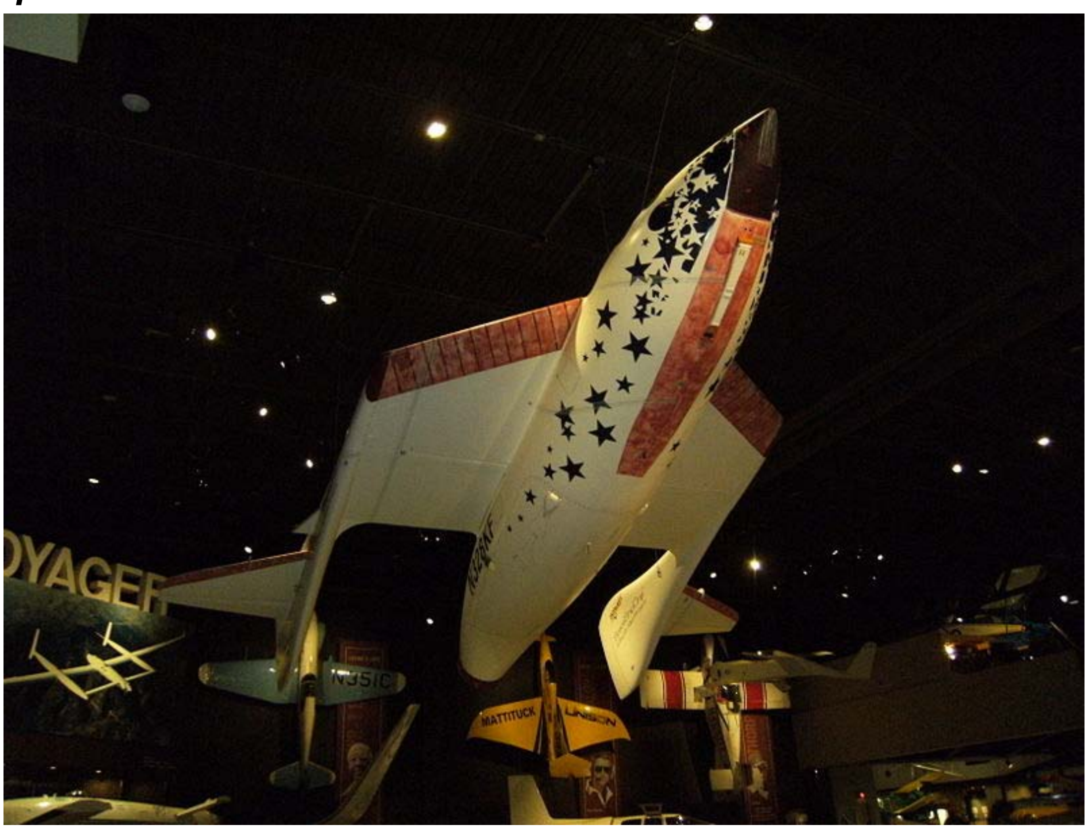
SpaceShipOne now hangs in the National Air and Space Museum in Washington D.C.

SpaceShipOne's spaceflights were watched by large crowds at Mojave Spaceport. A fourth suborbital flight, Flight 18P, was originally scheduled for October 13, 2004. However, Burt Rutan decided not to risk damage to the historic craft, and cancelled it and all future flights.

On July 25, 2005 SpaceShipOne was taken to the Oshkosh Airshow in Oshkosh, Wisconsin. After the airshow, Mike Melvill and crew flew the White Knight, carrying SpaceShipOne, to Wright-Patterson Air Force Base in Dayton, Ohio, where Mike spoke to a group of about 300 military and civilian personnel. Later in the evening, Mike gave a presentation at the Dayton Engineers Club, entitled "Some Experiments in Space Flight", in honor of Wilbur Wright's now famous presentation to the American Society of Mechanical Engineers in 1901 entitled "Some Experiments in Flight." The White Knight then transported SpaceShipOne to the Smithsonian Institution's National Air and Space Museum to be put on display. It was unveiled on Wednesday October 5, 2005 in the Milestones of Flight gallery and is now on display to the public in the main atrium between the Spirit of St. Louis and the Bell X-1.

SpaceShipOne became a popular model rocket in 2004. Estes Industries currently offers several flying model rockets of SpaceShipOne. A piece of SpaceShipOne's carbon fiber material was launched aboard the New Horizons mission to Pluto in 2006.

Replica



SpaceShipOne Replica in normal configuration

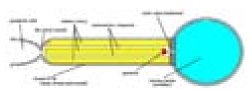
A year after its appearance in the Oshkosh Airventure airshow, the Experimental Aircraft Association featured a full-scale replica of the spacecraft in a wing of its museum which housed other creations of Burt Rutan. Using the same fiberglass molds as the original, it was so exact in its replication - despite not having any doors or interior - that it was dubbed "Serial 2 Scaled" by Scaled Composites. Each and every painstaking detail in its appearance was matched, down to the N328KF registration number on its fuselage. It is so precise that, during a video presentation held every hour in the museum, it can display the two different modes of its 'feathering' ability, albeit through the aid of pulleys and wires (there is no machinery in the replica).

Another full-scale replica of SpaceShipOne hangs in the rotunda of the William Thomas Terminal at Meadows Field Airport in Bakersfield and a third is on display in the Mojave Spaceport's Legacy Park alongside the original Roton Atmospheric Test Vehicle.

Future efforts

With the success of Tier One meeting its project goals, a successor project started in 2004 was Virgin Galactic Tier 1b. The successor ship names SpaceShipTwo and White Knight Two. The name of the joint venture between Virgin Group and Scaled Composites is called The Spaceship Company, with a goal of carrying passengers under the name Virgin Galactic spaceliner with an initial target of a commercial fleet of five spacecraft.

In August 2005, Virgin Galactic stated that if the upcoming suborbital service with SpaceShipTwo is successful, the follow-up SpaceShipThree.



Hybrid rocket engine detail of SpaceShipOne (more information).

SpaceShipOne landing after its June 21, 2004 space flight (Flight 15P)

SpaceShipOne in the National Air and Space Museum in Washington D.C. with the Spirit of Saint Louis and Bell X-1 "Glamorous Glennis"

Chapter 11

Tether Propulsion

Artist's conception of satellite with a tether

Tether propulsion systems are proposals to use long, very strong cables (known as tethers) to change the velocity of spacecraft and payloads. The tethers may be used to initiate launch, complete launch, or alter the orbit of a spacecraft. Spaceflight using this form of spacecraft propulsion may be significantly less expensive than spaceflight using rocket engines.

Tethers are kept straight by either rotating end for end, with very high tips speeds (several km/s), or by the difference in the strength of gravity over their length (tidal stabilisation). Tethers require strong, light materials. Some current tether designs use crystalline plastics such as ultra high molecular weight polyethylene, aramid or carbon fiber. A possible future material would be carbon nanotubes, which have an estimated tensile strength between 140 and 177 GPa (20.3-25.6 million psi), and a proven tensile strength in the range 50-60 GPa.

A **momentum exchange tether** is a rotating tether that would grab a spacecraft and then release it at later time. Doing this can transfer momentum and energy from the tether to and from the spacecraft with very little loss; this can be used for orbital manoeuvring. A rotating momentum exchange tether is known as a **bolo**.

Another type of tether is an **electrodynamic tether**, this is a conductive tether that carries a current that can generate thrust or drag from a planetary magnetic field, in much the same way as an electric motor.

History of tether propulsion

Some of the earliest writings on space tethers can be found in the work of Tsiolkovsky. He proposed a tower so tall that it reached into space, held there by the rotation of the Earth. However, there was no realistic way to build it.

Later, another Russian, Yuri Artsutanov, wrote in greater detail about a tensile cable to be deployed from a geosynchronous satellite in Komsomolskaya Pravda (July 31, 1960); downwards towards the ground, and upwards away; keeping the cable balanced.

Jerome Pearson explored synchronous tethers further, and in particular analysed the lunar elevator that can go through the L1 and L2 points.

Hans Moravec and Robert L. Forward investigated the physics of synchronous and non synchronous tethers, including space elevators and performed detailed simulations of tapered tethers that could pick objects off and place objects onto the Moon, Mars and other planets, with little, or even a net gain of energy.

More recently Brad Edwards has done a very great deal to popularise the subject again in the scientific community, and it is now an area of active research.

Construction

To achieve maximum performance and low cost, tethers need to be made of materials with the combination of high tensile strength and low density. Depending on the type of tether, the design equations describe the material by one of three typical quantities.

Space elevator equations typically use a ‘characteristic length’ (L_c). L_c is also known as its 'self-support length' and is the length of untapered cable it can support in a constant 1*g* gravity field. $\mathbf{L_c=\sigma/\rho g}$, where σ is the stress limit (in pressure units) and ρ is the density of the material.

Hypersonic skyhook equations use the material’s ‘specific velocity’ which is equal to the maximum tangential velocity a spinning hoop can attain without breaking. $\mathbf{V_s=\sqrt{(\sigma/\rho)}}$.

Finally, for rotating tethers (rotovators) the value used is the material’s ‘characteristic velocity’ which is the maximum tip velocity a rotating untapered cable can attain without breaking. $\mathbf{V_c=\sqrt{(2\sigma/\rho)}}$. The characteristic velocity equals the specific velocity multiplied by the square root of two.

These values are used in equations similar to the rocket equation and are analogous to specific impulse or exhaust velocity. The higher these values are, the more efficient and lighter the tether can be in relation to the payloads that they can carry. Eventually however, the mass of the tether propulsion system will be limited at the low end by other factors such as momentum storage.

Building materials

Materials proposed include Kevlar, ultra high molecular weight polyethylene, carbon nanotubes, M5 fiber, and diamond.

One material that has great potential is M5 fiber. This is a synthetic fiber that is lighter than Kevlar or Spectra. According to Pearson, Levin, Oldson, and Wykes in their article "The Lunar Space Elevator," an M5 ribbon 30 mm wide and 0.023 mm thick, would be able to support 2000 kg on the lunar surface (2005). It would also be able to hold 100 cargo vehicles, each with a mass of 580 kg, evenly spaced along the length of the elevator. Other materials that could be used are T1000G carbon fiber, Spectra 2000, or Zylon. All of these materials have breaking lengths of several hundred kilometers under 1*g* (10 m/s²).

Potential tether/elevator materials

Material	Density ρ (kg/m³)	Stress Limit σ (GPa)	Char. Length $L_c=\sigma/\rho g$, (km)	Specific Velocity $V_s=\sqrt{(\sigma/\rho)}$, (km/s)	Char. Velocity $V_c=\sqrt{(2\sigma/\rho)}$, (km/s)
Single-wall carbon nanotubes (laboratory measurements)	2266	50	2200	4.7	6.6
Aramid, Polybenzoxazole (PBO) fiber ("Zylon")	1340	5.9	450	2.1	3.0
Toray carbon fiber (T1000G)	1810	6.4	360	1.9	2.7
Magellan honeycomb polymer M5 (planned values)	1700	9.5	570	2.4	3.3
Magellan honeycomb polymer M5 (existing)	1700	5.7	340	1.8	2.6
Honeywell extended chain polyethylene fiber (Spectra 2000)	970	3.0	316	1.8	2.5
DuPont Aramid fiber (Kevlar 49)	1440	3.6	255	1.6	2.2
Specialty materials e.g. silicon carbide	3000	5.9	199	1.4	2.0
Aluminium (6061 T6)	2700	0.276	10.	0.32	0.45

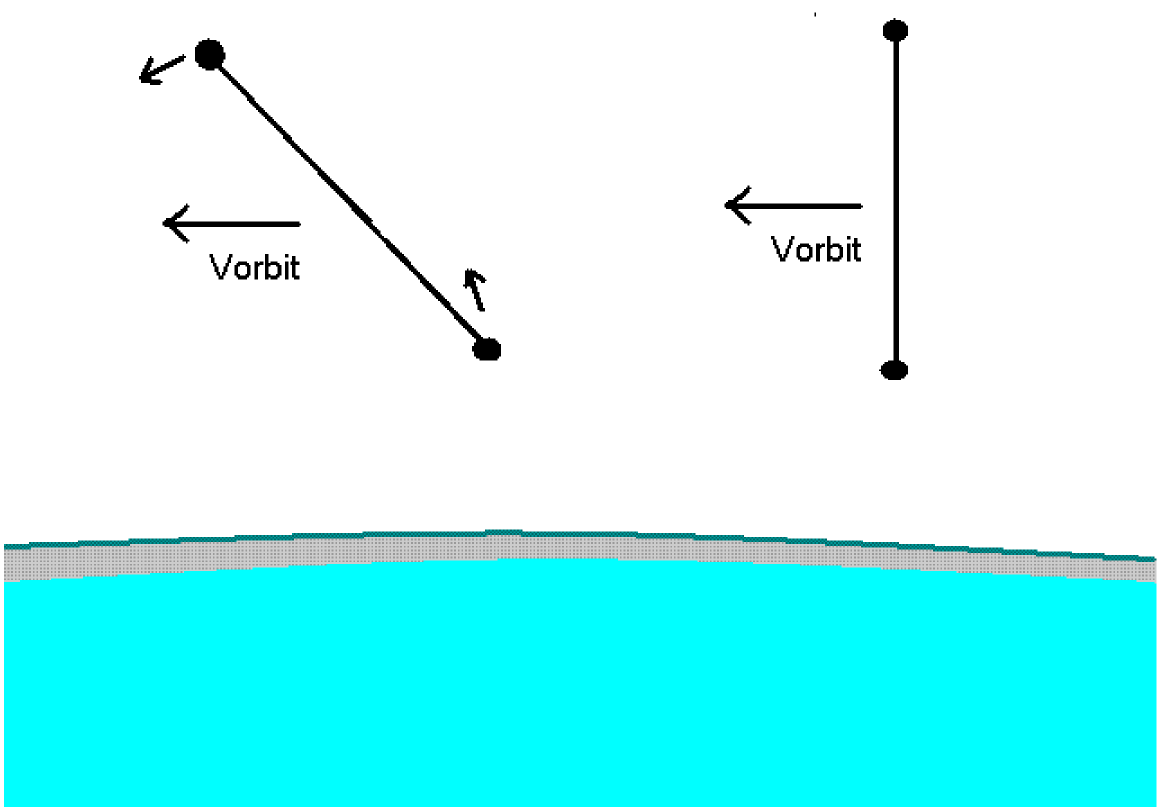
Shape

To exceed the self-support length the tether material can be tapered so that the cross-sectional area varies with the total load at each point along the length of the cable. Correct tapering ensures that the tensile stress at every point in the cable is exactly the same. For very demanding applications, such as an Earth Space Elevator, the tapering can result in excessive ratios of cable weight to payload weight.

In addition the cable must be constructed to withstand micrometeorites and space junk. This can be achieved with the use of redundant cables, such as the Hoytether; redundancy can ensure that it is very unlikely that multiple redundant cables would be damaged near the same point on the cable, and hence a very large amount of total damage can occur over different parts of the cable before failure occurs.

Tether systems

Tidal stabilization

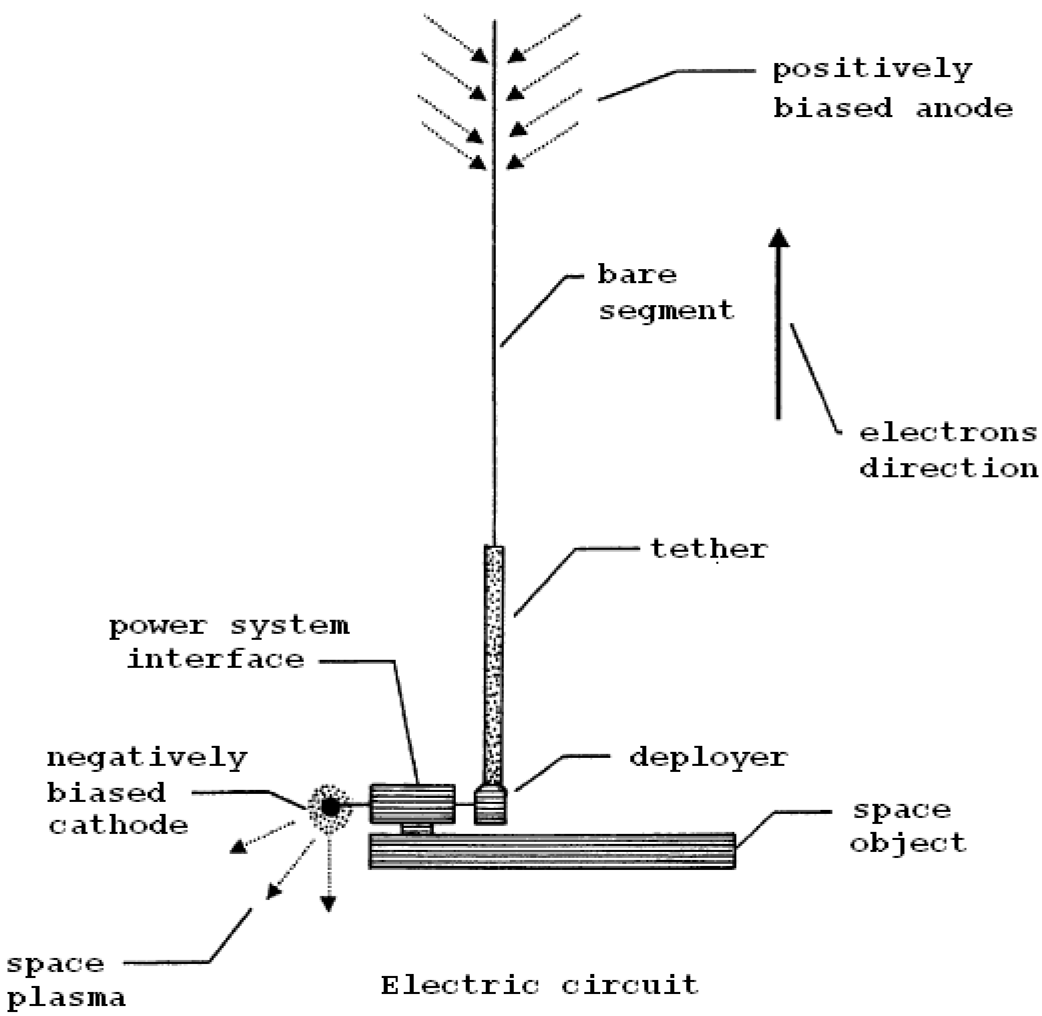


A rotating tether and a tidally stabilised tether in orbit

Gravity-gradient stabilization, also called "gravity stabilization" and "tidal stabilization", is cheap and reliable. It uses no electronics, rockets or fuel.

An attitude control tether has a small mass on one end, and a satellite on the other. Tidal forces stretch the tether between the two masses. There are two ways of explaining tidal forces: In one, the upper part of an object goes faster than its natural orbital speed, so centrifugal force stretches the object upwards. The lower part moves slower than the orbital speed, so it pulls down. Another way to explain tidal force is that the top of a tall object weighs less than the bottom, so they are pulled by different amounts. The "extra" pull on the "bottom" of the object stretches it out. On Earth, these are small effects, but in space, nothing opposes them.

The resulting tidal forces stabilize the satellite so that its long dimension points towards the planet it is orbiting. Simple satellites have often been stabilized this way, with tethers or mass distribution. A small bottle of fluid may be mounted in the spacecraft to damp pendulum vibrations with viscous friction of the fluid motion.



Electric circuit

Electrons flow through the conductive structure of the tether to the power system interface, where it supplies power to an associated load, not shown. (source: U.S. Patent 6,116,544, "Electrodynamic Tether And Method of Use".)

Electrodynamic tethers

In a strong planetary magnetic field such as around the Earth or Saturn, a conducting rotovator can be configured as an electrodynamic tether. This can either be used as a dynamo, which slows the tether and changes the angular momentum whilst generating electrical power, or alternatively, its orbital speed and/or angular momentum can be increased electrically from solar or nuclear power by running current through a wire that goes the length of the tether. Thus the tether can be used either to accelerate or brake an orbiting spacecraft.

In both cases the tether pushes against the planet, and thus the momentum gained or lost ultimately comes from the planet.

One complication to these techniques is that if the tether rotates, the direction of current must reverse (such as is the case in alternating currents).

Bolo

A rotating tether, or "bolo," is a high speed rotating tether, spinning so that the tips have a significant speed (~1–3 km/s).

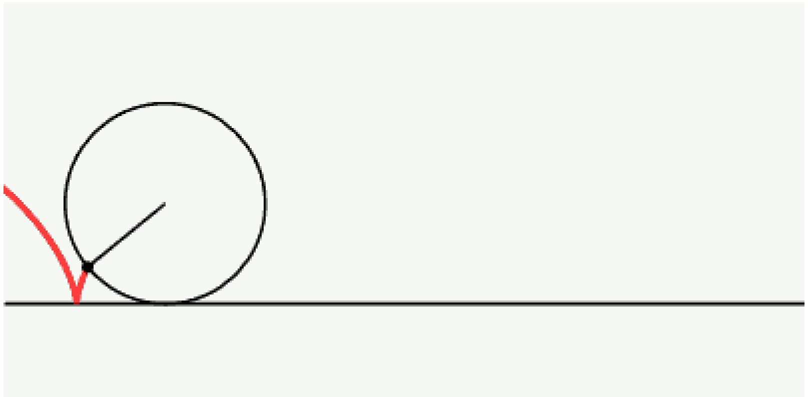
The maximum speed is limited by stress tolerance and safety factor of the tether but the speed can be greatly increased if it is of thicker cross-section in the middle and tapers and is lighter, thinner at the tips.

A spacecraft could rendezvous with one end of the tether, latch to it, and be accelerated by the tether's rotation. The tether and spacecraft would then separate at a later point when the spacecraft's velocity has been changed by the rotovator.

The momentum imparted to the spacecraft is not free. The tether's momentum and angular momentum is changed, and this costs energy that must be recouped. The idea is that the recharge could be done with some form of energy (for instance solar panels generating current for electromagnetic propulsion) that is far cheaper than multi-stage-rocket fuel.

Rotating tethers can also be used to slow down incoming spacecraft, thus increasing the rotational momentum. If the average momentum gained from inward traffic equals that imparted to outward traffic, there is no net energy cost, and thus nothing to recoup.

Rotovators



If the orbital velocity and the tether rotation rate are synchronized, in the rotovator concept the tether tip moves in a cycloid, and at the lowest point is momentarily stationary with respect to the ground. (Image from the cycloid article)

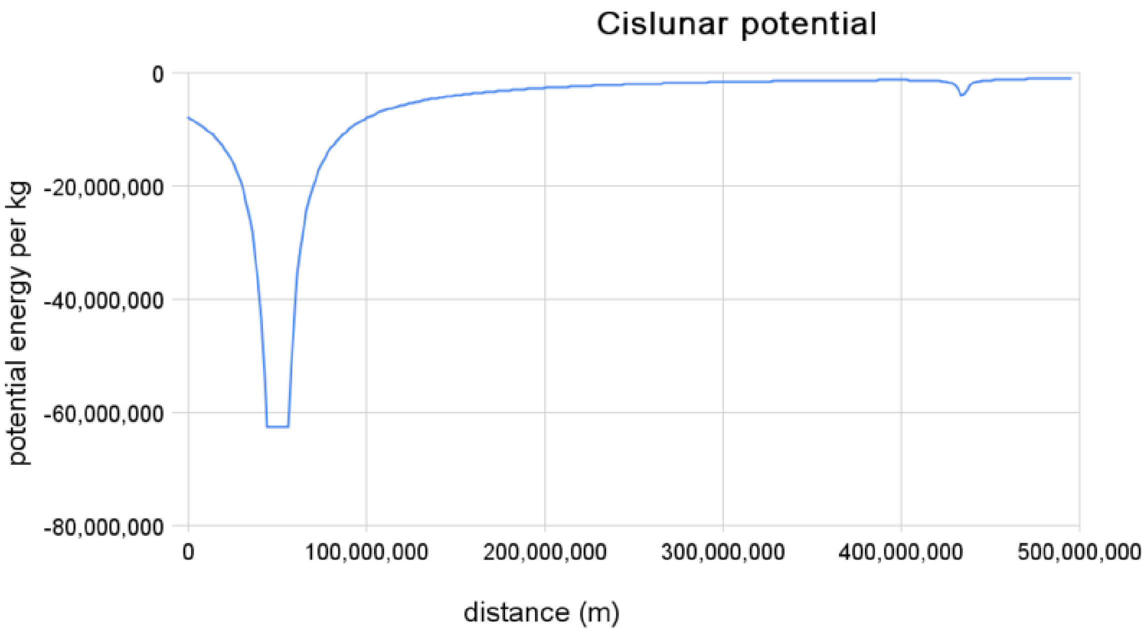
The word rotovator is a portmanteau derived from the words *rotor* and *elevator*. Rotovators would be momentum exchange tethers, with a retrograde motion of the tip closest to their parent body relative to the center of the tether.

Because the tips have a significant speed (typically 1–3 km/s), it can be possible in some cases to cancel the orbital speed such that the tips are stationary at their lowest point with respect to a planetary surface or lunar body. As described by Moravec, this is "a satellite that rotates like a wheel." The tip of the tether moves in approximately a cycloid, in which it is momentarily stationary with respect to the ground. In this case, a payload that is "grabbed" by a capture mechanism on the rotating tether during the moment when it is stationary would be picked up and lifted into orbit; and potentially could be released at the top of the rotation, at which point it is moving with a speed significantly greater than the escape velocity and thus could be released onto an interplanetary trajectory. (As with the bolo, discussed above, the momentum and energy given to the payload must be made up, either with a high-performance rocket engine, or with momentum gathered from payload moving the other direction.)

On bodies with an atmosphere, such as the Earth, the tether tip must stay above the dense atmosphere. On bodies with reasonably low orbital speed (such as the Moon and possibly Mars), a rotovator in low orbit can potentially touch the ground, thereby providing cheap surface transport as well as launching materials into cislunar space.

Cislunar transportation system

Although it might be thought that this requires constant energy input, it can in fact be shown to be energetically favourable to lift cargo off the surface of the Moon and drop it into a lower Earth orbit, and thus it can be achieved without any significant use of propellant, since the moon's surface is in a comparatively higher potential energy state.



Potential energy in the Earth Moon system. Because the moon has higher potential energy, tethers can work together to pick objects off the moon (the tiny dimple on the right), and place it closer to the Earth in LEO, taking essentially no propellant and even generating energy while doing so.

Rotovators can thus be charged by momentum exchange. Momentum charging uses the rotovator to move mass from a place that is "higher" in a gravity field to a place that is "lower". The technique to do this uses the Oberth effect, where releasing the payload when the tether is moving with higher linear speed, lower in a gravitational potential gives more specific energy, and ultimately more speed than the energy lost picking up the payload at a higher gravitational potential, even if the rotation rate is the same. For example, it is possible to use a system of two or three rotovators to implement trade between the Moon and Earth. The rotovators are charged by lunar mass (dirt, if exports are not available) dumped on or near the Earth, and can use the momentum so gained to boost Earth goods to the Moon. The momentum and energy exchange can be balanced with equal flows in either direction, or can increase over time.

Similar systems of rotovators could theoretically open up inexpensive transportation throughout the solar system.

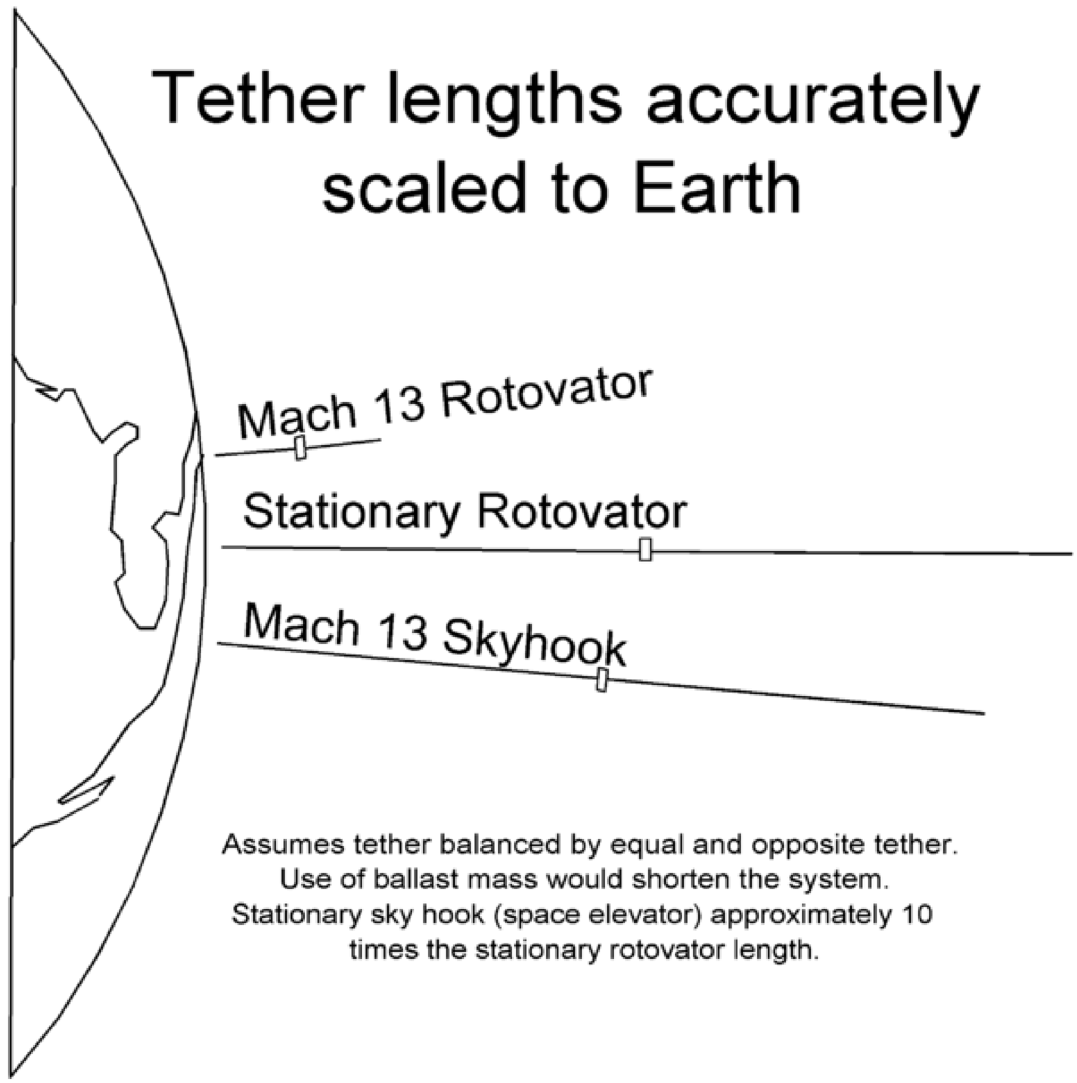
HASTOL — Earth launch assist rotovator

Unfortunately an Earth-to-orbit rotovator cannot be built from currently available materials since the thickness and tether mass to handle the loads on the rotovator would be uneconomically large. A "watered down" rotovator with two-thirds the rotational speed, however, would halve the centripetal acceleration stresses.

Therefore another trick to achieve lower stresses is that rather than picking up a cargo from the ground at zero velocity, a rotovator could pick up a moving vehicle and sling it into orbit. For example, a rotovator could pick up a Mach-12 aircraft from the upper atmosphere of the Earth and move it into orbit without using rockets, and could likewise catch such a vehicle and lower it into atmospheric flight. It is easier for a rocket to achieve the lower tip speed, so "Single Stage To Tether" has been proposed. One such is called the Hypersonic Airplane Space Tether Orbital Launch (HASTOL). Either air breathing or rocket to tether could save a great deal of fuel per flight, and would permit for both a simpler vehicle and more cargo.

An important practical modification of a rotovator would be to add several latch points to achieve different momentum transfers. Another useful concept would be to add a linear motor to the rotovator, to accelerate spacecraft or materials to higher speeds than the tip speed of the tether.

Skyhooks



Orbital tether lengths compared.

A tidal stabilized tether is called a "skyhook" since it appears to be "hooked onto the sky". This term was introduced relating to satellites and orbital mechanics by the Italian scientist Giuseppe Colombo. Skyhooks rotate precisely once per orbit and hence are always oriented the same way to the parent body.

Some are called "hypersonic skyhooks" because the tip nearest the earth travels about Mach-12 to 16 in typical designs. Longer tethers would travel more slowly. At the limit of zero ground speed, it would be re-classified as a *space elevator* or *beanstalk*.

An aircraft or sub-orbital vehicle transports cargo to one end of the skyhook.

Skyhook designs typically require climbers to transport the cargo to the other end (like a beanstalk).

Robert Raymond Boyd and Dimitri David Thomas (with Lockheed Martin Corporation) patented the Skyhook idea in 2000 in a patent titled "Space elevator".

The company Tethers Unlimited Inc (founded by Dr. Robert Forward and Dr. Robert P. Hoyt) has called this approach "Tether Launch Assist".

Space elevator (beanstalk)

A beanstalk (a type of space elevator) is a skyhook that is attached to planetary body. For example, on Earth, a beanstalk would go from the equator to geosynchronous orbit.

A beanstalk does not need to be powered as a rotovator does, because it gets any required angular momentum from the planetary body. The disadvantage is that it is much longer, and for many planets a beanstalk cannot be constructed from known materials. A beanstalk on Earth would require material strengths outside current technological limits (2007). Martian and Lunar beanstalks could be built with modern-day materials however. A space elevator on Phobos has also been proposed.

Beanstalks also have much larger amounts of potential energy than a rotovator, and if heavy parts should fail they might cause multiple impact events as objects hit the earth at near orbital speeds. Most anticipated cable designs would burn up before hitting the ground.

Tether cable catapult system

A tether cable catapult system is a system where two or more long conducting tethers are held rigidly in a straight line, attached to a heavy mass. Power is applied to the tethers and is picked up by a vehicle that has linear magnet motors on it, which it uses to push itself along the length of the cable. Near the end of the cable the vehicle releases a payload and slows and stops itself and the payload carries on at very high velocity. The calculated maximum speed for this system is extremely high, more than 30 times the speed of sound in the cable; and velocities of more than 30 km/s seem to be possible.

Challenges and other problems

Atomic oxygen

Objects in low earth orbit are subjected to noticeable erosion from monomolecular oxygen, due to the high orbital speed with which the molecules strike as well as their high reactivity.

Micrometeorites and space junk

Simple tethers are quickly cut by micrometeoroids and space junk. The lifetime of a simple, one-strand tether in space is on the order of five hours for a length of ten kilometers. This was originally a show stopper for the use of tethers.

Several systems have since been proposed to improve this. The US Naval Research Laboratory has successfully flown a long term tether that used very fluffy yarn. This is reported to remain uncut several years after deployment. Another proposal is to use a tape or cloth. Dr. Robert P. Hoyt patented an engineered circular net, such that a cut strand's strains would be redistributed automatically around the severed strand. This is called a Hoytether. Hoytethers have theoretical lifetimes of tens of years.

Large pieces of junk would cut most tethers, but these are currently tracked on radar and have predictable orbits. A tether could be wiggled to dodge known pieces of junk, or thrusters used to change the orbit, avoiding a collision.

Material strength

Beanstalks and rotovators are currently limited by the strengths of available materials. Although ultra-high strength plastic fibers (Kevlar and Spectra) permit rotovators to pluck masses from the surface of the Moon and Mars, a rotovator from these materials cannot lift from the surface of the Earth. In theory, high flying, supersonic (or hypersonic) aircraft could deliver a payload to a rotovator that dipped into Earth's upper atmosphere briefly at predictable locations throughout the tropic (and temperate) zone of Earth.

Vibrations

Computer models frequently show tethers can snap due to vibration.

Mechanical tether-handling equipment is often surprisingly heavy, with complex controls to damp vibrations. The one ton climber proposed by Dr. Brad Edwards for his Space Elevator may detect and suppress most vibrations by changing speed and direction. The climber can also repair or augment a tether by spinning more strands.

The vibration modes that may be a problem include skipping rope, transverse, longitudinal, and pendulum.

Tethers are nearly always tapered, and this can greatly amplify the movement at the thinnest tip in whip like ways.

Cargo capture

Cargo capture for rotovators is nontrivial, and failure to capture can cause problems. Several systems have been proposed, such as shooting nets at the cargo, but all add weight, complexity, and another failure mode.

Life Expectancy

Currently, the strongest materials in tension are plastics that require a coating for protection from UV radiation and (depending on the orbit) erosion by atomic oxygen. Disposal of waste heat is difficult in a vacuum, so over-heating may cause tether failures or damage.

Control and modelling issues

A tether is not a spherical object, and has significant extent. This means that, as an extended object, it is not directly modellable as a point source, and this means that the center of mass and center of gravity are not usually colocated, and the inverse square law does not apply except at large distances to the overall behaviour of a tether. This makes prediction and modelling extremely complex.

Real Missions

Gemini 11

In 1966, Gemini 11 deployed a 30m (100 foot) tether which was stabilized by a rotation which gave 0.00015 g.

SEDS I

In 1993, NASA launched the "Small Expendable Deployer System" experiments (SEDS-I), which deployed a 20 km tether attached to a spent Delta second stage. This was the first fully successful orbital flight test of a long tether system. The tether swung to the vertical and was cut 1 orbit after the start of deployment. This slung the payload and tether onto a reentry trajectory accurate enough that a pre-positioned observer was able to videotape the payload re-entry and burnup. In this experiments, not only were tether models verified, the test successfully showed that a reentry vehicle can be dropped into a reentry orbit using a tether.

SEDS II

SEDS-2 was a simple tether experiment launched March 9, 1994; and was successfully deployed, and met the mission objectives including having minimal swing and good deployment length. A feedback braking limited the swing after deployment to 4°. It was expected to last almost two weeks, but in fact was cut after 3.7 days and the lower end quickly experienced atmospheric entry.

A follow-on experiment using the SEDS deployer, PMG (Plasma Motor Generator) deployed a 500 m tether to demonstrate electrodynamic tether operation.

MAST

The MAST tether experiment was launched aboard a Dnepr rocket in April 2007. Unfortunately, the tether did not deploy successfully.

TSS-1 (NASA)

NASA deployed an electromagnetic tether from the Space Shuttle in the experiment "Tethered Satellite System 1" (TSS-1), flown on the mission STS-46 in June 1992. Unfortunately, a late-stage modification of the deployment reel system resulted in a protruding bolt jamming the deployment mechanism, and the tether was deployed only to a length of 260 meters. The experiment was reflown in the experiment TSS-1R, flown in February 1996 on the mission STS-75. While this tether successfully deployed to 19 kilometers, it burned through due to excessive current flow.

TiPS

The Tether Physics and Survivability Experiment (TiPS) was launched in 1996 as a project of the US Naval Research Laboratory, and was successfully deployed to a tether length of four kilometers. The tether broke finally in July 2006, in line with debris models published by J. Carroll.

YES2

The YES2 satellite was launched September 14, 2007 from Baikonur. The Young Engineers' Satellite 2 (YES2) was a 36 kg student-built tether satellite part of ESA's Foton-M3 microgravity mission. The YES2 satellite employed a 30 km long tether to deorbit a small re-entry capsule.

STARS

The STARS mission, developed by the Kagawa Satellite Development Project at Kagawa University, was launched 23 January 2009 as a secondary payload aboard H-IIA flight 15, which also launched GOSAT.