Handbook of Spacecraft Technology, Components and Space Programs

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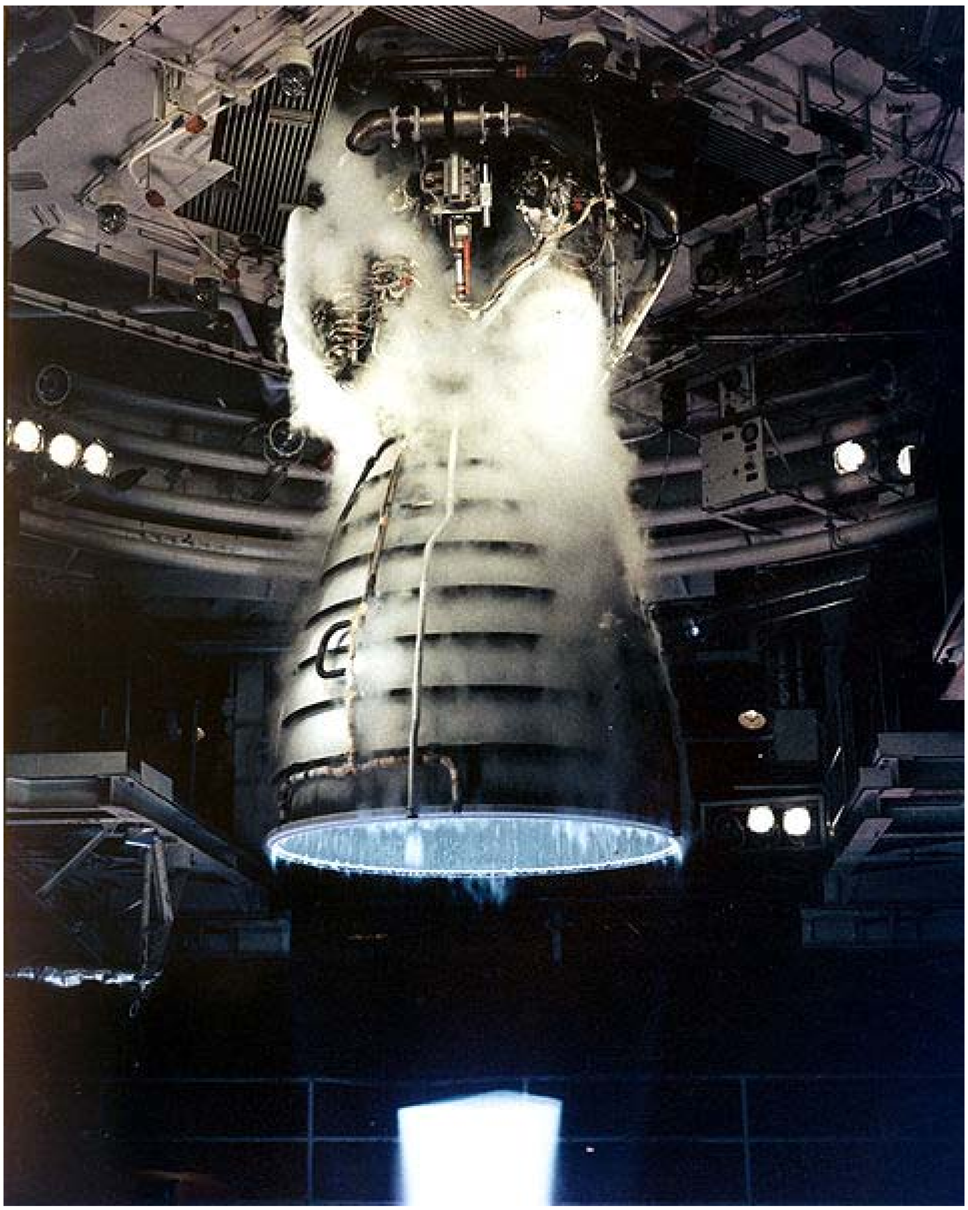
Table of Contents

Chapter- 1

Spacecraft Propulsion



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

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

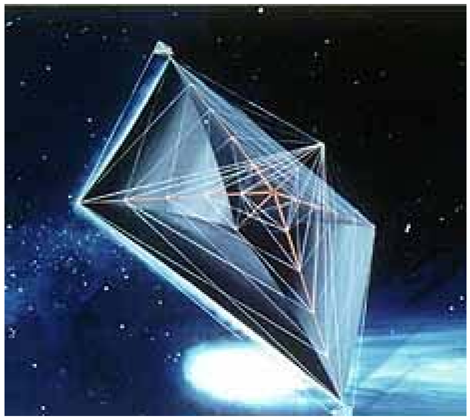
All current spacecraft use chemical rockets (bipropellant or solid-fuel) for launch, though some (such as the Pegasus rocket and SpaceShipOne) have used air-breathing engines on their first stage. Most satellites have simple reliable chemical thrusters (often monopropellant rockets) or resistojet rockets for orbital station-keeping and some use momentum wheels for attitude control. Soviet bloc satellites have used electric propulsion for decades, and newer Western geo-orbiting spacecraft are starting to use them for north-south stationkeeping. Interplanetary vehicles mostly use chemical rockets as well, although a few have used ion thrusters and Hall effect thrusters (two different types of electric propulsion) to great success.

Need

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

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

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



Artist's concept of a solar sail

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

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

Effectiveness

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

When launching a spacecraft from the Earth, a propulsion method must overcome a higher gravitational pull to provide a net positive acceleration. In orbit, any additional impulse, even very tiny, will result in a change in the orbit path.

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

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

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

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

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

A rocket with a high exhaust velocity can achieve the same impulse with less reaction mass. However, the energy required for that impulse is proportional to the exhaust velocity, so that more mass-efficient engines require much more energy, and are typically less energy efficient. This is a problem if the engine is to provide a large amount of thrust. To generate a large amount of impulse per second, it must use a large amount of energy per second. So high-mass-efficient engines require enormous amounts of energy per second to produce high thrusts. As a result, most high-mass-efficient engine designs also provide lower thrust due to the unavailability of high amounts of energy.

Methods

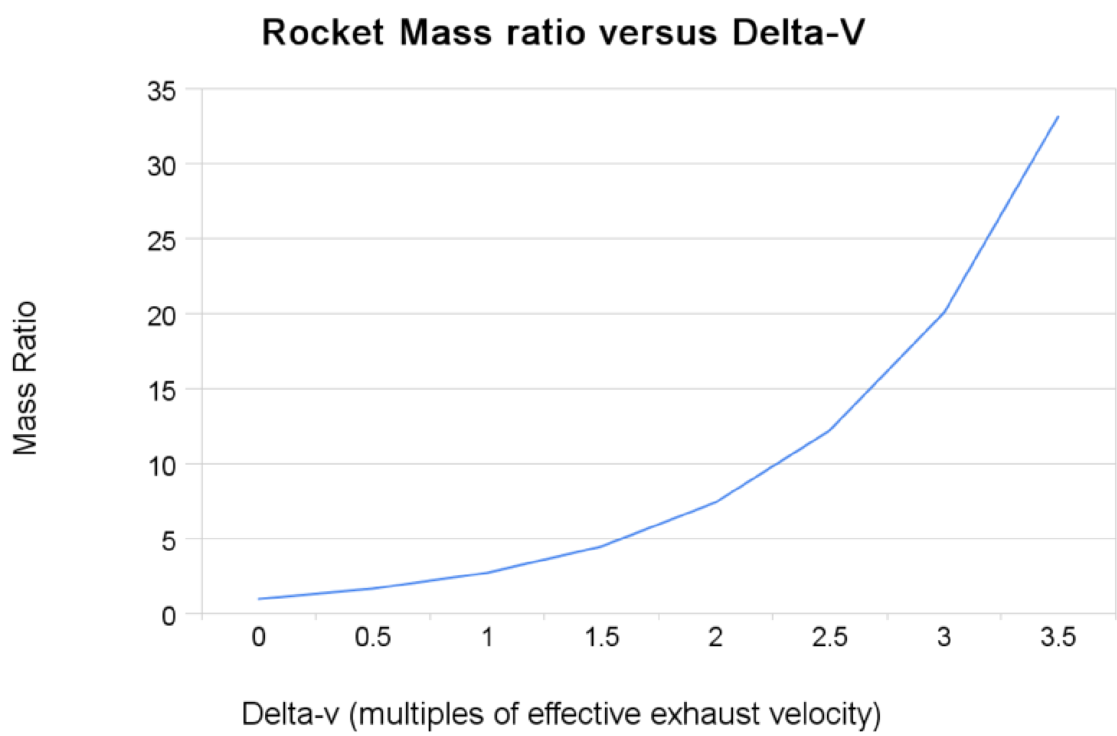
Propulsion methods can be classified based on their means of accelerating the reaction mass. There are also some special methods for launches, planetary arrivals, and landings.

Reaction engines

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

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

Delta-v and propellant



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

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

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

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

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

$$v_e = I_{sp} g_o$$

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

For a high delta-v mission, the majority of the spacecraft's mass needs to be reaction mass. Since a rocket must carry all of its reaction mass, most of the initially-expended reaction mass goes towards accelerating reaction mass rather than payload. If the rocket has a payload of mass P, the spacecraft needs to change its velocity by Δv, and the rocket engine has exhaust velocity v_e, then the mass M of reaction mass which is needed can be calculated using the rocket equation and the formula for I_{sp}:

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

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

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

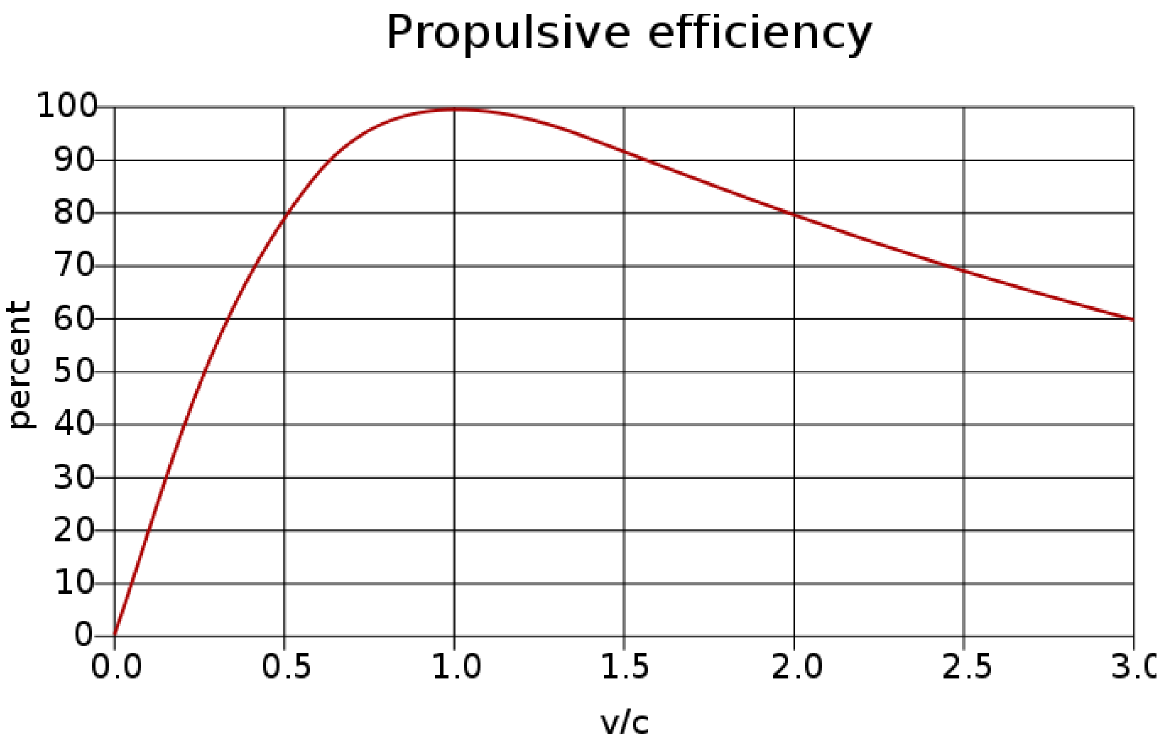
Some effects such as Oberth effect can only be significantly utilised by high thrust engines such as rockets, i.e. engines that can produce a high g-force (thrust per unit mass, equal to delta-v per unit time).

Power use and propulsive efficiency

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

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

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



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

Comparing the rocket equation (which shows how much energy ends up in the final vehicle) and the above equation (which shows the total energy required) shows that even with 100% engine efficiency, certainly not all energy supplied ends up in the vehicle - some of it, indeed usually most of it, ends up as kinetic energy of the exhaust.

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

- if the I_{sp} is fixed, for a mission delta-v, there is a particular I_{sp} that minimises the overall energy used by the rocket. This comes to an exhaust velocity of about ⅔ of the mission delta-v. Drives with a specific impulse that is both high and fixed such as Ion thrusters have exhaust velocities that can be enormously higher than this ideal for many missions.

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

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

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

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

Power to thrust ratio

The power to thrust ratio is simply:

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

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

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

Example

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

Engine	Effective Exhaust Velocity (km/s)	Specific impulse (s)	Fuel mass (kg)	Energy required (GJ)	Energy per kg of propellant	minimum power/thrust	Power generator mass/thrust*
Solid rocket	1	100	190,000	95	500 kJ	0.5 kW/N	N/A
Bipropellant rocket	5	500	8,200	103	12.6 MJ	2.5 kW/N	N/A
Ion thruster	50	5,000	620	775	1.25 GJ	25 kW/N	25 kg/N
Advance electrically powered drive	1,000	100,000	30	15,000	500 GJ	500 kW/N	500 kg/N

* - assumes a specific power of 1kW/kg

Observe that the more fuel-efficient engines can use far less fuel; its mass is almost negligible (relative to the mass of the payload and the engine itself) for some of the engines. However, note also that these require a large total amount of energy. For Earth launch, engines require a thrust to weight ratio of more than one. To do this with the ion or more theoretical electrical drives, the engine would have to be supplied with one to several gigawatts of power — equivalent to a major metropolitan generating station. From the table it can be seen that this is clearly impractical with current power sources.

Instead, a much smaller, less powerful generator may be included which will take much longer to generate the total energy needed. This lower power is only sufficient to accelerate a tiny amount of fuel per second, and would be insufficient for launching from the Earth. However, over long periods in orbit where there is no friction, the velocity will be finally achieved. For example. it took the SMART-1 more than a year to reach the Moon, while with a chemical rocket it takes a few days. Because the ion drive needs much less fuel, the total launched mass is usually lower, which typically results in a lower overall cost, but takes longer.

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

Rocket engines

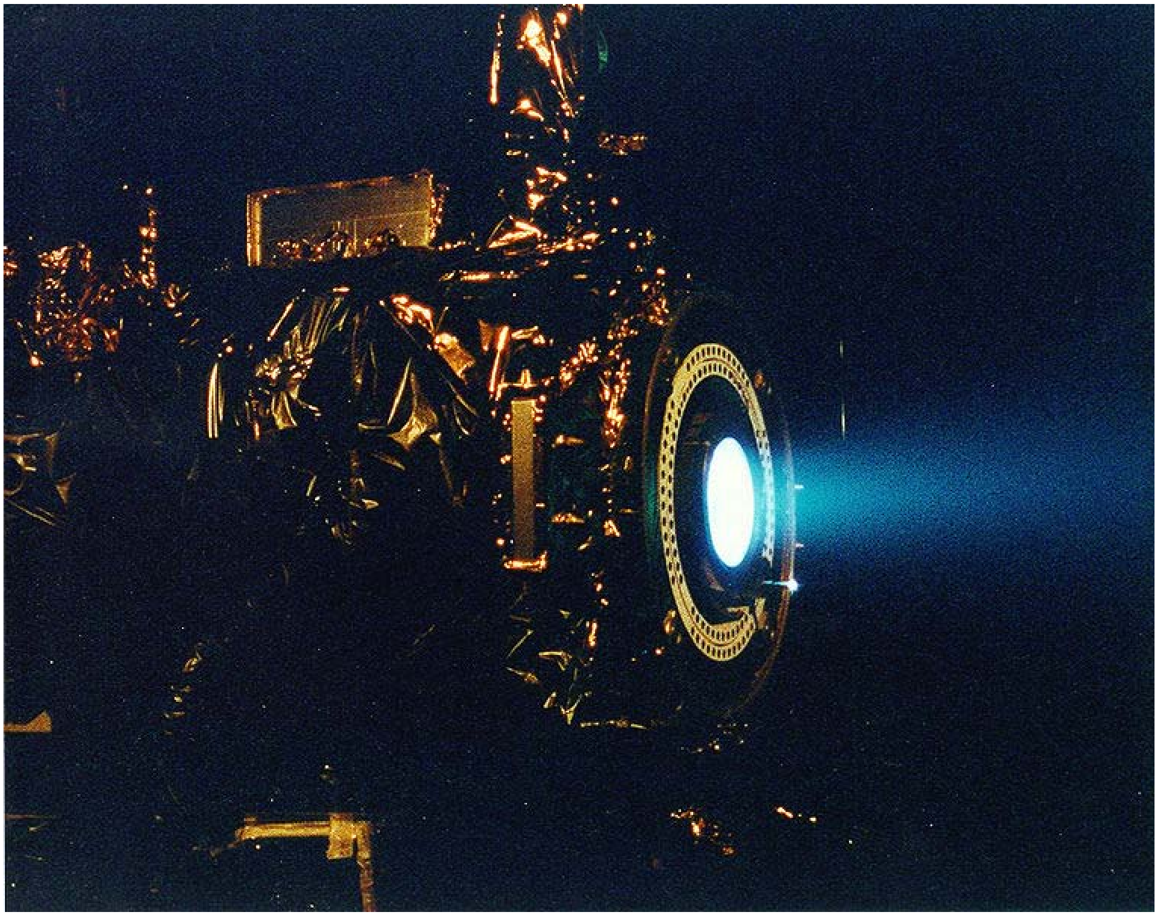
SpaceX's Kestrel engine is tested

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

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

Ion propulsion rockets can heat a plasma or charged gas inside a magnetic bottle and release it via a magnetic nozzle, so that no solid matter need come in contact with the plasma. Of course, the machinery to do this is complex, but research into nuclear fusion has developed methods, some of which have been proposed to be used in propulsion systems, and some have been tested in a lab.

Electromagnetic propulsion



This test engine accelerates ions using electrostatic forces

Rather than relying on high temperature and fluid dynamics to accelerate the reaction mass to high speeds, there are a variety of methods that use electrostatic or electromagnetic forces to accelerate the reaction mass directly. Usually the reaction mass is a stream of ions. Such an engine typically uses electric power, first to ionize atoms, and then to create a voltage gradient to accelerate the ions to high exhaust velocities.

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

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

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

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

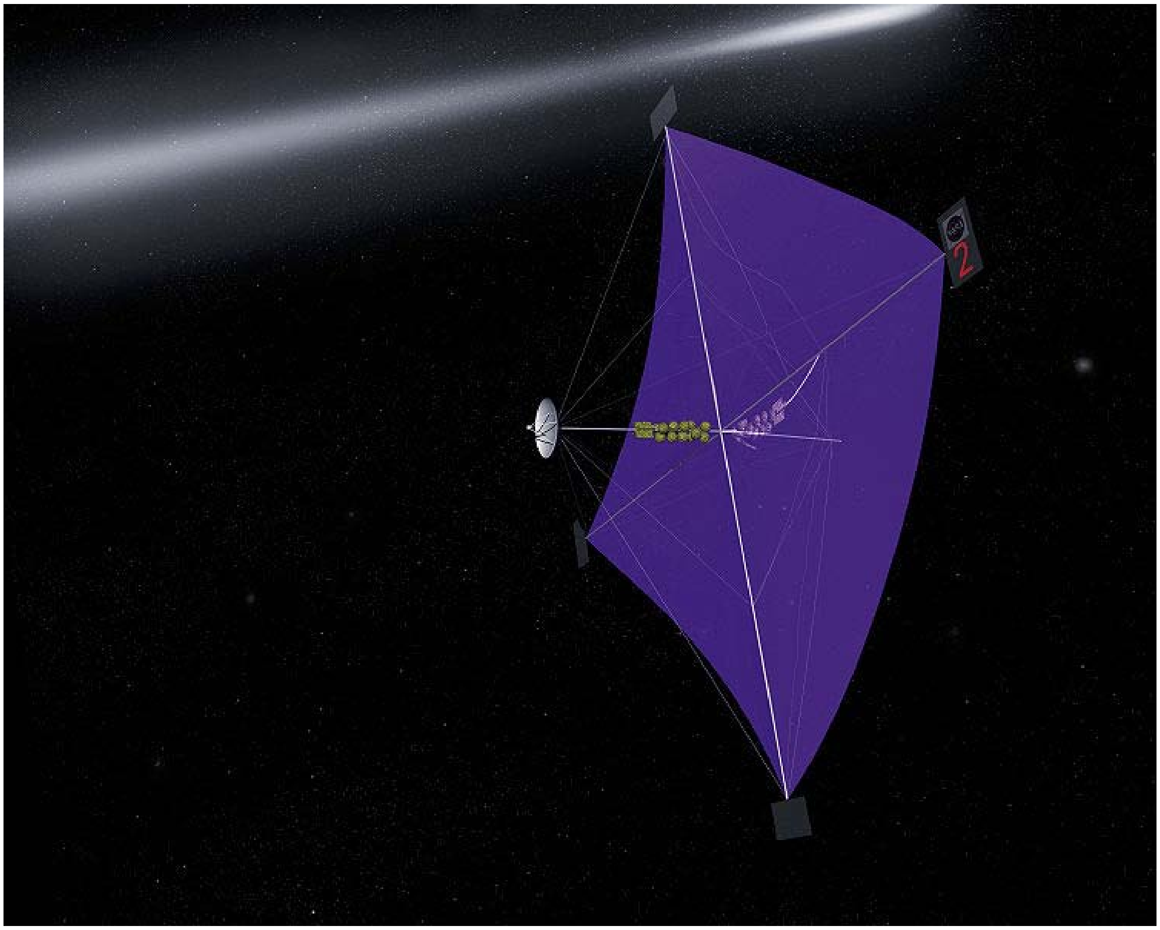
Current nuclear power generators are approximately half the weight of solar panels per watt of energy supplied, at terrestrial distances from the Sun. Chemical power generators are not used due to the far lower total available energy. Beamed power to the spacecraft shows some potential. However, the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

Some electromagnetic methods:

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

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

Without internal reaction mass



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

The law of conservation of momentum states that any engine which uses no reaction mass cannot accelerate the center of mass of a spaceship (changing orientation, on the other hand, is possible). But space is not empty, especially space inside the Solar System; there are gravitation fields, magnetic fields, solar wind and solar radiation. Various propulsion methods try to take advantage of these. However, since these phenomena are diffuse in nature, corresponding propulsion structures need to be proportionately large.

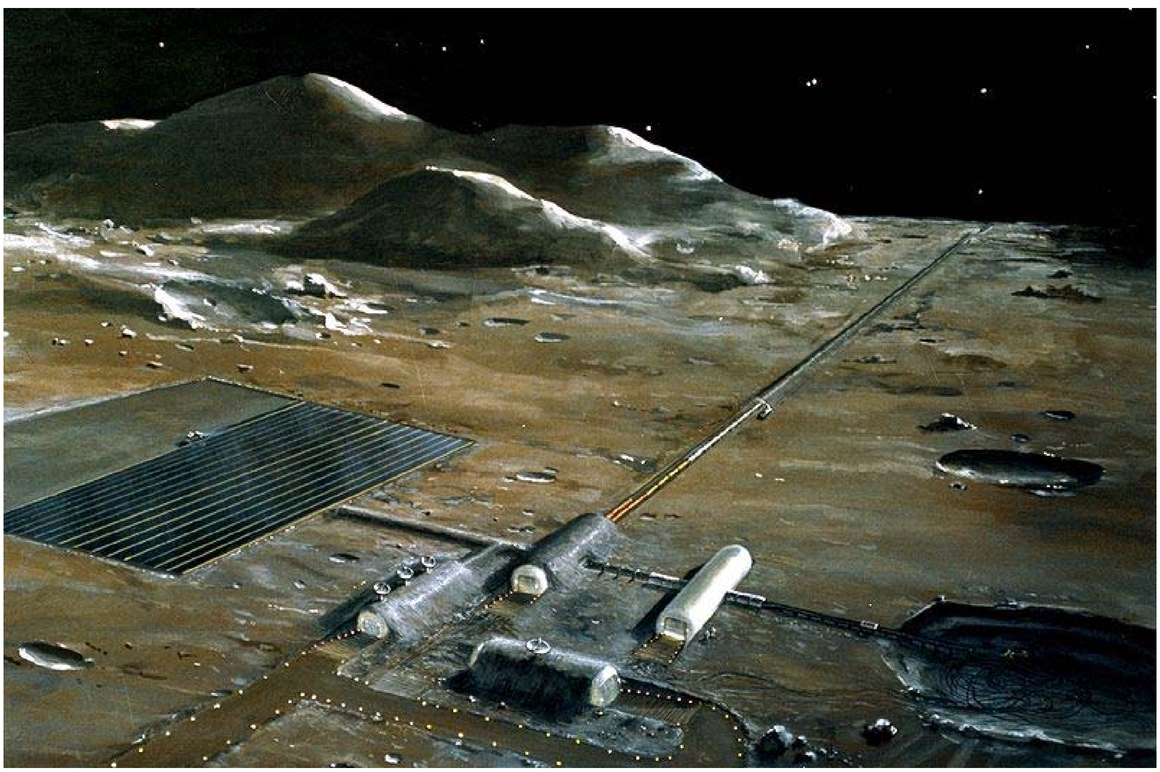
There are several different space drives that need little or no reaction mass to function. A tether propulsion system employs a long cable with a high tensile strength to change a spacecraft's orbit, such as by interaction with a planet's magnetic field or through momentum exchange with another object.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

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

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

Planetary and atmospheric propulsion

Launch mechanisms



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

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

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

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

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

Airbreathing engines

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

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

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

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

Planetary arrival and landing

A test version of the MARS Pathfinder airbag system

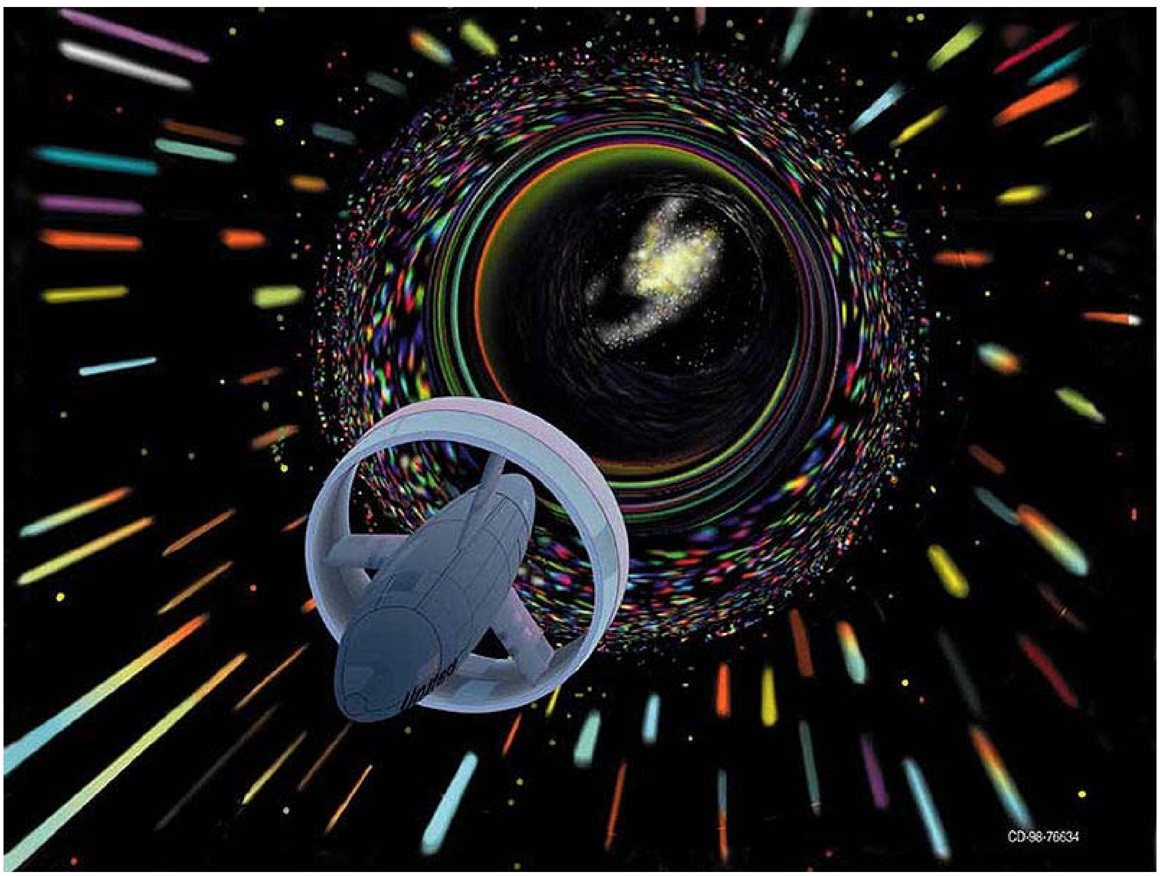
When a vehicle is to enter orbit around its destination planet, or when it is to land, it must adjust its velocity. This can be done using all the methods listed above (provided they can generate a high enough thrust), but there are a few methods that can take advantage of planetary atmospheres and/or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

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

upon lunar return were aerocapture maneuvers, since they turned a hyperbolic orbit into an elliptical orbit. On these missions, since there was no attempt to raise the perigee after the aerocapture, the resulting orbit still intersected the atmosphere, and re-entry occurred at the next perigee.

- a Ballute is an inflatable drag device
- a Parachutes can land a probe on a planet with an atmosphere, usually after the atmosphere has scrubbed off most of the velocity, using a heat shield.
- Airbags can soften the final landing.
- Lithobraking, or stopping by simply smashing into the target, is usually done by accident. However, it may be done deliberately with the probe expected to survive, in which case very sturdy probes and low approach velocities are required.

Hypothetical methods



Artist's conception of a warp drive design

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

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

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

Table of methods

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

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

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

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

The fourth is the maximum delta-v this technique can give (without staging). For rocket-like propulsion systems this is a function of mass fraction and exhaust velocity. Mass fraction for rocket-like systems is usually limited by propulsion system weight and tankage weight. For a system to achieve this limit, typically the payload may need to be a negligible percentage of the vehicle, and so the practical limit on some systems can be much lower.

Propulsion methods

Method	Effective Exhaust Velocity (km/s)	Thrust (N)	Firing Duration	Maximum Delta-v (km/s)	Technology readiness level
Solid-fuel rocket	1 - 4	10^3 - 10^7	minutes	~ 7	9:Flight proven
Hybrid rocket	1.5 - 4.2	<0.1 - 10^7	minutes	> 3	9:Flight proven
Monopropellant rocket	1 - 3	0.1 - 100	milliseconds-minutes	~ 3	9:Flight proven
Liquid-fuel rocket	1 - 4.7	0.1 - 10^7	minutes	~ 9	9:Flight proven
Electrostatic ion thruster	15 - 210	10^{-3} - 10	months/years	> 100	9:Flight proven
Hall effect thruster (HET)	8 - 50	10^{-3} - 10	months/years	> 100	9:Flight proven
Resistojet rocket	2 - 6	10^{-2} - 10	minutes	?	8:Flight qualified
Arcjet rocket	4 - 16	10^{-2} - 10	minutes	?	8:Flight qualified
Field Emission Electric Propulsion (FEEP)	100-130	10^{-6}-10^{-3}	months/years	?	8:Flight qualified
Pulsed plasma thruster (PPT)	~ 20	~ 0.1	~2,000-10,000 hours	?	7:Prototype demoed in space
Dual mode propulsion rocket	1 - 4.7	0.1 - 10^7	milliseconds-minutes	~ 3 - 9	7:Prototype demoed in space
Solar sails	300,000:Light 145-750:Wind	9/km^2 @ 1 AU 230/km^2@0.2AU 10^{-10}/km^2@4 ly	indefinite	> 40	9:Light pressure attitude-control flight proven 6:Deploy-only demoed in space 5:Light-sail validated in lit vacuum
Tripropellant rocket	2.5 - 5.3	0.1 - 10^7	minutes	~ 9	6:Prototype demoed on ground
Magnetoplasmadynamic thruster (MPD)	20 - 100	100	weeks	?	6:Model-1 kW demoed in space
Nuclear thermal rocket	9	10^7	minutes	> ~ 20	6:Prototype demoed on ground
Mass drivers (for propulsion)	0 - ~30	10^4 - 10^8	months	?	6:Model-32MJ demoed on ground
Tether propulsion	N/A	1 - 10^{12}	minutes	~ 7	6:Model-31.7 km demoed in space
Air-augmented rocket	5 - 6	0.1 - 10^7	seconds-minutes	> 7?	6:Prototype demoed on ground
Liquid air cycle engine	4.5	10^3 - 10^7	seconds-minutes	?	6:Prototype demoed on ground
Pulsed inductive thruster (PIT)	10-80	20	months	?	5:Component validated in vacuum
Variable Specific Impulse	10 - 300	40 - 1,200	days - months	> 100	5:Component-

Magnetoplasma Rocket (VASIMR)					200 kW validated in vacuum
Magnetic field oscillating amplified thruster	10 - 130	0.1 - 1	days - months	> 100	5:Component validated in vacuum
Solar thermal rocket	7 - 12	1 - 100	weeks	> ~ 20	4:Component validated in lab
Radioisotope rocket	7 - 8	1.3 - 1.5	months	*?*	4:Component validated in lab
Nuclear electric rocket(As electric prop. method used)	Variable	Variable	Variable	*?*	4:Component-400kW validated in lab
Orion Project (Near term nuclear pulse propulsion)	20 - 100	10^9 - 10^{12}	several days	~30-60	3:Validated-900 kg proof-of-concept
Space elevator	N/A	N/A	indefinite	> 12	3:Validated proof-of-concept
Reaction Engines SABRE	30/4.5	0.1 - 10^7	minutes	9.4	3:Validated proof-of-concept
Magnetic sails	145-750:Wind	70/40Mg	indefinite	*?*	3:Validated proof-of-concept
Magnetic sail#Mini-magnetospheric plasma propulsion	200	~1 N/kW	months	*?*	3:Validated proof-of-concept
Beam-powered/Laser(As prop. method powered by beam)	Variable	Variable	Variable	*?*	3:Validated-71m proof-of-concept
Launch loop/Orbital ring	N/A	~10^4	minutes	>>11-30	2:Technology concept formulated
Nuclear pulse propulsion (Project Daedalus' drive)	20 - 1,000	10^9 - 10^{12}	years	~15,000	2:Technology concept formulated
Gas core reactor rocket	10 - 20	10^3 - 10^6	*?*	*?*	2:Technology concept formulated
Nuclear salt-water rocket	100	10^3 - 10^7	half hour	*?*	2:Technology concept formulated
Fission sail	*?*	*?*	*?*	*?*	2:Technology concept formulated
Fission-fragment rocket	15,000	*?*	*?*	*?*	2:Technology concept formulated
Nuclear photonic rocket	300,000	10^{-5} - 1	years-decades	*?*	2:Technology concept formulated
Fusion rocket	100 - 1,000	*?*	*?*	*?*	2:Technology concept formulated
Antimatter catalyzed nuclear	200 - 4,000	*?*	days-weeks	*?*	2:Technology

pulse propulsion					concept formulated
Antimatter rocket	10,000-100,000	*?*	*?*	*?*	2:Technology concept formulated
Bussard ramjet	2.2 - 20,000	*?*	indefinite	~30,000	2:Technology concept formulated
Gravitoelectromagnetic toroidal launchers	300,000:GEM	*?*	*?*	<300,000	1:Basic principles observed & reported
Alcubierre Warp Drive	>300,000	*?*	*?*	∞	1:Basic principles observed & reported
Method	**Effective Exhaust Velocity (km/s)**	**Thrust (N)**	**Firing Duration**	**Maximum Delta-v (km/s)**	**Technology readiness level**

Testing

Spacecraft propulsion systems are often first statically tested on the Earth's surface, within the atmosphere but many systems require a vacuum chamber to test fully. Rockets are usually tested at a rocket engine test facility well away from habitation and other buildings for safety reasons. Ion drives are far less dangerous and require much less stringent safety, usually only a large-ish vacuum chamber is needed.

Famous static test locations can be found at Rocket Ground Test Facilities

Some systems cannot be adequately tested on the ground and test launches may be employed at a Rocket Launch Site.

Chapter- 2

Human Spaceflight

Edward White on a spacewalk during the Gemini 4 mission

Human spaceflight is spaceflight with a human crew and possibly passengers. This makes it unlike robotic space probes or remotely-controlled satellites. Human spaceflight is sometimes called **manned spaceflight**, a term now deprecated by major space agencies in favor of its gender-neutral alternative.

The first human spaceflight was accomplished on April 12, 1961 by Soviet cosmonaut Yuri Gagarin. The only countries to have independent human spaceflight capability are Russia, United States and China. As of 2010, human spaceflights are being actively launched by the Soyuz programme conducted by the Russian Federal Space Agency, the Space Shuttle program conducted by NASA, and the Shenzhou program conducted by the China National Space Administration.

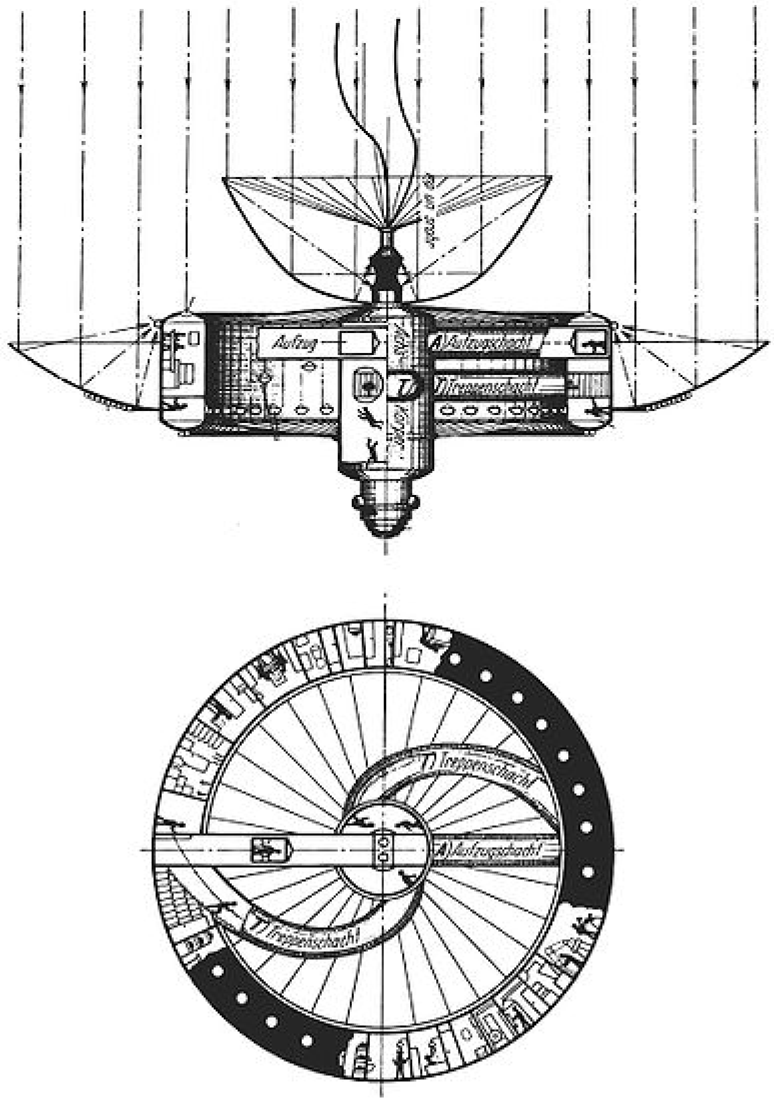
The US will lose governmental human spaceflight launch capability upon retirement of the Space Shuttle, expected in 2011. Under the Bush administration, the Constellation program included plans for canceling the Shuttle and replacing it with the capability for spaceflight beyond low Earth orbit. In the 2011 United States federal budget, the Obama administration proposed canceling Constellation. Under the new plan, NASA would rely on transportation services provided by the private sector, such as Space X's Falcon 9. The period between the retirement of the Shuttle and the initial operational capability of new systems (either Constellation or the new commercial proposals), similar to the gap between the cancellation of Apollo and the first Space Shuttle flight, is often referred to as the human spaceflight gap.

In recent years there has been a gradual movement towards more commercial forms of spaceflight. A number of non-governmental startup companies have sprung up in recent years, hoping to create a space tourism industry. For a list of such companies, and the spacecraft they are currently building. NASA has also tried to stimulate private spaceflight through programs such as Commercial Crew Development (CCDev) and Commercial Orbital Transportation Services (COTS). With its 2011 budget proposals released in early February 2010, the Obama administration is moving towards a model where commercial companies would supply NASA with transportation services of both crew and cargo to low Earth orbit. The vehicles used for these services would then serve both NASA and potential commercial customers. NASA intends to spend $6 billion in the coming years to develop commercial crew vehicles, using a model similar to that used under COTS.

History of Space Flight

Spaceflight, particularly human spaceflight, has long been a dream of humankind, but it was only in the 20th century that it became a reality.

Background



Description of a space station in Hermann Noordung's *The Problem of Space Travel* (1929).

The realistic proposal of spaceflight goes back to Konstantin Tsiolkovsky. His most famous work, "Исследование мировых пространств реактивными приборами" (*The Exploration of Cosmic Space by Means of Reaction Devices*), was published in 1903, but this theoretical work was not widely influential outside of Russia.

Spaceflight became an engineering possibility with the work of Robert H. Goddard's publication in 1919 of his paper 'A Method of Reaching Extreme Altitudes'; where his application of the de Laval nozzle to liquid fuel rockets gave sufficient power that interplanetary travel became possible. This paper was highly influential on Hermann Oberth and Wernher Von Braun, later key players in spaceflight.

In 1929, the Slovene officer Hermann Noordung was the first to imagine a quite complete space station in his book *The Problem of Space Travel*.

The first rocket to reach space was a German V-2 Rocket, on a test flight in June 1944.

Space Race

Orbital space flight, both unmanned and manned, was first developed by the Soviet Union and the United States during the Cold War, in a competition dubbed the *Space Race*.

The race began on July 29, 1957, when the US announced at the convention of the 1957-1958 International Geophysical Year, its intent to launch an artificial satellite known as Vanguard by the spring of 1958. The Soviets reacted on July 31 by announcing they would launch a satellite in the fall of 1957. They succeeded in launching Sputnik 1 on October 4, 1957. After a series of Vanguard failures, the US succeeded in launching its first satellite, Explorer 1 on February 1, 1958. This carried scientific instrumentation and detected the theorized Van Allen radiation belt.

The US public shock over Sputnik 1 became known as the Sputnik crisis. On July 29, 1958, the US Congress passed legislation turning the National Advisory Committee for Aeronautics (NACA) into the National Aeronautics and Space Administration (NASA) with responsibility for the nation's civilian space programs. In 1959, NASA began Project Mercury to launch single-man capsules into Earth orbit, and chose a corps of seven astronauts introduced as the *Mercury Seven*.

Yuri Gagarin, the first man in space, in his space suit in preparation for the Vostok 1 mission

On April 12, 1961, the USSR announced the successful launch and return of its first *cosmonaut* (their chosen term for space travelers), Yuri Gagarin who made a single orbit aboard Vostok 1. On May 5, 1961 the US launched its first Mercury astronaut Alan Shepard in a capsule he named Freedom 7, but on a suborbital flight.

John Glenn, Jr., as he enters his Friendship 7 spacecraft (NASA)

The US public was becoming increasingly shocked and alarmed at the widening lead obtained by the USSR, so President John F. Kennedy announced on May 25 a plan to land a man on the moon by 1970, launching the three-man Apollo program. In January 1962, NASA announced a two-man spacecraft program named Project Gemini to support Apollo.

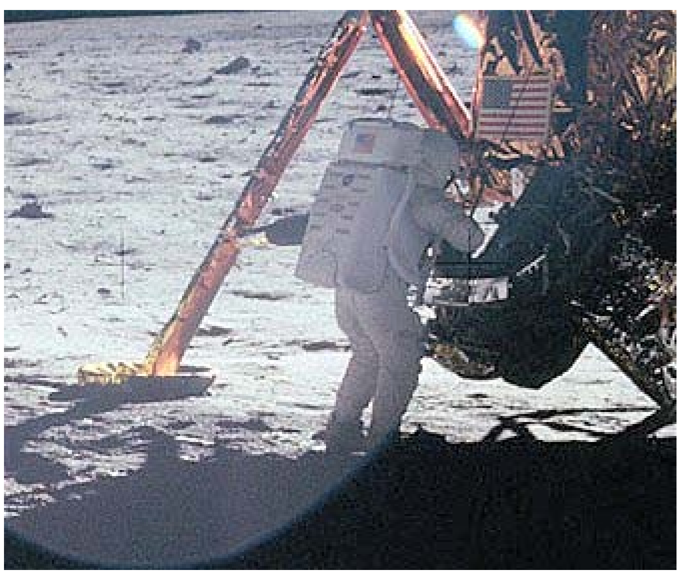
After one more suborbital Mercury flight, the US launched John Glenn to make three orbits in Friendship 7 on February 20, 1962. Project Mercury launched a total of six astronauts by May 16, 1963. The Soviets launched five more cosmonauts, including the first woman in space, the civilian parachutist Valentina Tereshkova in Vostok 6 on June 16, 1963, though this was done for political propaganda rather than a commitment to women's equality.

The Soviet government pressured its chief spacecraft designer, Sergey Korolyov, to quickly produce greater space achievements in competition with the announced Gemini and Apollo plans. Rather than allowing him to develop his plans for a crewed Soyuz spacecraft, he was forced to make modifications to squeeze two or three men into the Vostok capsule, calling the result Voskhod. Only two of these were launched. Voskhod 1 was the first spacecraft with a crew of three, who could not wear space suits because of size and weight constrictions. Alexei Leonov made the first spacewalk when he left the Voskhod 2 on March 8, 1965. He was almost lost in space when he had extreme difficulty fitting his inflated space suit back into the cabin through an airlock, and a landing error forced him and his crewmate to be lost in dangerous woods for hours before being found by the recovery crew.

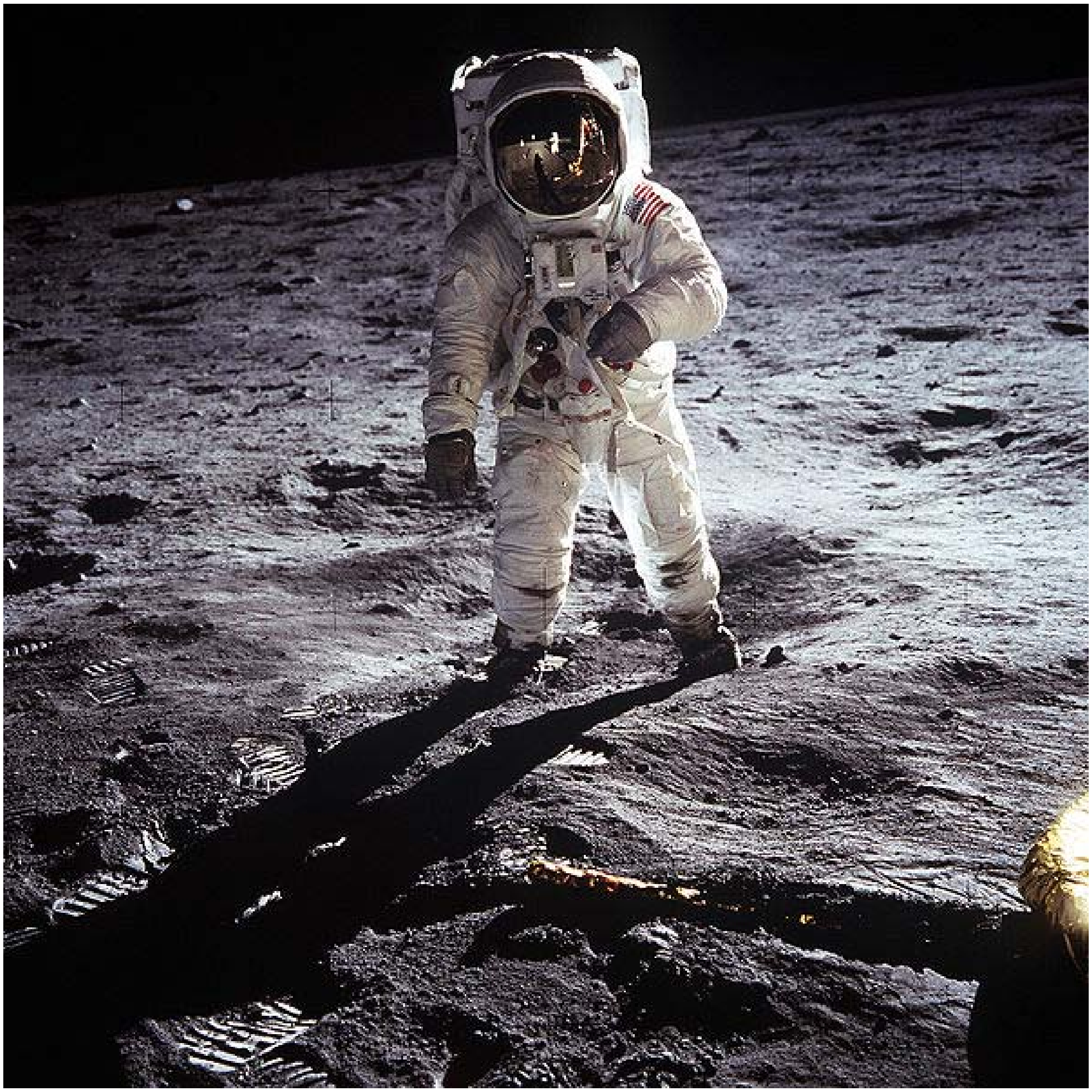
The start of manned Gemini missions was delayed a year later than NASA had planned, but ten largely successful missions were launched in 1965 and 1966, allowing the US to overtake the Soviet lead by achieving space rendezvous (Gemini 6A) and docking (Gemini 8) of two vehicles, long duration flights of eight days (Gemini 5) and fourteen days (Gemini 7), and demonstrating the use of extra-vehicular activity to do useful work outside a spacecraft (Gemini 12).

The USSR made no manned flights during this period, but continued to develop its Soyuz craft and secretly accepted Kennedy's implicit lunar challenge, designing Soyuz variants for lunar orbit and landing. They also attempted to develop the N1, a large, manned moon-capable launch vehicle similar to the US Saturn V.

As both nations rushed to get their new spacecraft flying with men, the intensity of the competition caught up to them in early 1967, when they suffered their first crew fatalities. On January 27, the entire crew of Apollo 1, "Gus" Grissom, Ed White, and Roger Chaffee, were killed by suffocation in a fire that swept through their cabin during a ground test approximately one month before their planned launch. Then on April 24, the single pilot of Soyuz 1, Vladimir Komarov, was killed in a crash when his landing parachutes tangled, after a mission cut short by electrical and control system problems. Both accidents were determined to be caused by design defects in the spacecraft, which were corrected before manned flights resumed.



Neil Armstrong works at the LM in one of the few photos taken of him from the lunar surface. NASA photo AS11-40-5886.



Buzz Aldrin poses on the Moon allowing Neil Armstrong to photograph both of them using the visor's reflection.

The US succeeded in achieving President Kennedy's goal on July 20, 1969, with the landing of Apollo 11. Neil Armstrong and Buzz Aldrin became the first men to set foot on the Moon. Six such successful landings were achieved through 1972, with one failure on Apollo 13.

The N1 rocket suffered four catastrophic unmanned launch failures between 1969 and 1972, and the Soviet government officially discontinued its manned lunar program on June 24, 1974 when Valentin Glushko succeeded Korolyov as General spacecraft Designer.

Both nations went on to fly relatively small, non-permanent manned space laboratories Salyut and Skylab, using their Soyuz and Apollo craft as shuttles. The US launched only one Skylab, but the USSR launched a total of seven "Salyuts", three of which were secretly Almaz military manned reconnaissance stations, which carried "defensive" cannons. Manned reconnaissance stations were found to be a bad idea, since unmanned satellites could do the job much more cost-effectively. The United States Air Force had planned a manned reconnaissance station, the Manned Orbital Laboratory which was cancelled in 1969. The Soviets cancelled Almaz in 1978.

In a season of detente, the two competitors declared an end to the race and shook hands (literally) on July 17, 1975 with the Apollo-Soyuz Test Project, where the two craft docked and the crews exchanged visits.

Post-Space Race US and Russian programs

US Space Shuttle

The Space Shuttle Columbia seconds after engine ignition, 1981 (NASA)

Although its pace slowed, space exploration continued after the end of the Space Race. The United States launched the first reusable spacecraft (Space Shuttle) on the 20th anniversary of Gagarin's flight, 12 April 1981. On 15 November 1988, the Soviet Union attempted to duplicate this with the Buran shuttle, its first and only reusable spacecraft. It was never been used again after the first flight; instead the Soviet Union continued to develop space stations using the Soyuz craft as the crew shuttle.

Sally Ride became the first American woman in space in 1983. Eileen Collins was the first female Shuttle pilot, and with Shuttle mission STS-93 in July 1999 she became the first woman to command a U.S. spacecraft.

The longest single human spaceflight is that of Valeriy Polyakov, who left earth on January 8, 1994, and didn't return until March 22, 1995 (a total of 437 days 17 hr. 58 min. 16 sec. aboard). Sergei Krikalyov has spent the most time of anyone in space, 803 days, 9 hours, and 39 seconds altogether. The longest period of continuous human presence in space lasted as long as 3,644 days, eight days short of 10 years, spanning the launch of Soyuz TM-8 on September 5, 1989 to the landing of Soyuz TM-29 on August 28, 1999.

International Space Station

Recent space exploration has proceeded, to some extent in worldwide cooperation, the high point of which was the construction and operation of the International Space Station. At the same time, the international space race between smaller space powers since the end of the 20th century can be considered the foundation and expansion of markets of commercial rocket launches and space tourism.

The United States continued missions to the ISS and other goals with the high-cost shuttle system, which will be retired in 2010. It also continues other space exploration, including major participation with the ISS with its own modules. It also plans a set of unmanned Mars probes, military satellites, and more. The Constellation space program, begun by President George W. Bush in 2004, aimed to launch a next-generation multifunction Orion spacecraft by 2018. A subsequent return to the Moon by 2020 was to be followed by manned flights to Mars, but the program was canceled in 2010 in favor of encouraging commercial US manned launch capabilities.

Russia, the successor to the Soviet Union, has high potential but smaller funding. Its own space programs, some of a military nature, perform several functions. They offer a wide commercial launch service while continuing to support the ISS with a several of their own modules. They also operate manned and cargo spacecrafts which will continue after US Shuttle program ends. They are developing a new multi-function PPTS manned spacecraft for use in 2018 and have plans to perform manned moon missions also. The program aims to put a man on the moon in the 2020s, becoming the second country to do so.

Programs of other nations

Later, cosmonauts and astronauts from other nations flew in space, beginning with the flight of Vladimir Remek, a Czech, on a Soviet spacecraft on March 2, 1978. As of 2007, citizens from 33 nations (including space tourists) have flown in space aboard Soviet, American, Russian, and Chinese spacecraft.

China, India, and Japan are increasingly capable of competing in space research and activity. These nations form the main players in the Asian space race.

European Union

The European Space Agency has taken the lead in commercial unmanned launches since the introduction of the Ariane 4 in 1988, but is in competition with NASA, Russia, Sea Launch (private), China, India and others. The ESA-designed manned shuttle Hermes and space station **Columbus**, were under development early on in Europe, however these projects were canceled, and Europe did not become the third major "space power".

Europe has launched various satellites, has utilized the manned Spacelab module aboard US shuttles, and has sent probes to comets and Mars. It also participates in **ISS** with its own module and the unmanned cargo spacecraft ATV.

Currently ESA has a program for development of an independent multi-function manned spacecraft CSTS scheduled for completion in 2018. Further goals include an ambitious plan called the Aurora Programme which intends to send a human mission to Mars soon after 2030. A set of various landmark missions to reach this goal are currently under consideration. The ESA has a multi-lateral partnership, and plans for spacecraft and further missions with foreign participation and co-funding.

China

The People's Republic of China, while possessing less funding than Europe's ESA and the United State's NASA, has achieved manned space flight, currently operate a commercial unmanned launch service, and owns multiple satellites. There are plans for a Chinese space station and a program to send unmanned probes to Mars in the near future. China stands poised to become the third *space power*.

China's first attempt at a manned spacecraft, Shuguang. was abandoned after years of development. But on October 15, 2003, it became the third nation to achieve human spaceflight when Yang Liwei launched into space on Shenzhou 5. This flight demonstrated China's capability to build its own manned spacecraft and launch vehicle.

The aggressiveness of China's progress has raised concerns by other nations. The US Pentagon released a report in 2006 detailing concerns of China's growing presence in space, including its capability for military action. In 2007 China tested a ballistic missile designed to destroy satellites in orbit, in violation of an international consensus against military maneuvers in space.

India

ISRO, India's national space agency, maintains an active space program and leads the group of Asian nations in major achievements and future plans. It operates a small commercial launch service and launched a successful unmanned lunar mission dubbed Chandrayaan-1 in October, 2007. India has plans for a further unmanned mission to the Moon in the near future, as well as a missions to Mars by 2012. The ISRO is currently developing a small shuttle system. With the recent success and a developing missions for manned inter-planet flights by 2025 to 2030, India has positioned itself as a contender for the third *space power*.

Japan

Japan's space agency, JAXA, is the third major player in the Asian space race. While not maintaining a commercial launch service, Japan has deployed a module in the **ISS** and operates an unmanned cargo spacecraft, the H-II Transfer Vehicle.

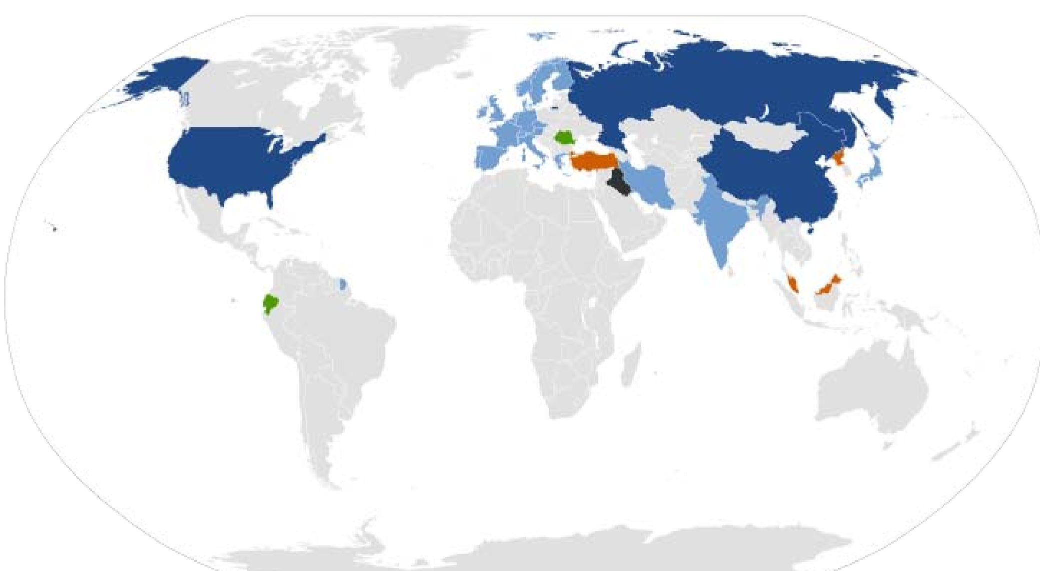
JAXA has plans to launch a Mars fly-by probe. Their lunar probe, SELENE, is touted as the most sophisticated lunar exploration mission in the post-Apollo era.

Although Japan developed the HOPE-X, Kankoh-maru, and Fuji manned capsule spacecraft, none of them have been launched. Japan's current ambition is to deploy a new manned spacecraft by 2025, and to establish a Moon base by 2030.

Space programs

As of 2010, human spaceflight missions have been conducted by the former Soviet Union/(Russia), the United States, the People's Republic of China and by the private spaceflight company Scaled Composites.

Several other countries and space agencies have announced and begun human spaceflight programs by their own technology, including India (ISRO), Ecuador (EXA), Japan (JAXA), Iran (ISA) and Malaysia (MNSA).



Countries which have human spaceflight agendas

Currently the following spacecraft and spaceports are used for launching human spaceflights:

- Soyuz with Soyuz rocket—Baikonur Cosmodrome
- Space Shuttle—Kennedy Space Center
- International Space Station (ISS)—Assembled in orbit; crews transported by the previous two spacecraft
- Shenzhou spacecraft with Long March rocket—Jiuquan Satellite Launch Center

Historically, the following spacecraft and spaceports have also been used for human spaceflight launches:

- Vostok—Baikonur Cosmodrome
- Mercury—Cape Canaveral Air Force Station
- Voskhod—Baikonur Cosmodrome
- X-15—Edwards Air Force Base, (two internationally recognized suborbital flights in program)
- Gemini—Cape Canaveral Air Force Station
- Apollo—Kennedy Space Center (Apollo 7 at Cape Canaveral Air Force Station)
- Salyut space station—Baikonur Cosmodrome
- Almaz space station—Baikonur Cosmodrome (Almaz was a series of military space stations under cover of the civilian name Salyut)
- Skylab space station—Kennedy Space Center
- Mir space station—Baikonur Cosmodrome
- SpaceShipOne with White Knight—Mojave Spaceport

Numerous private companies attempted human spaceflight programs in an effort to win the $10 million Ansari X Prize. The first private human spaceflight took place on June 21, 2004, when SpaceShipOne conducted a suborbital flight. SpaceShipOne captured the prize on October 4, 2004, when it accomplished two consecutive flights within one week. SpaceShipTwo, launching from the carrier aircraft White Knight Two, is planned to conduct regular suborbital space tourism.

Most of the time, the only humans in space are those aboard the ISS, whose crew of six spends up to six months at a time in low Earth orbit.

NASA and ESA now use the term "human spaceflight" to refer to their programs of launching people into space. Traditionally, these endeavors have been referred to as "manned space missions."

Safety concerns

Life support

In human spaceflight, the **life support system** is a group of devices that allow a human being to survive in outer space. NASA often uses the phrase **Environmental Control**

and Life Support System or the acronym **ECLSS** when describing these systems for its human spaceflight missions. The life support system may supply air, water and food. It must also maintain the correct body temperature, an acceptable pressure on the body and deal with the body's waste products. Shielding against harmful external influences such as radiation and micro-meteorites may also be necessary. Components of the life support system are life-critical, and are designed and constructed using safety engineering techniques.

Human physiological & metabolic needs.

A crewmember of typical size requires approximately 5 kg (total) of food, water, and oxygen per day to perform the standard activities on a space mission, and outputs a similar amount in the form of waste solids, waste liquids, and carbon dioxide. The mass breakdown of these metabolic parameters is as follows: 0.84 kg of oxygen, 0.62 kg of food, and 3.52 kg of water consumed, converted through the body's physiological processes to 0.11 kg of solid wastes, 3.87 kg of liquid wastes, and 1.00 kg of carbon dioxide produced. These levels can vary due to activity level, specific to mission assignment, but will correlate to the principles of mass balance. Actual water use during space missions is typically double the specified values mainly due to non-biological use (i.e. personal cleanliness). Additionally, the volume and variety of waste products varies with mission duration to include hair, finger nails, skin flaking, and other biological wastes in missions exceeding one week in length. Other environmental considerations such as radiation, gravity, noise, vibration, and lighting also factor into human physiological response in space, though not with the more immediate effect that the metabolic parameters have.

Atmosphere

Space life support systems maintain atmospheres composed, at a minimum, of oxygen, water vapor and carbon dioxide. The partial pressure of each component gas adds to the overall barometric pressure.

By reducing or omitting diluents (constituents other than oxygen, e.g., nitrogen and argon) the total pressure can be lowered to a minimum of 21 kPa, the partial pressure of oxygen in the Earth's atmosphere at sea level. This can lighten spacecraft structures, reduce leaks and simplify the life support system.

However, the elimination of diluent gases substantially increases fire risks, especially in ground operations when for structural reasons the total cabin pressure must exceed the external atmospheric pressure. For this reason, most modern crewed spacecraft use conventional air (nitrogen/oxygen) atmospheres and use pure oxygen only in pressure suits during extravehicular activity where acceptable suit flexibility mandates the lowest inflation pressure possible.

Water

Water is consumed by crewmembers through drinking, cleaning activities, EVA thermal control, and emergency uses. It must be stored, used, and reclaimed (from waste water) efficiently since no in-situ sources currently exist for the environments reached in the course of human space exploration.

Food

Life support systems often include an indoor plant cultivation system which allows food to be grown within buildings and/or vessels. Often, the system is designed so that it reuses all (otherwise lost) nutrients. This is done, for example, by composting toilets which reintegrate waste material (excrement) back into the system, allowing the nutrients to be taken up by the food crops. The food coming from the crops is then consumed again by the system's users and the cycle continues.

Microbe detection and control

The NASA LOCAD (Lab-on-a-Chip Applications Development) project is working on systems to help detect bacterial and fungal growths in spacecraft used for long-duration spaceflight.

Space vehicle systems

Space Shuttle

For the Space Shuttle, NASA includes in the ECLSS category systems that provide both life support for the crew and environmental control for payloads. The *Shuttle Reference Manual* contains ECLSS sections on: Crew Compartment Cabin Pressurization, Cabin Air Revitalization, Water Coolant Loop System, Active Thermal Control System, Supply and Waste Water, Waste Collection System, Waste Water Tank, Airlock Support, Extravehicular Mobility Units, Crew Altitude Protection System, and Radioisotope Thermoelectric Generator Cooling and Gaseous Nitrogen Purge for Payloads.

Orion Crew Module

The Orion crew module life support system is being designed by Lockheed Martin in Houston, Texas.

Soyuz

The life support system on the Soyuz spacecraft is called the Kompleks Sredstv Obespecheniya Zhiznideyatelnosti (KSOZh).

EVA Systems

Extra-vehicular activity (EVA) systems primarily consist of the traditional space suit, but can also include self-contained individual spacecraft.

Space suits

Both space suit models currently in use, the U.S. EMU and the Russian Orlan, include Primary Life Support Systems (PLSSs) allowing the user to work independently without an umbilical connection from a spacecraft. A space suit must provide life support, either through an umbilical connection or an independent PLSS.

Medical issues

Effects of microgravity

Medical data from astronauts in low earth orbits for long periods, dating back to the 1970s, show several adverse effects of a microgravity environment: loss of bone density, decreased muscle strength and endurance, postural instability, and reductions in aerobic capacity. Over time these deconditioning effects can impair astronauts' performance or increase their risk of injury.

In a weightless environment, astronauts put almost no weight on the back muscles or leg muscles used for standing up. Those muscles then start to weaken and eventually get smaller. If there is an emergency at landing, the loss of muscles, and consequently the loss of strength can be a serious problem. Sometimes, astronauts can lose up to 25% of their muscle mass on long term flights. When they get back to ground, they will be considerably weakened and will be out of action for a while.

Astronauts experiencing weightlessness will often lose their orientation, get motion sickness, and lose their sense of direction as their bodies try to get used to a weightless environment. When they get back to Earth, or any other mass with gravity, they have to readjust to the gravity and may have problems standing up, focusing their gaze, walking and turning. Importantly, those body motor disturbances after changing from different gravities only get worse the longer the exposure to little gravity. These changes will affect operational activities including approach and landing, docking, remote manipulation, and emergencies that may happen while landing. This can be a major roadblock to mission success.

Weightlessness

Astronauts on the International Space Station display an example of weightlessness. Michael Foale can be seen exercising in the foreground.

Weightlessness is a phenomenon experienced by people during free-fall. The term **zero gravity** is often used as a synonym. Weightlessness in orbit is not the result of the force of gravity being eliminated, or even significantly reduced, by distance (in fact, the influence of the Earth's gravity at an altitude of 200 km is only 6% less than at the Earth's surface). Rather, the loss of the influence of gravity is due to the inertial motion of the flight path.

It is helpful to realize that (to an approximation limited by tidal forces) gravity cannot be felt as a force, by either objects or persons. Only the forces that resist gravity, or act apart from it, can be felt by people, or measured by accelerometers. These other forces (such as the force of the ground pushing upward on the feet) are those that produce the sensation and force of weight. Objects following inertial paths do not feel these other forces, and thus feel no g-force, and thus experience weightlessness.

Weightlessness, the sensation of feeling no forces, typically occurs when an object or person is falling freely, in orbit, in deep space (far from a planet, star, or other massive body), in an airplane following a particular parabolic flight path (e.g., the "Vomit Comet"), or in one of several other more unusual situations.

The physics of weightlessness

Weightlessness occurs whenever all forces applied to a person or object are *uniformly distributed* across the object's mass (as in a uniform gravitational field), or when the object is not acted upon by any force. This is in contrast with typical human experiences in which a non-uniform force is acting, such as:

- standing on the ground, sitting in a chair on the ground, etc., where gravity is countered by the **reaction force** of the ground
- flying in a plane, where a reaction force is transmitted from the **lift** the wings provide (special trajectories which form an exception are described below)
- during atmospheric reentry, or during the use of a parachute, when **atmospheric drag** decelerates a vehicle
- during an orbital maneuver in a spacecraft, or during the launch phase, when rocket engines provide **thrust**

In cases where an object is *not* weightless, as in the above examples, a force acts *non-uniformly* on the person or object in question. Aero-dynamic lift, drag, and thrust are all non-uniform forces (they are applied at a point or surface, rather than acting on the entire mass of an object), and thus prevent the phenomenon of weightlessness. This non-uniform force may also be transmitted to an object at the point of contact with a second object, such as the contact between the surface of the Earth and one's feet, or between a parachute harness and one's body.

Gravity is a field force which can usually be considered to act uniformly on the mass of all people and objects in the frame of reference. This assumption is valid when the size of the region being considered is small relative to its distance from the center of mass of the gravitational attractor. The small size of a person relative to the radius of Earth is one such example. In contrast, objects near a black hole are subject to a highly non-uniform gravitational field.

Terminology

Apparent weight

While the technical definition of *weight* is the size of the force of gravity acting on an object, humans experience their own body weight as a result of what is called *apparent weight*, or the normal force applied to a person by the surface on which the person is standing or sitting. In the absence of this reaction force, a person would be in free-fall, and would experience weightlessness. It is the transmission of this reaction force through the human body, and the resultant compression and tension of the body's tissues, that results in the sensation of weight.

Because of the distribution of mass throughout a person's body, the magnitude of the reaction force varies between a person's feet and head. At any horizontal cross-section of a person's body (as with any column), the size of the compressive force being resisted by the tissues below the cross-section is equal to the weight of the portion of the body above the cross-section. (In the arms, the reaction force is equal to the weight of the portion of the arm *below* the cross-section, and is a *tensile*, rather than a compressive, force, just as in a hanging rope.)

Zero gravity: several views of the state

Sensititivity to forces

In Newton's view, astronauts in Earth orbit are in free fall, since in one sense they are “falling” around the Earth. In effect, they are falling toward the Earth, but moving sideways enough to continuously miss it. The net result is they follow the curvature of the Earth, always falling, but never hitting.

One way to view this situation, is to note that gravity by itself does not produce a weight-like force (a g-force) that people can directly sense, since gravity acts upon all parts of the body and the body only senses mechanical stresses (which to a good approximation, gravity does not produce, by itself). Thus, even a person standing on the Earth does not actually feel the pull of "gravity," but actually feels only the push of the ground, acting upward. If this push of the ground is suddenly removed (for example, in a free fall in an elevator), the person experiences weightlessness, because all the forces which have caused the sensation of "weight" have been removed, even though gravitational interactions continue.

Often, the terms *zero gravity* or *reduced gravity* are used to mean weightlessness as it is experienced by orbiting spacecraft. The idea of gravitation itself being greatly reduced in this situation is not technically accurate in the physics of Newton, although it is accurate in the physics of Einstein (general relativity).

Spacecrafts are held in orbit by the gravity of the planet which they are orbiting. In Newtonian physics, the sensation of weightlessness experienced by astronauts is not the result of there being zero gravitational acceleration (as seen from the Earth), but of there being no g-force that an astronaut can feel because of the free-fall condition, and also there being zero difference between the acceleration of the spacecraft and the acceleration of the astronaut. Space journalist James Oberg explains the phenomenon this way:

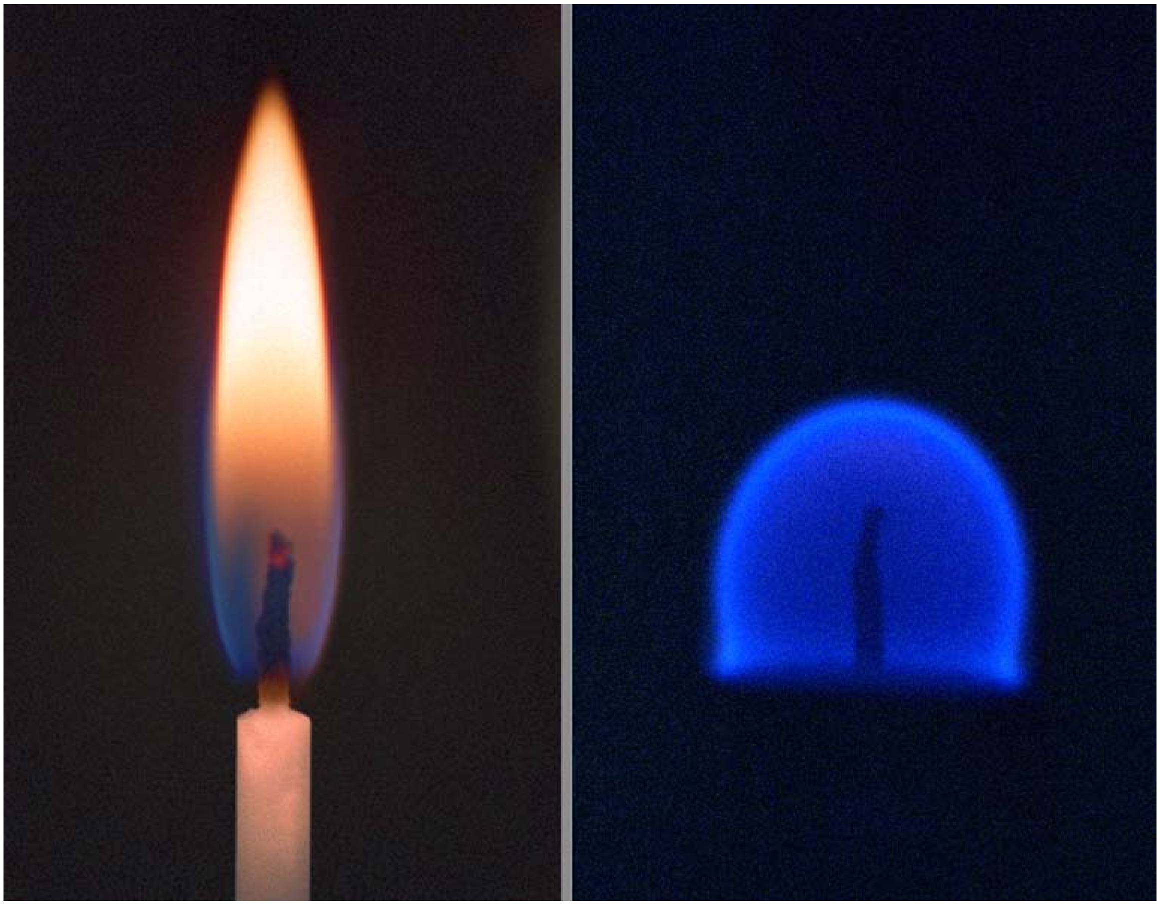
The myth that satellites remain in orbit because they have "escaped Earth's gravity" is perpetuated further (and falsely) by almost universal misuse of the word "zero gravity" to describe the free-falling conditions aboard orbiting space vehicles. Of course, this isn't true; gravity still exists in space. It keeps satellites from flying straight off into interstellar emptiness. What's missing is "weight", the resistance of gravitational attraction by an anchored structure or a counterforce. Satellites stay in space because of their tremendous horizontal speed, which allows them — while being unavoidably pulled toward Earth by gravity — to fall "over the horizon." The ground's curved withdrawal along the Earth's round surface offsets the satellites' fall toward the ground. Speed, not position or lack of gravity, keeps satellites in orbit around the earth.

Relativity

To a modern physicist working with Einstein's general theory of relativity, the situation is even more complicated than is suggested above. Einstein's theory suggests that it actually is valid to consider that objects in inertial motion (such as falling in an elevator, or in a parabola in an airplane, or orbiting a planet) can indeed be considered to experience a local loss of the gravitational field responsible for their general motion. Thus, in the point of view (or frame) of the astronaut or orbiting ship, there actually is nearly-zero proper acceleration (the acceleration felt locally), just as would be the case far out in space, away from any mass. It is thus valid to consider that most of the gravitational field in such situations is actually absent from the point of view of the falling observer, just as the colloquial view suggests. However, this loss of gravity for the falling or orbiting observer, in Einstein's theory, is due to the falling motion itself, and (again as in Newton's theory) not due to increased distance from the Earth. However, the gravity nevertheless is considered to be absent. In fact, Einstein's realization that a pure gravitational interaction cannot be felt, if all other forces are removed, was the key insight to leading him to the view that the gravitational "force" can in some ways be viewed as non-existent.

In the theory of general relativity, the only gravity which remains for the observer following a falling path or "inertial" path, is that which is due to non-uniformities in the gravitational field. This non-uniformity, which is a tidal effect, constitutes part of the "microgravity" which is felt by all spacially-extended objects falling in any natural gravitational field originating from a mass. The reason is that such a field will have its origin in a centralized place (the compact mass), and thus will vary slightly in strength, according to distance from the mass. Thus, the term "microgravity," described above as a "techweenie" term from the Newtonian view, is a quite valid and descriptive term in the Einsteinian or general relativistic view.

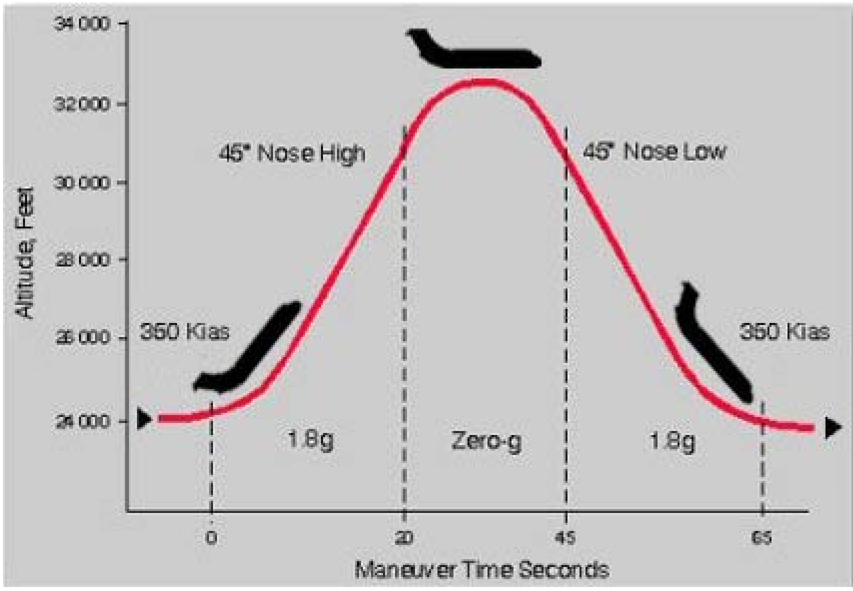
Microgravity



Candle flame in orbital conditions (right) versus on Earth (left)

The term *microgravity* is used to describe environments where the force of gravity is present but has a negligible effect. Objects in orbit are not perfectly weightless due to several effects.

Weightless and reduced weight environments



Zero gravity flight maneuver

Reduced weight in aircraft

Airplanes have been used since 1959 to provide a nearly weightless environment in which to train astronauts, conduct research, and film motion pictures. Such aircraft are commonly referred by the nickname "Vomit Comet".

To create a weightless environment, the airplane flies in a six-mile long parabolic arc, first climbing, then entering a powered dive. During the arc, the propulsion and steering of the aircraft are controlled such that the drag (air resistance) on the plane is canceled out, leaving the plane to behave as it would if it were free-falling in a vacuum. During this period, the plane's occupants experience about 25 seconds of weightlessness, before experiencing about 25 seconds of 2 *g* acceleration (twice their normal weight) during the pull-out from the parabola. A typical flight lasts around two hours, during which 40 parabolas are flown.

NASA's KC-135A plane ascending for a zero gravity maneuver

NASA's Reduced Gravity Aircraft

Versions of such airplanes have been operated by NASA's Reduced Gravity Research Program since 1973, where the unofficial nickname originated. NASA later adopted the official nickname 'Weightless Wonder' for publication. NASA's current Reduced Gravity Aircraft, "Weightless Wonder VI", a McDonnell Douglas C-9, is based at Ellington Field (KEFD), near Lyndon B. Johnson Space Center.

NASA's Microgravity University - Reduced Gravity Flight Opportunities Plan, also known as the Reduced Gravity Student Flight Opportunities Program, allows teams of undergraduates to submit a microgravity experiment proposal. If selected, the teams design and implement their experiment, and students are invited to fly on NASA's Vomit Comet.

European Space Agency A300 Zero-G

The European Space Agency flies parabolic flights on a specially-modified Airbus A300 aircraft, in order to research microgravity. The ESA flies *campaigns* of three flights on consecutive days, each flight flying about 30 parabolas, for a total of about 10 minutes of weightlessness per flight. The ESA campaigns are currently operated from Bordeaux - Mérignac Airport in France by the company Novespace, while the aircraft is operated by the Centre d'essais en Vol (CEV - French Test Flight Centre). The first ESA Zero-G flights were in 1984, using a NASA KC-135 aircraft in Houston, Texas. As of March 2006, the ESA has flown 43 campaigns. Other aircraft it has used include the Russian Ilyushin Il-76 MDK and French Caravelle.

Ecuadorian T-39 Condor

Ecuadorian crew in weightlessness onboard the T-39 FG1-CONDOR

The Ecuadorian Space Agency jointly operates, with the Ecuadorian Air Force, the Ecuadorian Micro Gravity Flight Program, using a T-39 Sabreliner, modified in-house to fly "cybernetically assisted" parabolas. It has been in operation since May 2008. It is the first Latin American microgravity aircraft. On June 19, 2008, the plane carried seven-year-old Jules Nader as he set the first Guinness World record for the youngest human being to fly in microgravity. Nader worked on a fluid dynamics experiment designed by his brother, Gerard Nader.

Others

The Zero Gravity Corporation, founded in 1993 by Peter Diamandis, Byron Lichtenberg, and Ray Cronise, operates a modified Boeing 727 which flies parabolic arcs like those of NASA's Reduced Gravity Aircraft. Flights may be purchased for both tourism and research purposes.

Reduced weight in pilot training

People have differing reactions to reduced weight sensations, and these reactions can compromise flight safety if an aircraft pilot is not trained to respond properly, particularly in an emergency. Normally in flight training, flight instructors will gradually introduce reduced weight maneuvers, while carefully monitoring the student pilot. Most students become accustomed to the sensation and are able to perform satisfactorily with some training. Students who are not able to overcome their anxiety are not able to complete flight training.

Ground-based drop facilities

Zero-gravity testing at the NASA Zero Gravity Research Facility

Ground-based facilities that produce weightless conditions for research purposes are typically referred to as drop tubes or drop towers.

NASA's Zero Gravity Research Facility, located at the Glenn Research Center in Cleveland, Ohio, is a 145-meter vertical shaft, largely below the ground, with an integral vacuum drop chamber, in which an experiment vehicle can have a free fall for a duration of 5.18 seconds, falling a distance of 132 meters. The experiment vehicle is stopped in approximately 4.5 meters of pellets of expanded polystyrene and experiences a peak deceleration rate of 65 *g*.

Also at NASA Glenn is the 2.2 Second Drop Tower, which has a drop distance of 24.1 meters. Experiments are dropped in a drag shield, in order to reduce the effects of air drag. The entire package is stopped in a 3.3 meter tall air bag, at a peak deceleration rate of approximately 20 *g*. While the Zero Gravity Facility conducts one or two drops per day, the 2.2 Second Drop Tower can conduct up to twelve drops per day.

NASA's Marshall Space Flight Center hosts another drop tube facility that is 105 meters tall and provides a 4.6 second free fall under near-vacuum conditions.

Humans cannot utilize these gravity shafts, as the deceleration experienced by the drop chamber would likely kill or seriously injure anyone using them; 20 *g* is about the highest deceleration that a fit and healthy human being can withstand momentarily without sustaining injury.

Other drop facilities worldwide include:

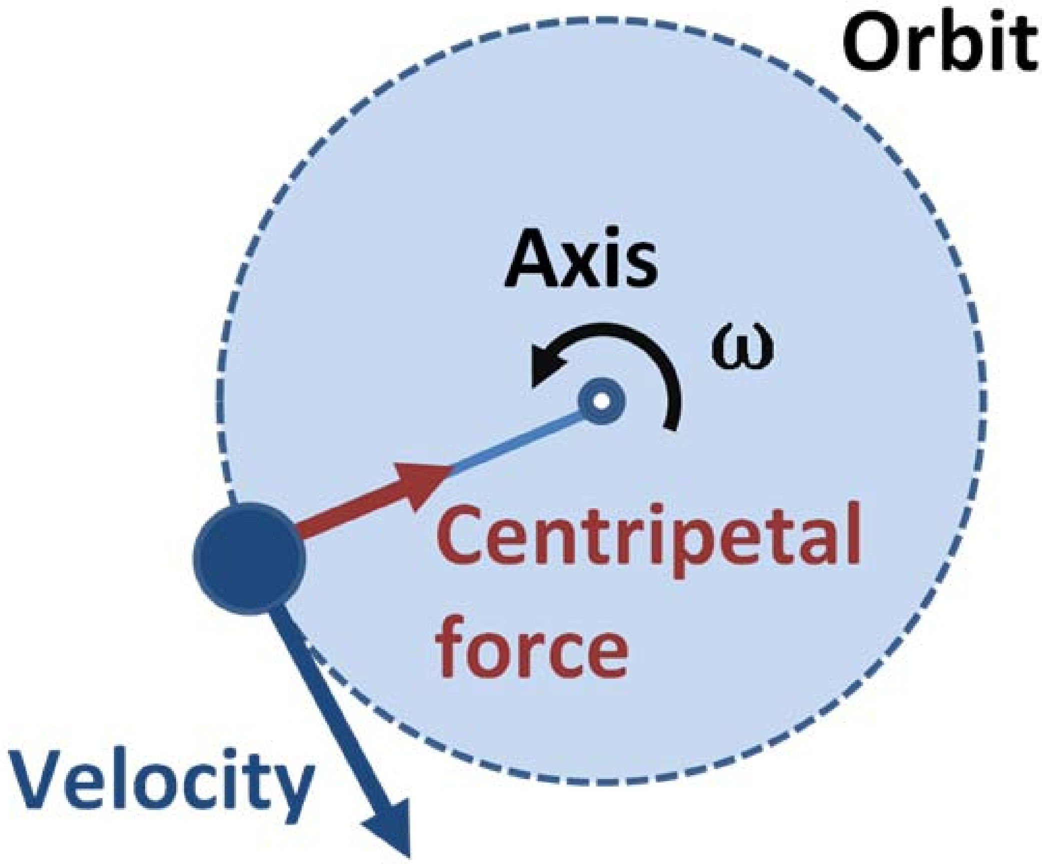
- Micro-Gravity Laboratory of Japan (MGLAB) – 4.5 s free fall
- Experimental drop tube of the metallurgy department of Grenoble – 3.1 s free fall
- Fallturm Bremen University of Bremen in Bremen – 4.74 s free fall
- Queensland University of Technology Drop Tower - 2.0 s free fall

Neutral buoyancy

Weightlessness can also be simulated with the use of neutral buoyancy, in which human subjects and equipment are placed in a water environment and weighted or buoyed until they hover in place. NASA uses neutral buoyancy to prepare for extra-vehicular activity (EVA) at its Neutral Buoyancy Laboratory. Neutral buoyancy is also used for EVA research at the University of Maryland's Space Systems Laboratory, which operates the only neutral buoyancy tank at a college or university.

It is important to note that neutral buoyancy is not identical to weightlessness. Gravity still acts on all objects in a neutral buoyancy tank; thus, astronauts in neutral buoyancy training still feel their full body weight *within* their spacesuits, though the suit and astronaut together are under no net force. Drag is also a significant factor when moving in a neutral buoyancy environment, whereas astronauts on EVA do not experience any drag.

Weightlessness in a spacecraft



The relationship between acceleration and velocity vectors in an orbiting spacecraft

Astronaut Marsha Ivins demonstrates the effect of weightlessness on long hair during STS-98

Long periods of weightlessness occur on spacecraft outside a planet's atmosphere, provided no propulsion is applied and the vehicle is not rotating. Weightlessness does not occur when a spacecraft is firing its engines or when re-entering the atmosphere, even if the resultant acceleration is constant. The thrust provided by the engines acts at the surface of the rocket nozzle rather than acting uniformly on the spacecraft, and is transmitted through the structure of the spacecraft via compressive and tensile forces to the objects or people inside.

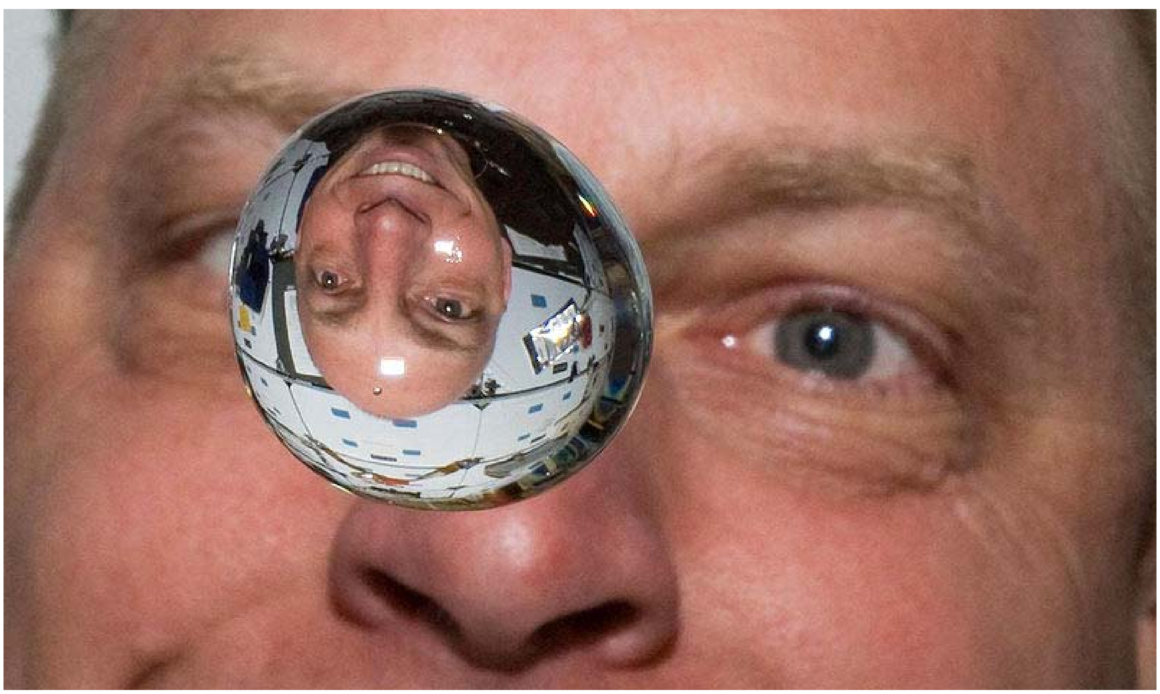
Weightlessness in an orbiting spacecraft is physically identical to free-fall, with the difference that gravitational acceleration causes a net change in the *direction*, rather than the *magnitude*, of the spacecraft's velocity. This is because the acceleration vector is perpendicular to the velocity vector.

In typical free-fall, the acceleration of gravity acts along the direction of an object's velocity, linearly increasing its speed as it falls toward the Earth, or slowing it down if it is moving away from the Earth. In the case of an orbiting spacecraft, which has a velocity vector largely *perpendicular* to the force of gravity, gravitational acceleration does not produce a net change in the object's speed, but instead acts centripetally, to constantly "turn" the spacecraft's velocity as it moves around the Earth. Because the acceleration vector turns along with the velocity vector, they remain perpendicular to each other. Without this change in the direction of its velocity vector, the spacecraft would move in a straight line, leaving the Earth altogether.

Weightlessness at the center of a planet

The net gravitational force is zero *everywhere* within a hollow, spherically symmetrical planet. This is known as the shell theorem. For example, if a person were able to survive at the center of Earth, the main remaining gravity would be that of the Sun at Earth, which is 600μ*g*.

Health effects of weightlessness



Astronaut Clayton Anderson watches as a water bubble floats in front of him on the Discovery. Cohesion plays a bigger role in space

Following the advent of space stations that can be inhabited for long periods of time, exposure to weightlessness has been demonstrated to have some deleterious effects on human health. Humans are well-adapted to the physical conditions at the surface of the Earth. In response to an extended period of weightlessness, various physiological systems begin to change and atrophy. Though these changes are usually temporary, long term health issues can result.

The most common problem experienced by humans in the initial hours of weightlessness is known as space adaptation syndrome or SAS, commonly referred to as space sickness. Symptoms of SAS include nausea and vomiting, vertigo, headaches, lethargy, and overall malaise. The first case of SAS was reported by cosmonaut Gherman Titov in 1961. Since then, roughly 45% of all people who have flown in space have suffered from this condition. The duration of space sickness varies, but in no case has it lasted for more than 72 hours, after which the body adjusts to the new environment. NASA jokingly measures SAS using the "Garn scale", named for United States Senator Jake Garn, whose SAS during STS-51-D was the worst on record. Accordingly, one "Garn" is equivalent to the most severe possible case of SAS.

The most significant adverse effects of long-term weightlessness are muscle atrophy and deterioration of the skeleton, or spaceflight osteopenia. These effects can be minimized through a regimen of exercise. Astronauts subject to long periods of weightlessness wear pants with elastic bands attached between waistband and cuffs to compress the leg bones and reduce osteopenia. Other significant effects include fluid redistribution (causing the "moon-face" appearance typical of pictures of astronauts in weightlessness), a slowing of the cardiovascular system, decreased production of red blood cells, balance disorders, and a weakening of the immune system. Lesser symptoms include loss of body mass, nasal congestion, sleep disturbance, excess flatulence, and puffiness of the face. These effects begin to reverse quickly upon return to the Earth.

Many of the conditions caused by exposure to weightlessness are similar to those resulting from aging. Scientists believe that studies of the detrimental effects of weightlessness could have medical benefits, such as a possible treatment for osteoporosis and improved medical care for the bed-ridden and elderly.

Effects on non-human organisms

Russian scientists have observed differences between cockroaches conceived in space and their terrestrial counterparts. The space-conceived cockroaches grew more quickly, and also grew up to be faster and tougher.

Fowl eggs which are fertilized in microgravity may not develop properly.

Technical adaptation due to weightlessness

Weightlessness can cause serious problems on technical instruments, especially those consisting of many mobile parts. Physical processes that depend on the weight of a body (like convection, cooking water or burning candles) act differently without a certain amount of gravity. Cohesion and advection play a bigger role in space. Everyday work like washing or going to the bathroom are not possible without adaptation. To use toilets in space, like the one on the International Space Station, astronauts have to fasten themselves to the seat. A fan creates suction that carries the waste away. Drinking is done with a straw or from tubes.

Radiation

Without proper shielding the crews of missions beyond low Earth orbit (LEO) might be at risk from high-energy protons emitted by solar flares. Lawrence Townsend of the University of Tennessee and others have studied the most powerful solar flare ever recorded. That flare was seen by the British astronomer Richard Carrington in September 1859. Radiation doses astronauts would receive from a Carrington-type flare could cause acute radiation sickness and possibly even death.

Another type of radiation, galactic cosmic rays, present further challenges to human spaceflight beyond LEO.

Radiation damage to the immune system

There is also some scientific concern that extended space flight might slow down the body's ability to protect itself against diseases. Some of the problems are a weakened immune system and the activation of dormant viruses in the body. Radiation can cause both short and long term consequences to the bone marrow stem cells which create the blood and immune systems. Because the interior of a spacecraft is so small, a weakened immune system and more active viruses in the body can lead to a fast spread of infection.

Isolation

During long missions, astronauts are isolated and confined into small spaces. Depression, cabin fever and other psychological problems may result that impact crew safety and mission success.

Astronauts may not be able to quickly return to Earth or receive medical supplies, equipment or personnel if a medical emergency occurs. The astronauts may have to rely for long periods on their limited existing resources and medical advice from the ground.

Launch safety

Space launch is the earliest part of a flight that reaches space. Space launch involves liftoff, when a rocket or other space launch vehicle leaves the ground at the start of a flight. Liftoff is of two main types: rocket launch, the current conventional method, non-rocket spacelaunch where other forms of propulsion are employed, including airbreathing jet engines or other kinds.

Issues with reaching space

Definition of space

Space has no physical edge to it as the atmospheric pressure gradually reduces with altitude; instead, the edge of space is defined by convention, often the Kármán line of 100 km. Other definitions have been created as well, in the US for example space has been defined as 50 miles.

Energy

Therefore, by definition for spaceflight to occur, sufficient altitude is necessary. This implies a minimum specific gravitational potential energy needs to be overcome: for the Kármán line this is approximately 1 MJ/kg.

In practice, a higher energy than this is needed to be expended due to losses such as airdrag, propulsive efficiency, cycle efficiency of engines that are employed and gravity drag.

G-forces

Many cargoes, particularly humans have a limiting g-force that they can survive. For humans this is about 3-6 g. Some launchers such as gun launchers would give accelerations in the hundred or thousands of g and thus are completely unsuitable.

Reliability

Launchers vary with respect to their reliability for achieving the mission.

Safety

Safety is the probability of causing injury or loss of life. Unreliable launchers are not necessarily unsafe, whereas reliable launchers are usually, but not invariably safe.

Apart from catastrophic failure of the launch vehicle itself other safety hazards include depressurisation, and the Van Allen radiation belts which preclude orbits which spend long periods within them.

Sustained spaceflight

Suborbital launch

Orbital launch

In addition, if orbit is required, then much higher energy is needed as some sideways speed is needed. The speed needed depends on the altitude, less speed is needed at high altitude; however allowing for the extra potential energy due to altitude, overall, far more energy is needed to orbit at high altitude than lower.

The speed needed to maintain an orbit, near to the Earth's surface corresponds to a sideways speed of about 7.8 km/s, an energy of about 60MJ/kg. This is several times the energy per kg of practical rocket propellant mixes.

Gaining the kinetic energy is awkward as the airdrag tends to slow the spacecraft, so rocket powered spacecraft generally fly a compromise trajectory that leaves the thickest part of the atmosphere very early on, and then fly on for example, a Hohmann transfer orbit to reach the particular orbit that is required. This minimises the airdrag as well as minimising the time that the vehicle spends holding itself up. Airdrag is a significant issue with essentially all proposed and current launch systems, although usually less so than the difficulty of obtaining enough kinetic energy to simply reach orbit at all.

Escape velocity

If the Earth's gravity is to be overcome entirely then sufficient energy must be obtained by a spacecraft to exceed the depth of the gravity potential energy well. Once this has occurred, provided the energy is not lost in any non conservative way, then the vehicle will leave the influence of the Earth. The depth of the potential well depends on the vehicle's position, and the energy depends on the vehicles speed. The kinetic energy exceeds the potential energy then escape occurs. At the Earths surface this occurs at a speed of 11.2 km/s, but in practice a much higher speed would be needed due to airdrag.

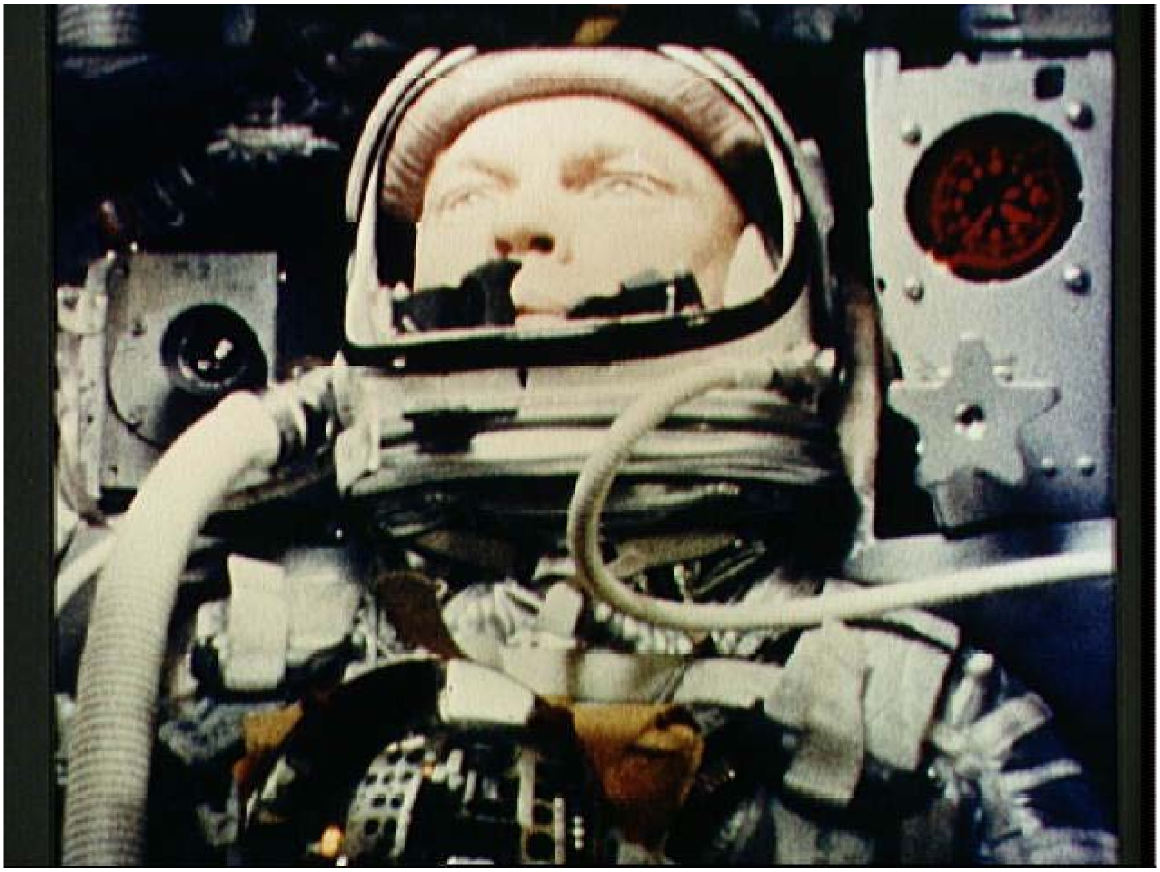
Chapter- 3

American Space Programs

Project Mercury

The Mercury spacecraft with escape tower

Project Mercury was the first human spaceflight program of the United States. It ran from 1959 through 1963 with the goal of putting a human in orbit around the Earth. The Mercury-Atlas 6 flight on February 20, 1962, was the first American flight to achieve this goal.



John Glenn during the first orbital manned Mercury flight in 1962

The program included 20 unmanned launches, followed by two suborbital and six orbital flights with astronaut pilots. Early planning and research were carried out by the National Advisory Committee for Aeronautics, but the program was officially conducted its successor, NASA. Mercury laid the groundwork for Project Gemini and the follow-on Apollo moon-landing program.

The project name came from Mercury, a Roman mythological god who is often seen as a symbol of speed. Mercury is also the name of the innermost planet of the solar system, which moves faster than any other and hence provides an image of speed, although Project Mercury had no other connection to that planet.

The Mercury program cost approximately $384 million, the equivalent of about $2.9 billion in 2010 dollars.

Goals and guidelines

The goals of the program were to orbit a manned spacecraft around Earth, investigate the pilot's ability to function in space and to recover both pilot and spacecraft safely. NASA also established program guidelines: existing technology and off-the-shelf equipment should be used wherever practical, the simplest and most reliable approach to system design would be followed, an existing launch vehicle would be employed to place the spacecraft into orbit, and use of a progressive and logical test program. Project requirements for the spacecraft were that it must be fitted with a reliable launch escape system to separate the spacecraft and its crewman from the launch vehicle in case of impending failure, the pilot must be given the capability of manually controlling spacecraft attitude, the spacecraft must carry a retrorocket system capable of reliably providing the necessary impulse to bring the spacecraft out of orbit, a zero-lift body utilizing drag braking would be used for reentry, and that the spacecraft design must satisfy the requirements for a water landing.

Research and development

On October 7, 1958, T. Keith Glennan, the first administrator of NASA, approved the Mercury project. On December 17 Glennan announced Project Mercury publicly.

Mercury spacecraft at McDonnell in St. Louis, Missouri

On December 29, 1958 North American Aviation was awarded a contract to design and build Little Joe boosters for test flights. In January 1959 McDonnell Aircraft Corporation was chosen to be prime contractor for the Mercury spacecraft, and the contract for 12 spacecraft was awarded in February. In April seven astronauts, known as the Mercury Seven or more formally as Astronaut Group 1, were selected to participate in the Mercury program.

In May 1959 North American Aviation delivered the first two Little Joe boosters, and in June the Big Joe booster was delivered. In July the planned use of Jupiter boosters in the Mercury program was canceled in favor of Atlas flights. In October General Electric delivered to McDonnell the ablative heat shield designated for installation on the first Mercury spacecraft. In December the launch vehicle for Mercury-Redstone 1 was ready to begin static tests installed on a test stand at ABMA.

In January 1960 NASA awarded Western Electric Company a contract for the Mercury tracking network. The value of the contract was over $33 million. Also in January, McDonnell delivered the first production-type Mercury spacecraft, less than a year after award of the formal contract. On February 12, Christopher C. Kraft, Jr. was appointed to head the Mercury operations coordination group. Kraft was asked to, "come up with a basic mission plan. You know, the bottom-line stuff on how we fly a man from a launch pad into space and back again. It would be good if you kept him alive." In April, the first spacecraft was delivered to Wallops Island for the beach-abort test. The test was completed successfully on May 9.

Spacecraft

Because of their small size, it was said that the Mercury spacecraft were worn, not ridden. With 1.7 m^3 of habitable volume, the spacecraft was just large enough for the single crew member. Inside were 120 controls: 55 electrical switches, 30 fuses and 35 mechanical levers. The spacecraft was designed by Max Faget and NASA's Space Task Group.

Despite the astronauts' test pilot experience NASA at first envisioned them as "minor participants" during their flights, causing many conflicts between the astronauts and engineers during the spacecraft's design. Nonetheless, contrary to other reports, the project's leaders always intended for pilots to be able to control their spacecraft, as they valued humans' ability to contribute to missions' success. John Glenn's manual attitude adjustments during the first orbital flight was an example of the value of such control. The astronauts requested—and received—a larger window and manual reentry controls.

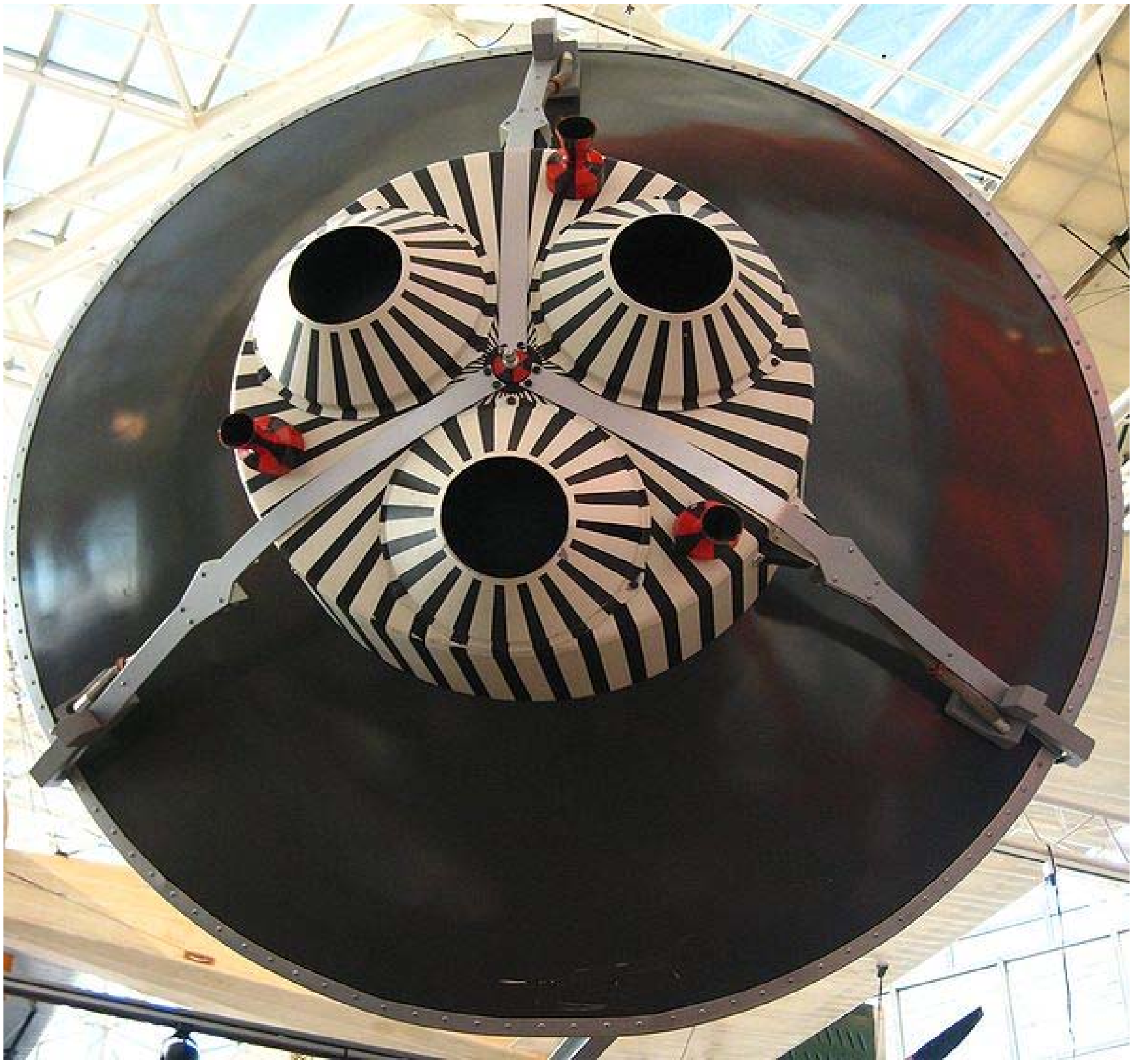
Mercury 8 spacecraft in Hanger S at Cape Canaveral

During the launch phase of the mission, the Mercury spacecraft and astronaut were protected from launch vehicle failures by the Launch Escape System. The LES consisted of a solid fuel, 52,000 lbf (231 kN) thrust rocket with three engine bells mounted on a tower above the spacecraft. In the event of a launch abort, the LES would fire for one second, pulling the spacecraft and astronaut away from the booster and a possible explosion. The spacecraft would then descend on its parachute recovery system. After booster engine cutoff (BECO), the LES was no longer needed and was separated from the spacecraft by a solid fuel, 800 lbf (3.6 kN) thrust jettison rocket that fired for 1.5 seconds.

After a successful liftoff, the spacecraft fired three small clustered solid-fuel, 400 lbf (1.8 kN) thrust rockets for 1 second to separate the spacecraft from the launch vehicle. These rockets were called the posigrade rockets.

The spacecraft was only equipped with attitude control thrusters; after orbit insertion and before retrofire they could not change the orbit. There were three sets of high and low powered automatic control jets and separate manual jets, one for each axis (yaw, pitch, and roll), and supplied from two separate fuel tanks, one automatic and one manual. The pilot could use any one of the three thruster systems and fuel them from either of the two fuel tanks to provide spacecraft attitude control. The Mercury spacecraft was designed to be completely controllable from the ground in the event that something impaired the pilot's ability to function.

The spacecraft had three solid-fuel, 1000 lbf (4.5 kN) thrust retrorockets that fired for 10 seconds each. One was sufficient to return the spacecraft to Earth if the other two failed. The firing sequence (known as ripple firing) required firing the first retro, followed by the second retro five seconds later (while the first was still firing). Five seconds after that, the third retro fired (while the second retro was still firing).



Mercury heat shield and retrorocket pack

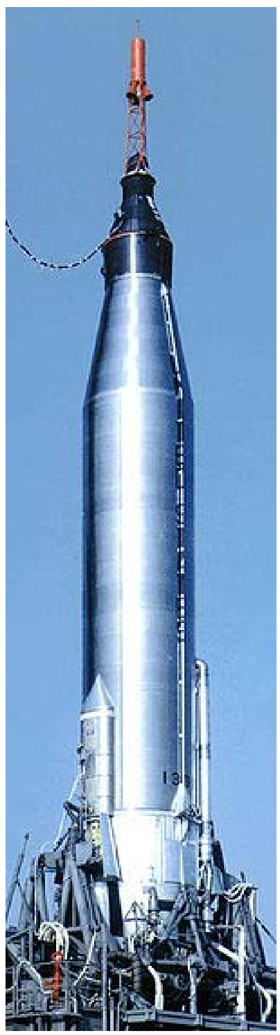
There was a small hinged metal flap at the nose of the spacecraft called the spoiler. If the spacecraft started to reenter nose first (another stable reentry attitude for the spacecraft), airflow over the spoiler would flip the spacecraft around to the proper, heatshield-first reentry attitude, a technique called shuttlecocking. During reentry, the astronaut would experience about 8 g-forces on an orbital mission, and 11-12 gs on a suborbital mission.

Initial designs for the spacecraft suggested the use of either beryllium heat-sink heat shields or an ablative shield. Extensive testing settled the issue - ablative shields proved to be reliable (so much so that the initial shield thickness was safely reduced, allowing a lower total spacecraft weight), and were easier to produce — at that time, beryllium was only produced in sufficient quantities by a single company in the U.S. — and cheaper.

NASA ordered 20 production spacecraft, numbered 1 through 20, from McDonnell Aircraft Company, St. Louis, Missouri. Five of the 20, Nos. 10, 12, 15, 17, and 19, were not flown. Spacecraft No. 3 and No. 4 were destroyed during unmanned test flights. Spacecraft No. 11 sank and was recovered from the bottom of the Atlantic Ocean after 38 years. Some spacecraft were modified after initial production (refurbished after launch abort, modified for longer missions, etc.) and received a letter designation after their number, examples 2B, 15B. Some spacecraft were modified twice; for example, spacecraft 15 became 15A and then 15B.

A number of Mercury Boilerplate spacecraft (including mockup/prototype/replica spacecrafts, made from non-flight materials or lacking production spacecraft systems and/or hardware) were also made by NASA and McDonnell Aircraft. They were designed and used to test spacecraft recovery systems, and escape tower and rocket motors. Formal tests were done on test pad at Langley and at Wallops Island using the Little Joe and Big Joe Atlas rockets.

Boosters



Mercury-Atlas 9

The Mercury program used three boosters:

- Little Joe - 8 suborbital robotic flights, 2 carrying monkeys. Launch escape system tests.
- Redstone - 4 suborbital robotic flights, 1 carrying a chimpanzee; 2 piloted suborbital flights.
- Atlas - 4 suborbital robotic flights; 2 orbital robotic flights, 1 carrying a chimpanzee; 4 piloted orbital flights.

Little Joe and a Mercury Boilerplate was used to test the escape tower and abort procedures. Redstone was used for suborbital flights, and Atlas for orbital ones. Starting in October, 1958, Jupiter missiles were also considered as suborbital launch vehicles for the Mercury program, but were cut from the program in July 1959 due to budget constraints. The Atlas boosters required extra strengthening in order to handle the increased weight of the Mercury spacecraft beyond that of the nuclear warheads they were designed to carry. Little Joe was a solid-propellant booster designed specially for the Mercury program. The Titan missile was also considered for use for later Mercury missions; however, the Mercury program was terminated before these missions were flown. The Titan was used for the Gemini program which followed Mercury.

The Mercury program used a Scout booster for a single flight, Mercury-Scout 1, which launched a small satellite intended to evaluate the worldwide Mercury Tracking Network. The rocket was destroyed by the Range Safety Officer after 44 seconds of flight.

Unmanned flights

Mercury Control at Cape Canaveral, Florida

The program included 20 robotic launches. Not all of these were intended to reach space and not all were successful in completing their objectives. Four of these flights included non-human primates, starting with the fifth flight (1959) which launched a Rhesus macaque named Sam (after the Air Force's **S**chool of **A**erospace **M**edicine). The Mercury program's complete roster of non-human space-farers is given below:

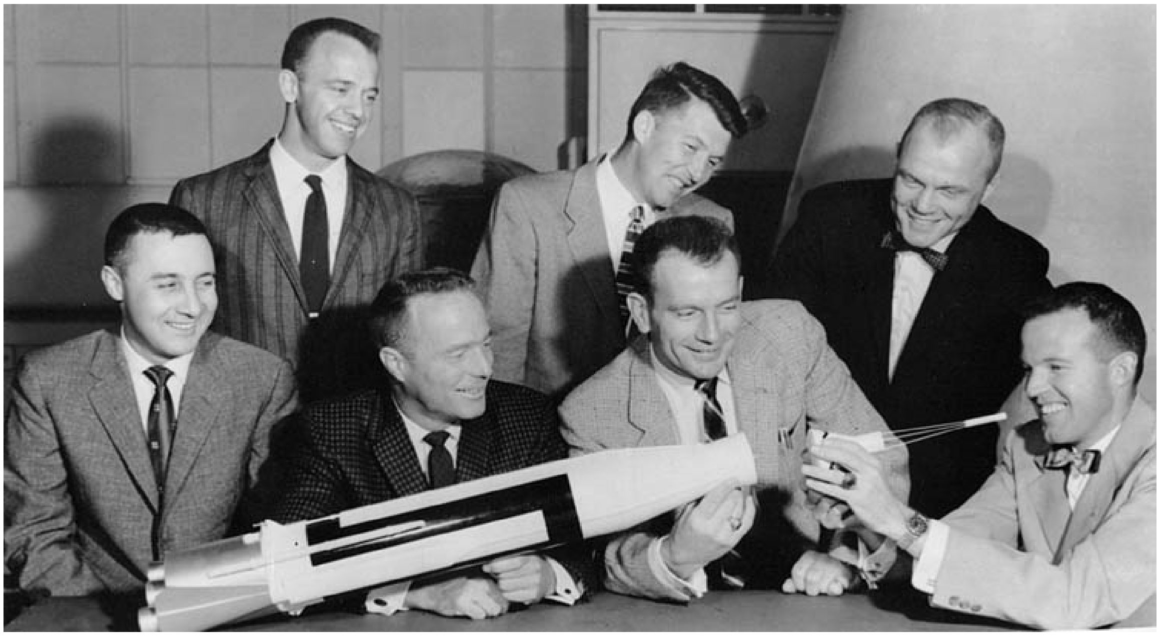
- Sam, a Rhesus macaque, launched 4 December 1959 on Little Joe 2 to 85 km altitude.
- Miss Sam, a Rhesus macaque, launched 21 January 1960 on Little Joe 1B to 15 km altitude.
- Ham, a chimpanzee, launched 31 January 1961 on Mercury-Redstone 2 for a suborbital flight.
- Enos, a chimpanzee, launched 29 November 1961 on Mercury-Atlas 5 for a 2-orbit flight.

Mission	Rocket	Call Sign	Launch Date	Launch Time	Duration	Remarks
Mercury-Jupiter	Jupiter	N/A	N/A	N/A	N/A	Canceled in July, 1959 - Proposed suborbital launch vehicle for Mercury. Not flown.
Little Joe 1	Little Joe	LJ-1	21 August 1959	N/A	00d 00h 00 m 20s	Test of launch escape system during flight.
Big Joe 1	Atlas 10-D	Big Joe 1	9 September 1959	N/A	00d 00h 13 m	Test of heat shield and Atlas / spacecraft interface.
Little Joe 6	Little Joe	LJ-6	4 October 1959	N/A	00d 00h 05 m 10s	Test of spacecraft aerodynamics and integrity.
Little Joe 1A	Little Joe	LJ-1A	4 November 1959	N/A	00d 00h 08 m 11s	Test of launch escape system during flight.
Little Joe 2	Little Joe	LJ-2	4 December 1959	N/A	00d 00h 11 m 06s	Carried Sam the monkey to 85 kilometres in altitude.
Little Joe 1B	Little Joe	LJ-1B	21 January 1960	N/A	00d 00h 08 m 35s	Carried Miss Sam the monkey to 9.3 statute miles (15 kilometres) in altitude.

Beach Abort	Launch escape system	Beach Abort	9 May 1960	N/A	00d 00h 01 m 31s	Test of the Off-The-Pad abort system.
Mercury-Atlas 1	Atlas	MA-1	29 July 1960	13:13 UTC	00d 00h 03 m 18s	First flight of Mercury spacecraft and Atlas Booster.
Little Joe 5	Little Joe	LJ-5	8 November 1960	N/A	00d 00h 02 m 22s	First flight of a production Mercury spacecraft.
Mercury-Redstone 1	Redstone	MR-1	21 November 1960	N/A	00d 00h 00 m 02s	Launched 4 inches (100 mm). Settled back on pad due to electrical malfunction.
Mercury-Redstone 1A	Redstone	MR-1A	19 December 1960	N/A	00d 00h 15 m 45s	First flight of Mercury spacecraft and Redstone booster.
Mercury-Redstone 2	Redstone	MR-2	31 January 1961	16:55 UTC	00d 00h 16 m 39s	Carried Ham the Chimpanzee on suborbital flight.
Mercury-Atlas 2	Atlas	MA-2	21 February 1961	14:10 UTC	00d 00h 17 m 56s	Test of Mercury spacecraft and Atlas Booster.
Little Joe 5A	Little Joe	LJ-5A	18 March 1961	N/A	00d 00h 23 m 48s	Test of the launch escape system during the most severe conditions of a launch.

Mercury-Redstone BD	Redstone	MR-BD	24 March 1961	17:30 UTC	00d 00h 8 m 23s	Redstone Booster Development - test flight.
Mercury-Atlas 3	Atlas	MA-3	25 April 1961	16:15 UTC	00d 00h 07 m 19s	Test of Mercury spacecraft and Atlas Booster.
Little Joe 5B	Little Joe	AB-1	28 April 1961	N/A	00d 00h 05 m 25s	Test of the launch escape system during the most severe conditions of a launch.
Mercury-Atlas 4	Atlas	MA-4	13 September 1961	14:09 UTC	00d 01h 49 m 20s	Test of Mercury spacecraft and Atlas Booster. Completed 1 orbit.
Mercury-Scout 1	Scout	MS-1	1 November 1961	15:32 UTC	00d 00h 00 m 44s	Test of Mercury tracking network.
Mercury-Atlas 5	Atlas	MA-5	29 November 1961	15:08 UTC	00d 03h 20 m 59s	Carried Enos the Chimpanzee on a two orbit flight.

Manned flights



The Mercury Seven astronauts with an Atlas model July 12, 1962. L to R: Grissom, Shepard, Carpenter, Schirra, Slayton, Glenn, Cooper

Wernher von Braun and astronaut Gordon Cooper in the blockhouse during MR-3 recovery operations May 5, 1961.

Astronauts

The first Americans to venture into space were drawn from a group of 110 military pilots chosen for their flight test experience and because they met certain physical requirements. NASA announced the selection of seven of these - known as the Mercury Seven - as astronauts on 9 April 1959, though only six of the seven flew Mercury missions, after Slayton was grounded due to a heart condition.

- Malcolm Scott Carpenter, USN (born 1925)
- Leroy Gordon "Gordo" Cooper, Jr., USAF (1927–2004)
- John Herschel Glenn, Jr., USMC (born 1921) First American to orbit the Earth.
- Virgil Ivan "Gus" Grissom, USAF (1926–1967) Died during Apollo 1 Pre-Launch Test
- Walter Marty "Wally" Schirra, Jr., USN (1923–2007)
- Alan Bartlett Shepard, Jr., USN (1923–1998) First American in space
- Donald Kent "Deke" Slayton, USAF (1924–1993) Grounded in 1962 due to irregular heartbeat, reinstated in 1972 and later flew on the Apollo-Soyuz Test Project in 1975.

Beginning with Alan Shepard's *Freedom 7* flight, the astronauts named their own spacecraft, and all added "7" to the name to acknowledge the teamwork of their fellow astronauts.

Piloted Mercury launches

Mission	Callsign	Rocket	Designation	Pilot	Launch Date	Launch Time	Duration	Remarks
Mercury-Redstone 3	*Freedom 7*	Redstone	MR-3	Shepard	5 May 1961	14:34 UTC	00d 00h 15 m 28s	First American to make a suborbital flight into space.
Mercury-Redstone 4	*Liberty Bell 7*	Redstone	MR-4	Grissom	21 July 1961	12:20 UTC	00d 00h 15 m 37s	Second suborbital flight. Spacecraft sank before recovery when hatch unexpectedly blew off, recovered 1999.

Mercury-Atlas 6	*Friendship 7*	Atlas	MA-6	Glenn	20 February 1962	14:47 UTC	00d 04h 55 m 23s	First American to orbit the Earth (for a total of 3 orbits). Spacecraft's retropack retained during re-entry due to concerns about heatshield.
Mercury-Atlas 7	*Aurora 7*	Atlas	MA-7	Carpenter	24 May 1962	12:45 UTC	00d 04h 56 m 15s	3 orbits. Reentered off-target by 402 km. Pilot Carpenter replaced Deke Slayton.
Mercury-Atlas 8	*Sigma 7*	Atlas	MA-8	Schirra	3 October 1962	12:15 UTC	00d 09h 13 m 11s	Carried out engineering tests. 6 orbits.
Mercury-Atlas 9	*Faith 7*	Atlas	MA-9	Cooper	15 May 1963	13:04 UTC	01d 10h 19 m 49s	First American in space for over a day. Last American to orbit the Earth solo. 22 orbits.
Mercury-Atlas 10	*Freedom 7-II*	Atlas	MA-10	Shepard	N/A	N/A	N/A	Intended to be a 3-day mission in October 1963. Cancelled 13 June 1963.
Mercury-Atlas 11		Atlas	MA-11	Grissom	N/A	N/A	N/A	Intended to be a 1-day mission in 1963. Cancelled by October 1962.

Mercury-Atlas 12		Atlas	MA-12	Schirra	N/A	N/A	N/A	Intended to be a 1-day mission in 1963. Cancelled by October 1962.

Piloted Mercury Launches

Mercury flight insignias

Mercury program monument at LC-14

Flight patches that purport to be patches from various Mercury missions are available to the public. In reality, these patches were designed by private entrepreneurs long after the Mercury program ended. When genuine flight patches were created by crews in the Gemini program, this caused a public demand for Mercury flight patches, which was filled by these private entrepreneurs. The only patches the Mercury astronauts wore were the NASA logo and a name tag. Each manned Mercury spacecraft, however, was decorated with a flight insignia. These are the genuine Mercury flight insignias.

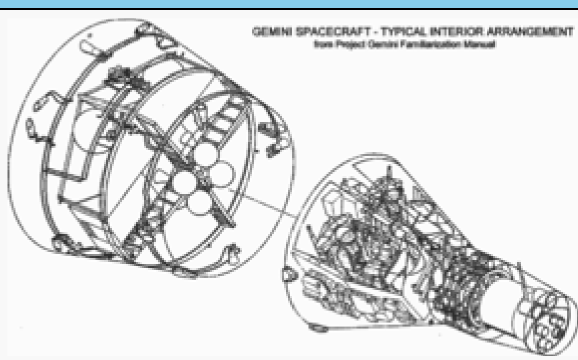
Project Mercury Issue of 1962

Project Mercury stamp

In 1962, the US Post Office honored the Mercury-Atlas 6 flight with the Project Mercury commemorative stamp, the first U.S. postal issue to depict a manned spacecraft. The stamp first went on sale in Cape Canaveral, Florida on February 20, 1962, the same day as the Project Mercury launch putting the first U.S. astronaut into orbit.

Project Gemini

McDonnell Gemini spacecraft		
 Gemini 7 in orbit, as seen by the crew of Gemini 6.		
Volume:	90 ft³	2.55 m³
Weights		
Retrograde module:	1,303 lb	591 kilograms (1,300 lb)

Equipment module:	2,815 lb	1,277 kilograms (2,820 lb)
Total:	8,490 lb	3,851 kilograms (8,490 lb)
Rocket engines		
Retros (solid fuel) x 4:	2,500 lbf ea	11.12 kN
Reentry Control System (N_2O_4/MMHH) x 16:	25 lbf ea	111 N
OAMS (N_2O_4/MMHH) x 2:	85 lbf ea	378 N
OAMS (N_2O_4/MMHH) x 6:	100 lbf ea	445 N
OAMS (N_2O_4/MMHH) x 8:	25 lbf ea	111 N
Performance		
Endurance:	14 days	206 orbits
Apogee:	250 miles	402 kilometres (250 mi)
Perigee:	100 miles	160 kilometres (99 mi)
Spacecraft delta v:	728 ft/s	222 m/s
Gemini spacecraft diagram		
 Gemini spacecraft diagram (NASA)		
McDonnell Gemini Spacecraft		

Project Gemini was the second human spaceflight program of NASA, the civilian space agency of the United States government. Project Gemini was conducted between Projects Mercury and Apollo, with 10 manned flights occurring in 1965 and 1966.

Its objective was to develop techniques for advanced space travel, notably those necessary for Apollo, whose objective was to land humans on the Moon. Gemini missions included missions long enough for a trip to the Moon and back, the first American spacewalks, and new orbital maneuvers including rendezvous and docking. All manned Gemini flights were launched from Cape Canaveral, Florida atop Titan II GLV boosters.

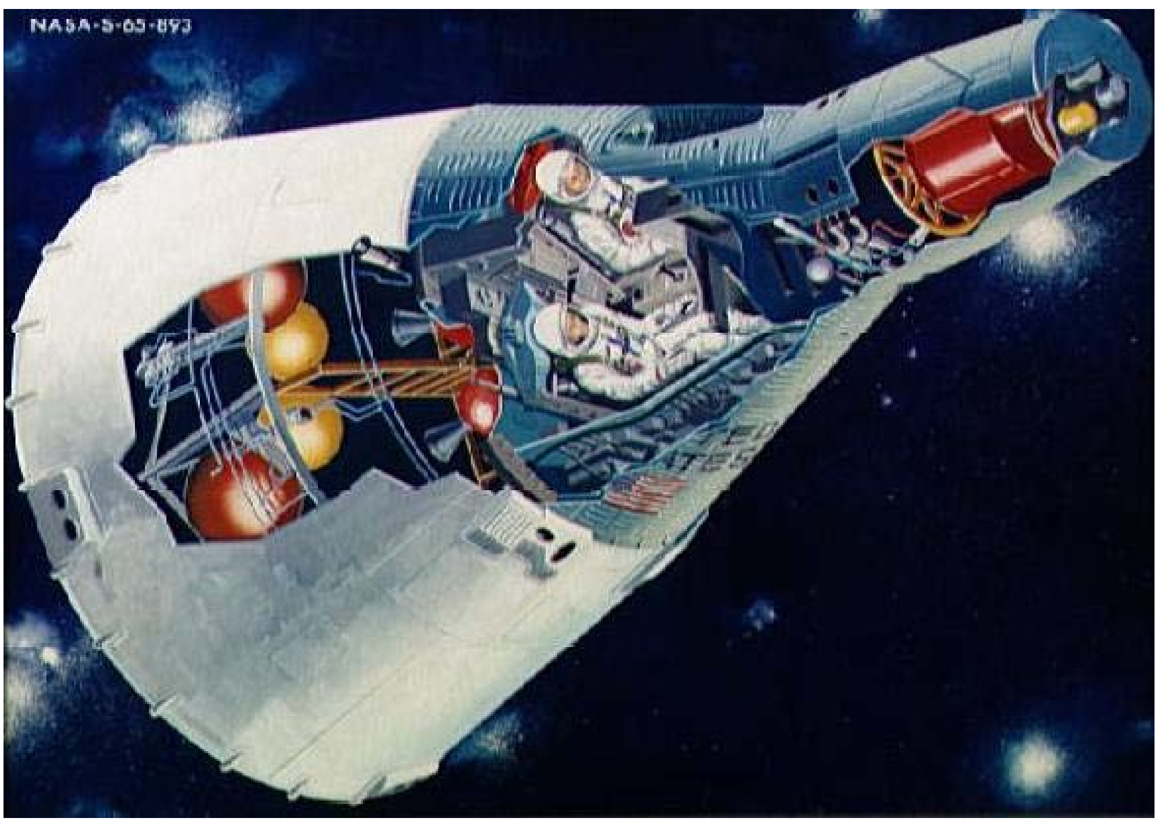
Program objectives

After the existing Apollo program was chartered by President John F. Kennedy on May 25, 1961 to land men on the Moon, it became evident to NASA officials that a follow-on to the Mercury program was required to develop certain spaceflight capabilities in support of Apollo. Originally introduced on December 7 as *Mercury Mark II*, it was re-christened Project Gemini on January 3, 1962. The major objectives were:

- To demonstrate endurance of humans and equipment to spaceflight for extended periods, at least eight days required for a Moon landing, to a maximum of two weeks
- To effect rendezvous and docking with another vehicle, and to maneuver the combined spacecraft using the propulsion system of the target vehicle
- To demonstrate Extra-Vehicular Activity (EVA), or space-"walks" outside the protection of the spacecraft, and to evaluate the astronauts' ability to perform tasks there
- To perfect techniques of atmospheric reentry and landing at a pre-selected location
- To provide the astronauts with zero-gravity and rendezvous and docking experience required for Apollo

Spacecraft

Replica of a Gemini spacecraft at the Neil Armstrong Air and Space Museum



A cutaway of the Project Gemini spacecraft

Gemini's primary difference from Mercury was that the earlier spacecraft had all systems other than the reentry rockets situated within the capsule, most of which were accessed through the astronaut's hatchway. In contrast, Gemini housed power, propulsion, and life support systems in a detachable Equipment Module located behind the Reentry Module, which made it similar to the Apollo Command/Service Module design. Many components in the capsule itself were reachable through their own small access doors.

The original intention was for Gemini to land on solid ground instead of at sea, using a Rogallo wing paraglider rather than a parachute, with the crew seated upright controlling the forward motion of the craft. To facilitate this, the paraglider did not attach just to the nose of the craft, but to an additional attachment point for balance near the heat shield. This cord was covered by a strip of metal which ran between the twin hatches. However, this design was ultimately dropped and parachutes were used in a conventional nose-up sea landing.

Early short-duration missions had their electrical power supplied by batteries; later endurance missions used the first fuel cells in manned spacecraft.

The "Gemini" designation comes from the fact that each spacecraft held two crewmen, as "gemini" in Latin means "twins". Gemini is also the name of the third constellation of the Zodiac and its twin stars, Castor and Pollux.

Unlike Mercury, which could only change its orientation in space, the Gemini spacecraft could translate in all six directions, and alter its orbit. It was designed to dock with the Agena Target Vehicle, which had its own large rocket engine which was used to perform large orbital changes.

Gemini was the first American manned spacecraft to include an onboard computer, the Gemini Guidance Computer, to facilitate management and control of mission maneuvers. It was also unlike other NASA craft in that it used ejection seats, in-flight radar and an artificial horizon—devices borrowed from the aviation industry. Using ejection seats to propel astronauts to safety was first employed by the Soviet Union in the Vostok craft manned by cosmonaut Yuri Gagarin.

The Gemini program cost $5.4 billion.

Team

Gemini was designed by a Canadian, Jim Chamberlin, formerly the chief aerodynamicist on the Avro Arrow fighter interceptor program with Avro Canada. Chamberlin joined NASA along with 25 senior Avro engineers after cancellation of the Arrow program, and became head of the U.S. Space Task Group’s engineering division in charge of Gemini. The prime contractor was McDonnell Aircraft, which had also been the prime contractor for the Mercury capsule.

In addition, astronaut Gus Grissom was heavily involved in the development and design of the Gemini spacecraft. He writes in his posthumous 1968 book *Gemini!* that the realization of Project Mercury's end and the unlikelihood of his having another flight in that program prompted him to focus all of his efforts on the upcoming Gemini Program.

The Gemini program was managed by the Manned Spacecraft Center, Houston, Texas, under direction of the Office of Manned Space Flight, NASA Headquarters, Washington, D.C, Dr. George E. Mueller, Associate Administrator of NASA for Manned Space Flight, served as acting director of the Gemini program. William C. Schneider, Deputy Director of Manned Space Flight for Mission Operations, served as mission director on all Gemini flights beginning with Gemini VI.

Guenther Wendt was a McDonnell engineer who supervised launch preparations for both the Mercury and Gemini programs. His team was responsible for completion of the complex pad close-out procedures just prior to spacecraft launch, and he personally closed the hatches before flight. The astronauts appreciated his taking absolute authority over, and responsibility for, the condition of the spacecraft and developed a good-humored rapport with him.

Astronauts

The following astronauts flew on the 10 manned Gemini missions:

Group	Astronaut	Service	Mission
Astronaut Group 1	L. Gordon Cooper	USAF	Gemini V
	Virgil "Gus" Grissom		Gemini III
	Walter M. Schirra	USN	Gemini VI-A
Astronaut Group 2	Neil A. Armstrong	Civilian	Gemini VIII
	Frank Borman	USAF	Gemini VII
	Charles "Pete" Conrad	USN	Gemini V Gemini XI
	James A. Lovell	USN	Gemini VII Gemini XII
	James A. McDivitt	USAF	Gemini IV
	Thomas P. Stafford		Gemini VI-A Gemini IX-A
	Edward H. White II		Gemini IV
	John W. Young	USN	Gemini III Gemini X
Astronaut Group 3	Edwin "Buzz" Aldrin	USAF	Gemini XII
	Eugene A. Cernan	USN	Gemini IX-A
	Michael Collins	USAF	Gemini X
	Richard F. Gordon	USN	Gemini XI
	David R. Scott	USAF	Gemini VIII

Mission	Commander	Group	Flight #	Pilot	Group	Flight #
Gemini III	Grissom	1	2	Young	2	1

Gemini IV	McDivitt	2	1	White	2	1
Gemini V	Cooper	1	2	Conrad	2	1
Gemini VI	Schirra	1	2	Stafford	2	1
Gemini VII	Borman	2	1	Lovell	2	1
Gemini VIII	Armstrong	2	1	Scott	3	1
Gemini IX	Stafford	2	2	Cernan	3	1
Gemini X	Young	2	2	Collins	3	1
Gemini XI	Conrad	2	2	Gordon	3	1
Gemini XII	Lovell	2	2	Aldrin	3	1

Crew selection

Deke Slayton, as head of the Astronaut Office, had the main role in the choice of crews for the Gemini program. With Gemini it became a procedure that each flight had a primary crew and backup crew, and that the backup crew would rotate to primary crew status three flights later. Slayton also intended for first choice of mission commands to be given to the four remaining active astronauts of the Mercury Seven: Alan Shepard, Grissom, Cooper, and Schirra. (John Glenn had retired from NASA in January 1964 and Scott Carpenter, who was blamed by some in NASA management for the problematic reentry of *Aurora 7*, was on leave to participate in the Navy's SEALAB project and was grounded from flight in July 1964. Slayton himself continued to be grounded due to a heart problem.)

In late 1963, Slayton selected Shepard and Stafford for Gemini 3, McDivitt and White for Gemini 4, and Schirra and Young for Gemini 5 (which was to be the first Agena rendezvous mission). Backup crew for Gemini 3 was Grissom and Borman, who were also slated for Gemini 6, to be the first long-duration mission. Finally Conrad and Lovell were assigned as backup crew for Gemini 4.

Delays in the production of the Agena Target Vehicle caused the first rearrangement of the crew rotation. The Schirra and Young mission was bumped to Gemini 6 and they now were the backup crew for Shepard and Stafford. Grissom and Borman now had their long-duration mission assigned to Gemini 5.

The second rearrangement occurred when Shepard developed Ménière's disease, an inner ear problem. Grissom was then moved to command Gemini 3. Slayton felt that Young was a better personality match with Grissom and switched Stafford and Young. Finally, Slayton tapped Cooper to command the long-duration Gemini 5. Again for reasons of compatibility, he moved Conrad from backup commander of Gemini 4 to pilot of Gemini 5, and Borman to backup command of Gemini 4. Finally he assigned Armstrong and Elliot See to be the backup crew for Gemini 5.

The third rearrangement of crew assignment occurred when Slayton felt that See wasn't up to the physical demands of EVA on Gemini 8. He reassigned See to be the prime commander of Gemini 9 and put Scott as pilot of Gemini 8 and Charles Bassett as the pilot of Gemini 9.

The fourth and final rearrangement of the Gemini crew assignment occurred after the deaths of See and Bassett when their trainer jet crashed, ironically into a McDonnell building which held their Gemini 9 capsule in St. Louis. The backup crew of Stafford and Cernan was then moved up to the new prime crew of the re-designated Gemini 9A. Lovell and Aldrin were moved from being the backup crew of Gemini 10 to be the backup crew of Gemini 9. This cleared the way through the crew rotation for Lovell and Aldrin to become the prime crew of Gemini 12.

Along with the deaths of Grissom, White, and Roger Chaffee in the fire of Apollo 1, this final arrangement helped determine the makeup of the first seven Apollo crews, and who would be in position for a chance to be the first to walk on the Moon.

In his autobiography *Deke!* Slayton relates that he would probably have replaced Aldrin with Cernan, the backup pilot for Gemini 12, on Apollo 11 if the second use of the Astronaut Maneuvering Unit (AMU) had been on Gemini 12. (The first use was by Cernan on Gemini IX-A.) Cernan makes a similar claim in his autobiography.

As it happened, despite these random substitutions and similar ones in Apollo, and a different number of unmanned flights in both programs, Slayton's rotation philosophy dominated to create a curious coincidence: most of the Gemini astronauts who went on to fly in Apollo occupied an Apollo mission numbered one more than their corresponding Gemini mission:

- Schirra commanded Gemini 6 and Apollo 7.
- Borman and Lovell flew together on Gemini 7 and Apollo 8.
- David Scott flew on Gemini 8 and Apollo 9.
- Stafford and Cernan flew together on Gemini 9A and Apollo 10.
- Collins flew on Gemini 10 and Apollo 11.
- Conrad and Gordon flew together on Gemini 11 and Apollo 12.
- Lovell commanded Gemini 12 and Apollo 13.

The only exceptions to this pattern were:

- McDivitt, who commanded Gemini 4 and Apollo 9
- Young, who flew Gemini 3, Gemini 10, and Apollo 10
- Armstrong, who commanded Gemini 8 and Apollo 11

Missions

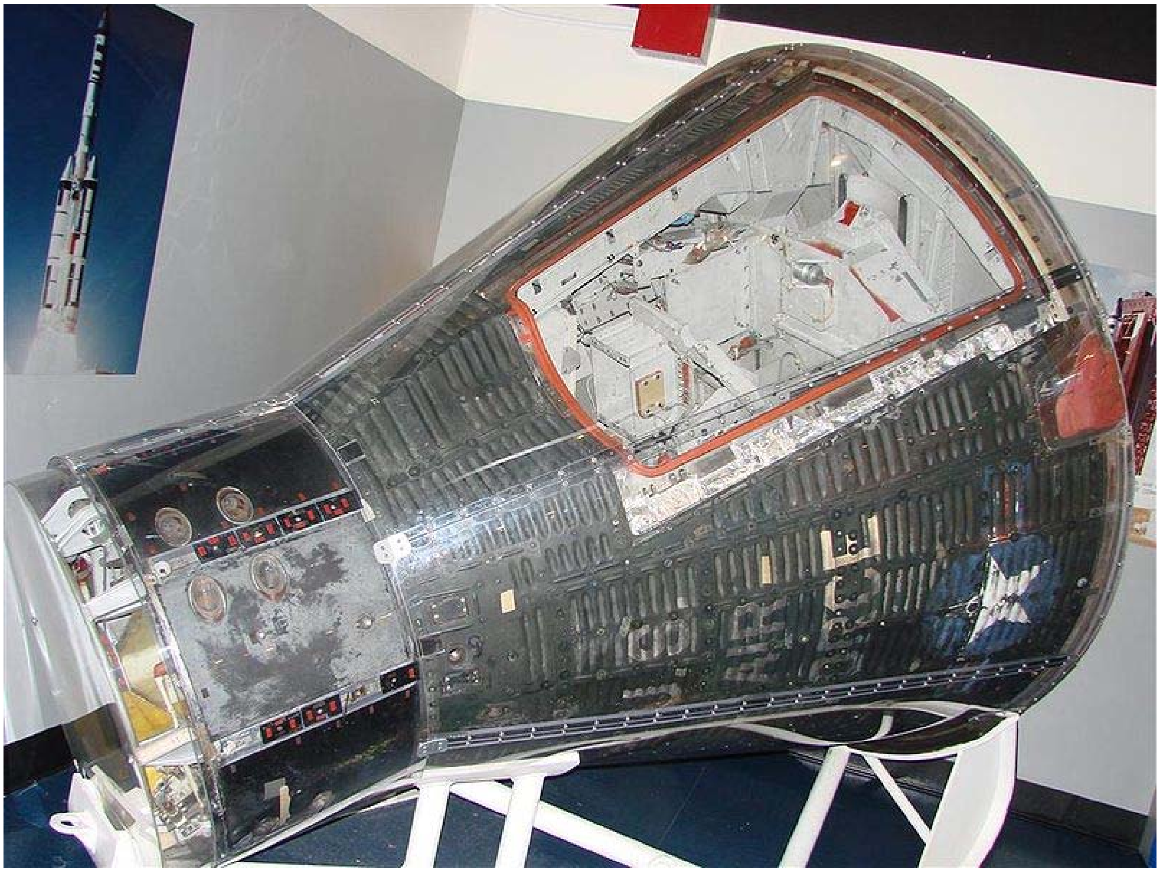
Liftoff of Gemini 6A from Pad 19 with astronauts Walter Schirra and Thomas Stafford aboard (15 December 1965)

There were 12 Gemini flights, including two unmanned flight tests. All were launched by Titan II rockets.

Unmanned events

Mission	LV Serial Nº	Mission Dates	Launch Time	Duration	Remarks
Gemini	GLV-1	8–12 April	16:01 UTC	03d 23h	First test flight of

1	12556	1964			Gemini
Gemini 2	GLV-2 12557	19 January 1965	14:03 UTC	00d 00h 18m 16s	Suborbital flight to test heat shield



Gemini 2 on display at Air Force Space and Missile Museum

Manned events

Mission	LV Serial Nº	Command Pilot	Pilot	Mission Dates	Launch Time	Duration
Gemini III	GLV-3 12558	Grissom	Young	23 March 1965	14:24 UTC	00d 04h 52m 31s
	First manned Gemini flight, three orbits.					
Gemini IV	GLV-4 12559	McDivitt	White	3–7 June 1965	15:15 UTC	04d 01h 56m 12s
	Included first extravehicular activity (EVA) by an American; White's "space walk" was a 22 minute EVA exercise.					
Gemini V	GLV-5 12560	Cooper	Conrad	21–29 August 1965	13:59 UTC	07d 22h 55m 14s
	First week-long flight; first use of fuel cells for electrical power; evaluated					

	guidance and navigation system for future rendezvous missions. Completed 120 orbits.					
Gemini VII	GLV-7 12562	Borman	Lovell	4–18 December 1965	19:30 UTC	13d 18h 35m 01s
	When the original Gemini VI mission was scrubbed because its Agena target for rendezvous and docking failed, Gemini VII was used for the rendezvous instead. Primary objective was to determine whether humans could live in space for 14 days.					
Gemini VI-A	GLV-6 12561	Schirra	Stafford	15–16 December 1965	13:37 UTC	01d 01h 51m 24s
	First space rendezvous accomplished with Gemini VII, station-keeping for over five hours at distances from 0.3 to 90 m (1 to 300 ft).					
Gemini VIII	GLV-8 12563	Armstrong	Scott	16–17 March 1966	16:41 UTC	00d 10h 41m 26s
	Accomplished first docking with another space vehicle, an unmanned Agena stage. While docked, a Gemini spacecraft thruster malfunction caused near-fatal tumbling of the craft, which, after undocking, Armstrong was able to overcome; the crew effected the first emergency landing of a manned U.S. space mission.					
Gemini IX-A	GLV-9 12564	Stafford	Cernan	3–6 June 1966	13:39 UTC	03d 00h 21m 50s
	Rescheduled from May to rendezvous and dock with augmented target docking adapter (ATDA) after original Agena target vehicle failed to orbit. ATDA shroud did not completely separate, making docking impossible. Three different types of rendezvous, two hours of EVA, and 44 orbits were completed.					
Gemini X	GLV-10 12565	Young	Collins	18–21 July 1966	22:20 UTC	02d 22h 46m 39s
	First use of Agena target vehicle's propulsion systems. Spacecraft also rendezvoused with Gemini VIII target vehicle. Collins had 49 minutes of EVA standing in the hatch and 39 minutes of EVA to retrieve experiment from Agena stage. 43 orbits completed.					
Gemini XI	GLV-11 12566	Conrad	Gordon	12–15 September 1966	14:42 UTC	02d 23h 17m 08s
	Gemini record altitude, 1,189.3 kilometres (739.0 mi) (739.2 mi) reached using Agena propulsion system after first orbit rendezvous and docking. Gordon made 33-minute EVA and two-hour standup EVA. 44 orbits.					
Gemini XII	GLV-12 12567	Lovell	Aldrin	11–15 November 1966	20:46 UTC	03d 22h 34m 31s

	Final Gemini flight. Rendezvoused and docked manually with its target Agena and kept station with it during EVA. Aldrin set an EVA record of 5 hours 30 minutes for one space walk and two stand-up exercises, and demonstrated improvements to previous EVA problems.

Gemini-Titan launches and serial numbers

Gemini 6A launch. USAF serial number location on Titan II

The Gemini-Titan launch vehicles, like the Mercury-Atlas vehicles before them, were ordered by NASA through the U. S. Air Force and were in reality missiles. The Gemini-Titan II rockets were assigned U.S. Air Force serial numbers, which were painted in four places on each Titan II (on opposite sides on each of the first and second stages). U.S. Air Force crews maintained Launch Complex 19 and prepared and launched all of the Gemini-Titan II launch vehicles.

The USAF serial numbers assigned to the Gemini-Titan launch vehicles are given in the tables above. Fifteen Titan IIs were ordered in 1962 so the serial is "62-12XXX", but only "12XXX" is painted on the Titan II. The order for the last three of the 15 launch vehicles was cancelled on July 40, 1964, and they were never built. Serial numbers were, however, assigned to them prospectively: *12568* - GLV-13; *12569* - GLV-14; and *12570* - GLV-15.

All Gemini Launches from GT-1 through GT-12

Current location of hardware

Spacecraft

Gemini 1

Destroyed

Gemini 2

Air Force Space & Missile Museum, Cape Canaveral Air Force Station, Fla.

Gemini III

Grissom Memorial, Spring Mill State Park, Mitchell, Ind.

Gemini IV

National Air and Space Museum, Washington D.C.

Gemini V

Johnson Space Center, NASA, Houston, Texas

Gemini VI

Oklahoma History Center, Oklahoma City, Okla.

Gemini VII

Steven F. Udvar-Hazy Center, Chantilly, Va.

Gemini VIII

Armstrong Air and Space Museum, Wapakoneta, Ohio

Gemini IX

Kennedy Space Center, NASA, Cape Canaveral, Fla.

Gemini X

Kansas Cosmosphere and Space Center, Hutchinson, Kan.

Gemini XI

California Museum of Science and Industry, Los Angeles, Calif.

Gemini XII

Adler Planetarium, Chicago, Ill.

Trainers

Gemini 3A - St. Louis Science Center, St. Louis, Mo.

Gemini MOL-B - National Museum of the United States Air Force, Wright-Patterson Air Force Base, Dayton, Ohio

Gemini Trainer - U.S. Space & Rocket Center, Huntsville, Ala.

Gemini Trainer - Goddard Space Flight Center (Visitor Center), NASA, Greenbelt, Md.

Gemini Trainer - Louisville Science Center, Louisville, Ken.

6165 - National Air and Space Museum, Washington D.C. (not on display)

El Kabong - Kalamazoo Air Museum, Kalamazoo, Mich.

Gemini Trainer - Kalamazoo Air Museum, Kalamazoo, Mich.

TTV-2 Royal Museum, Edinburgh, Scotland

Trainer - Pate Museum of Transportation, Fort Worth, Texas

MSC 313 - Private residence, San Jose, Calif.

Rogallo Test Vehicle - White Sands Space Harbor, White Sands, N. M.

TTV-1 - Stephen F. Udvar-Hazy Center, Chantilly, Va.

unnamed - U.S. Air Force Space Museum, Cape Canaveral Air Force Station, Fla.

unnamed - U.S. Air Force Space Museum, Cape Canaveral Air Force Station, Fla.

Gemini Trainer - BDL Aerospace and Flight Museum, NAS Whidbey Island, Oak Harbor, Wash.

Trainer - U.S. Astronaut Hall of Fame, Titusville, Fla.

MSC-307 - USS Hornet Museum, Alameda, Calif.

Proposed applications

McDonnell Aircraft was one of the original bidders on the prime contract for Apollo, but lost out to North American Aviation. McDonnell later sought to extend the Gemini program by proposing a derivative which could be used to fly a cislunar mission and even achieve a manned lunar landing earlier and at less cost than Apollo, but these proposals were rejected by NASA.

Military

The United States Air Force had an interest in the system, and decided to use its own modification of the spacecraft as the crew vehicle for the Manned Orbital Laboratory. To this end, one of the unmanned Gemini spacecraft was refurbished and flown again atop a mockup of the MOL, sent into space by a Titan III-M. This was the first time a spacecraft went into space twice.

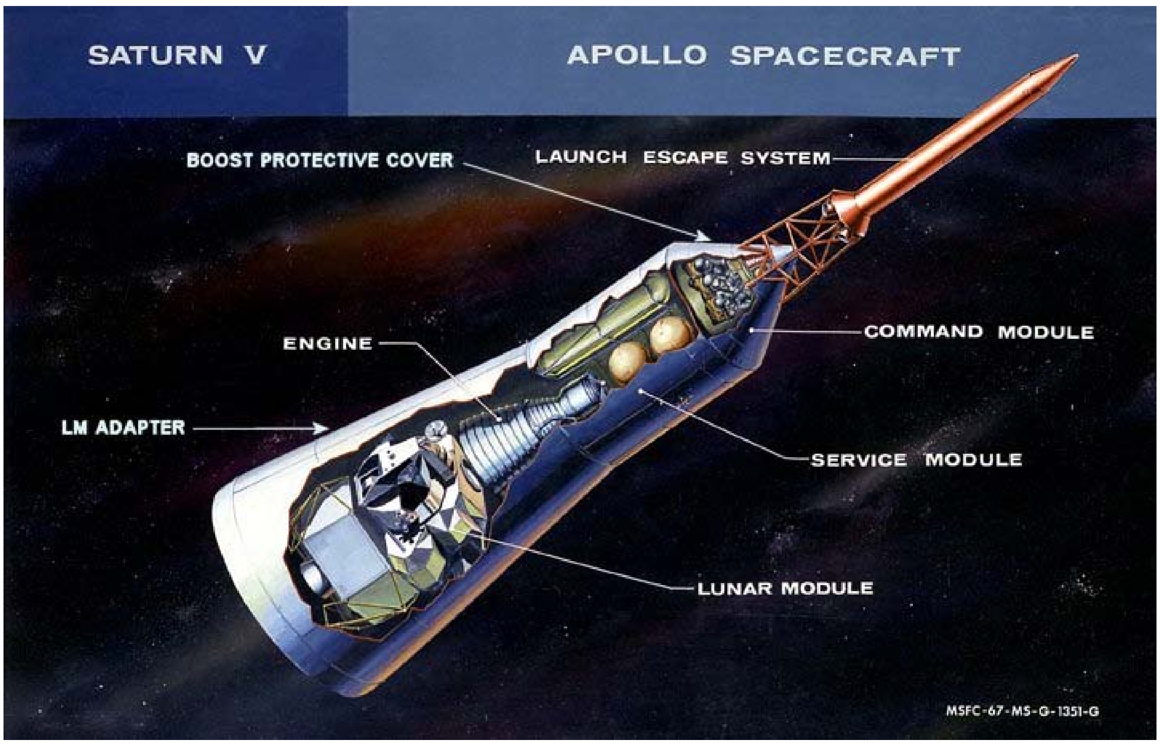
The USAF also had the notion of adapting the Gemini spacecraft for military applications, such as crude observation of the ground (no specialized reconnaissance camera could be carried) and practicing making rendezvous with suspicious satellites. This project was called Blue Gemini. The US Air Force did not like the fact that Gemini would have to be recovered by the US Navy, so they intended for Blue Gemini eventually to use the paraglider and land on three skids, something from the original design of Gemini.

At first some within NASA welcomed sharing of the cost with the USAF, but it was later agreed that NASA was better off operating Project Gemini by itself. MOL was cancelled in 1968 and Blue Gemini too was cancelled without any use by military astronauts.

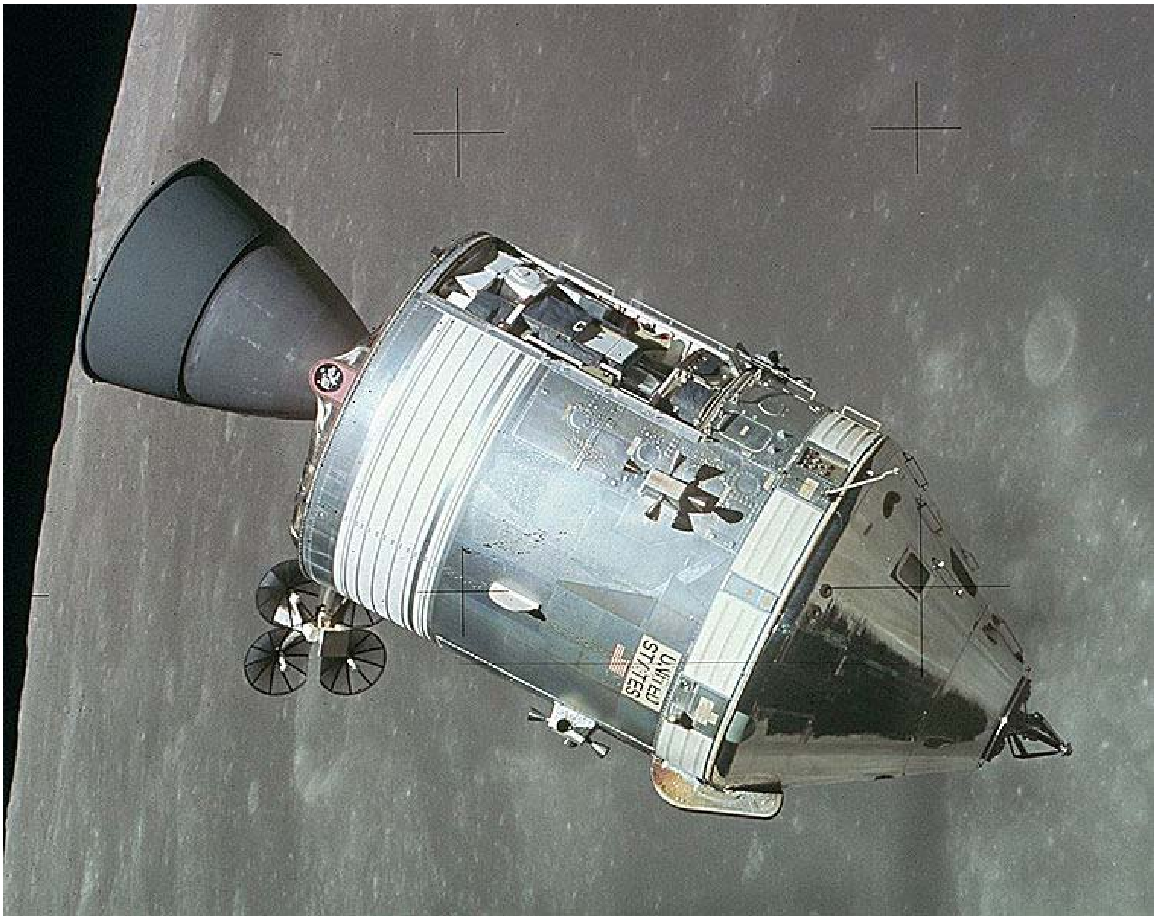
Chapter- 4

Apollo Spacecraft and Space Shuttle Orbiter

Apollo Spacecraft



Complete Apollo spacecraft: Command Module, Service Module, Lunar Module, Launch Escape System, Spacecraft LM Adapter



The Apollo 15 Command/Service Module as viewed from the Lunar Module on August 2, 1971.

The **Apollo spacecraft** was composed of five combined parts designed to accomplish the American Apollo program's goal of landing astronauts on the Moon by the end of the 1960s and returning them safely to Earth. The spacecraft was made up of (from top to bottom) the **Launch Escape System**, the **Command Module**, the **Service Module**, and the **Lunar Module** inside the **Spacecraft Lunar Module Adapter**. These components were assembled atop launch vehicles including the Saturn I and Saturn IB (earth orbit checkout missions), and the Saturn V (primarily lunar landing missions).

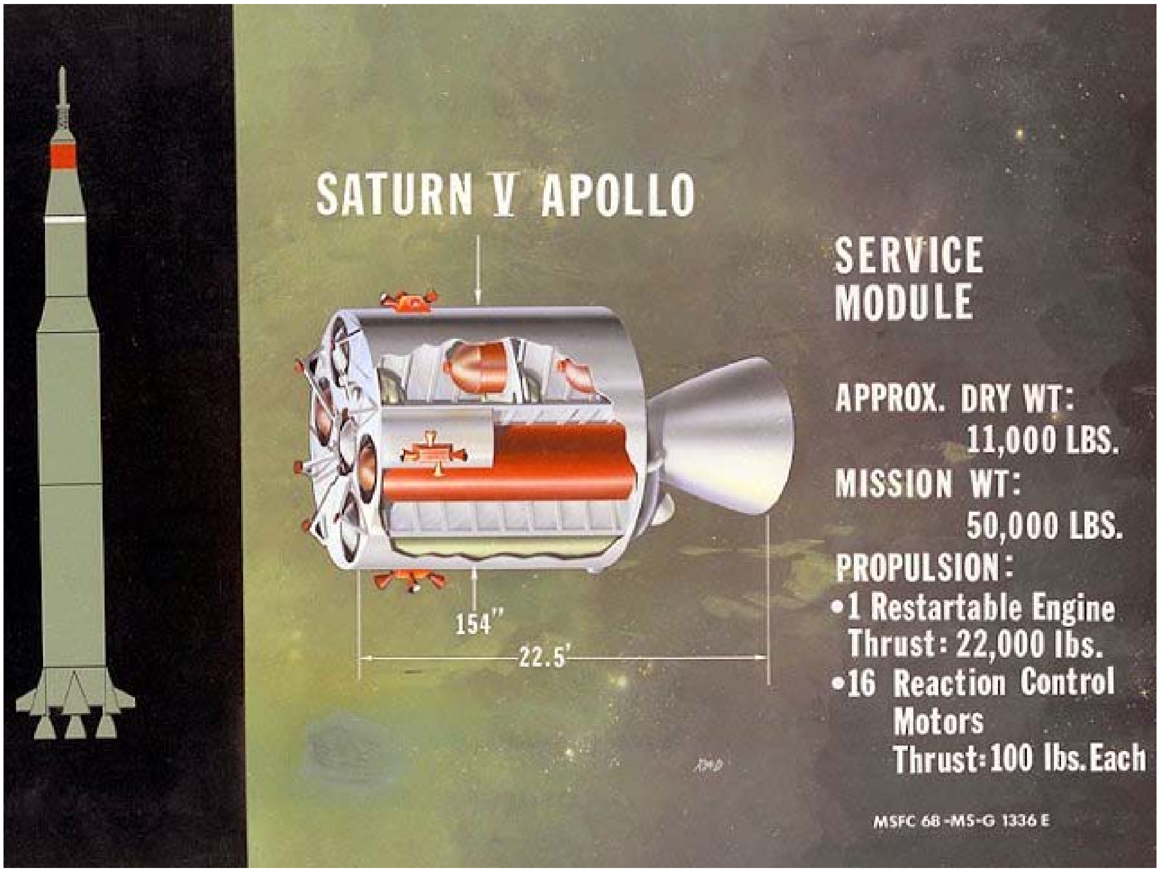
The design was based on the Lunar Orbit Rendezvous approach: two docked spacecraft were sent to the Moon and went into lunar orbit. While one separated and landed, the other remained in orbit. The two craft later rendezvoused and docked in lunar orbit, and one spacecraft returned the crew to Earth.

Command Module (CM)

Apollo Command Module

The Command Module was the control center for the Apollo spacecraft and living quarters for the three crewmen. It contained the pressurized main crew cabin, crew couches, control and instrument panel, optical and electronic guidance systems, communications systems, environmental control system, batteries, heat shield, reaction control system, forward docking hatch, side hatch, five windows and the parachute recovery system. It was the only part of the Apollo/Saturn launch vehicle that returned to Earth intact.

Service Module (SM)



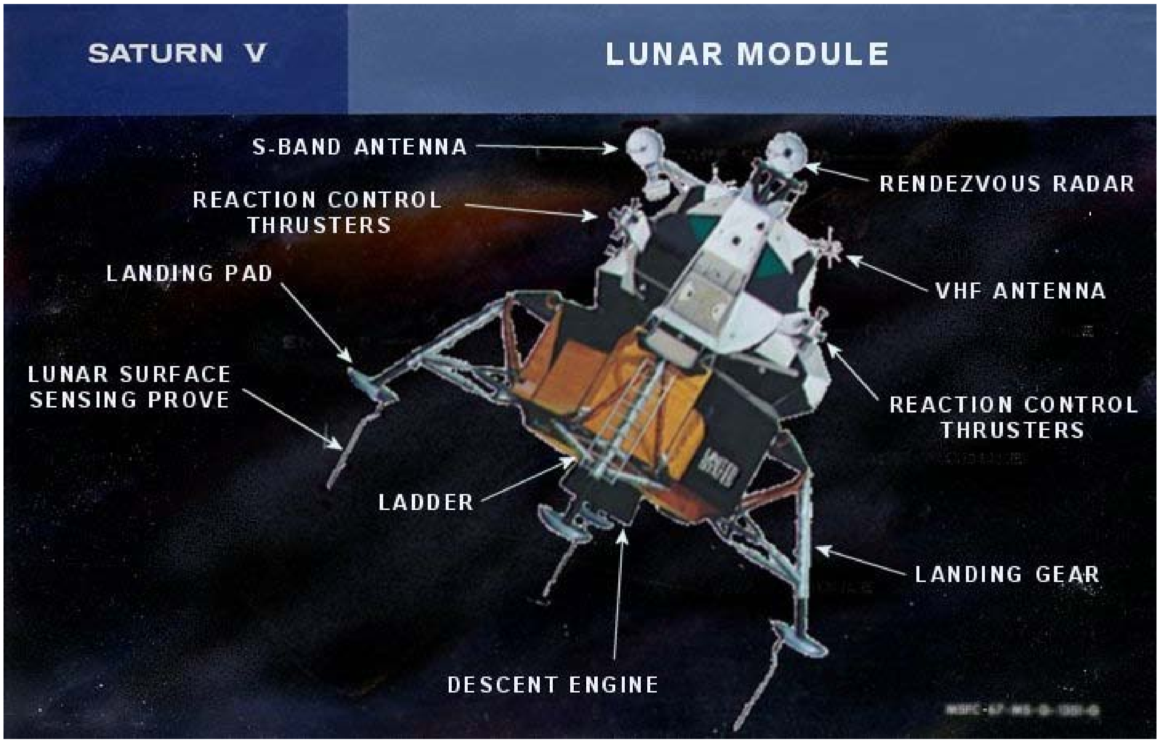
Apollo Service Module

The Service Module was a portion of the spacecraft that was unpressurized and contained fuel cells, batteries, a high gain antenna, radiators, water, hydrogen, oxygen, a reaction control system and propellant to enter and leave lunar orbit, and service propulsion systems. On Apollo 15, 16 and 17 it also carried a scientific instrument package, mapping camera and a small sub-satellite to study the moon.

A major portion of the service module was taken up by propellant and the main rocket engine. Capable of multiple restarts, this engine placed the Apollo spacecraft into and out of lunar orbit, and was used for mid-course corrections between the earth and the moon.

The Service Module remained attached to the Command Module throughout the mission. It was jettisoned just prior to reentry into the Earth's atmosphere.

Lunar Module (LM)



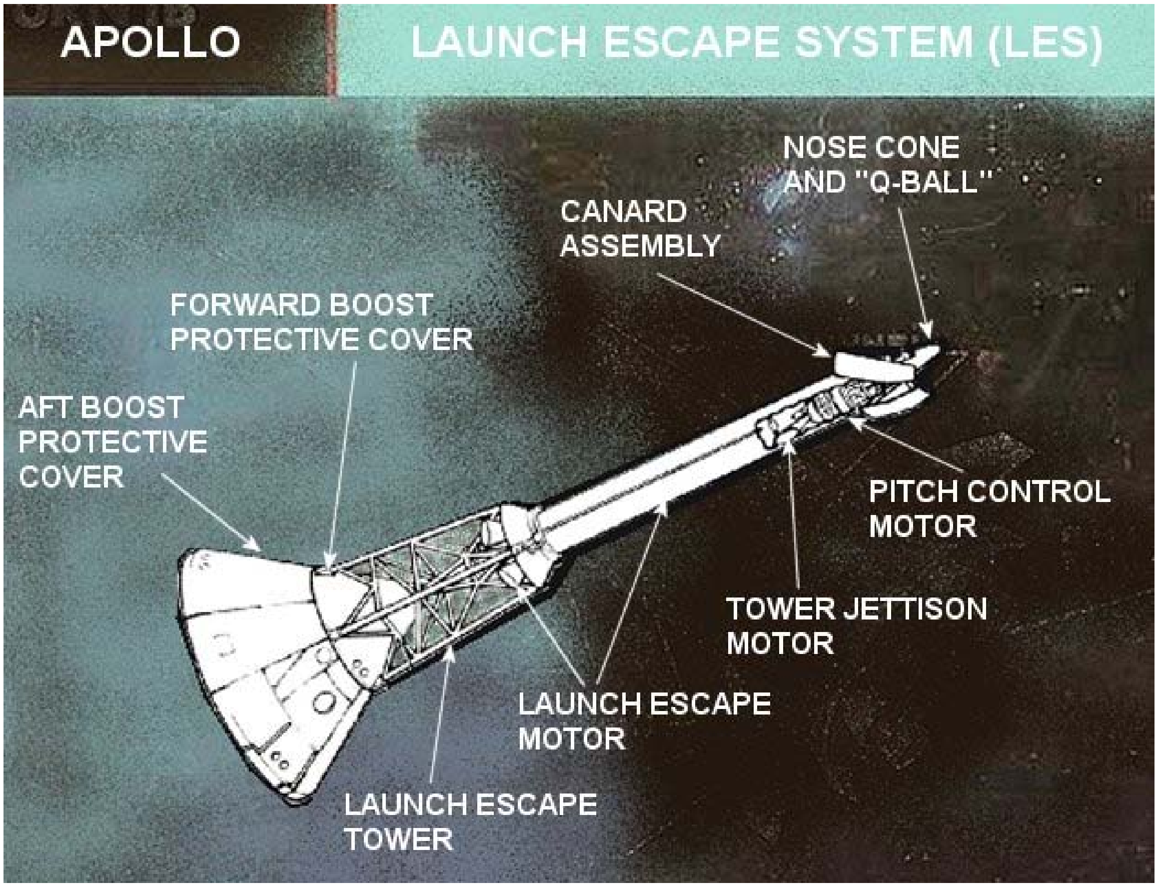
Apollo Lunar Module

The Lunar Module was the portion of the Apollo spacecraft that landed on the moon and returned to lunar orbit and was the first true "spaceship" since it was designed to fly solely in the vacuum of space. It was divided into two major parts, the Descent Module and the Ascent Module. It supplied life support systems for two astronauts for a total of four to five days. The spacecraft was designed and manufactured by the Grumman Aircraft Company led by Tom Kelly.

The Descent Stage contained the landing gear, landing radar antenna, descent rocket engine, and fuel to land on the moon. It also had several cargo compartments used to carry among other things, the Apollo Lunar Surface Experiment Packages ALSEP, the Modularized Equipment Transporter (MET) (a hand-pulled equipment cart used on Apollo 14), the Lunar Rover (moon car - Apollo 15, 16 and 17), surface television camera, surface tools and lunar sample collection boxes.

The Ascent Stage contained the crew cabin, instrument panels, overhead hatch/docking port, forward hatch, optical and electronic guidance systems, reaction control system, radar and communications antennas, ascent rocket engine and fuel to return to lunar orbit and rendezvous with the Apollo Command and Service Modules.

Launch Escape System (LES)



Apollo Launch Escape System

Pad Abort Test, showing pitch motor and launch escape motor in operation

The purpose of the Apollo launch escape system was to pull the Command Module (which contained the crew cabin) away from the launch vehicle in an abort. The emergency could be a pad fire, exploding launch vehicle or a launch vehicle going off course.

The Launch Escape System would work automatically (or through manual activation) to fire a solid fuel escape rocket and open a canard system to direct the Command Module away from, and off the path of, a launch vehicle in trouble. The Launch Escape System would then jettison and the Command Module would land with its parachute recovery system.

If the emergency happened on the launch pad, the Launch Escape System would lift the Command Module to a sufficient height to allow the recovery parachutes to deploy safely before coming in contact with the ground.

Major components of the Launch Escape System

- **Nose Cone and Q-Ball**—The nosecone of the LES contained sensors to sense aerodynamic pressure ("Q"), and thereby determine the angle of attack, airspeed, and attitude of the spacecraft and launch vehicle. This structure, known as the Q-ball, relayed this information to the command module and the launch vehicle guidance system.
- **Q-Ball cover**—The Q-ball's pitot tubes, which could easily be clogged by debris, were protected by a styrofoam cover that was removed a few seconds before launch. The Q-ball cover was split in half vertically and held together by a 2-inch (51 mm) rubber band. A razor blade was positioned behind the rubber band, pinched between the halves of the cover. A wire rope was connected to the top and bottom of the razor blade and to both halves of the cover. The wire rope was routed through a pulley on the hammerhead crane at the top of the launch umbilical tower (LUT) down to a tube on the right side of the 360-foot (110 m) level of the LUT. The wire rope was connected to a cylindrical weight inside a tube. The weight rested on a lever controlled by a pneumatic solenoid valve. When the valve was actuated from the Launch Control Center (LCC), the pneumatic pressure of 600 PSI GN2 (nitrogen gas) rotated the lever down allowing the weight to drop down the tube. The dropping weight pulled the wire rope, which pulled the blade cutting the rubber band, and the wire rope pulled the halves of the cover away from the launch vehicle. The apparent overengineering of this simple system was due to the fact that the launch escape system, which depended on the Q-ball data, was armed 5 minutes before launch, so retraction of the Q-ball cover was a life-critical part of a possible pad abort.
- **Canard Assembly and Pitch Motor**—These worked in combination to direct the Command Module off a straight path and to the side during an emergency. This would direct the Command Module off the flight path of an exploding launch vehicle. It would also direct the Command Module to land off to the side of any launch pad fire and not in the middle of it.
- **Tower Jettison Motor**—A smaller solid fuel motor that jettisons the Launch Escape System after it is no longer needed. This usually happens after second stage ignition.
- **Launch Escape Motor**—The main solid fuel rocket motor that, firing through four rocket nozzles, pulls the Command Module rapidly away from a launch emergency.
- **Launch Escape Tower**—Assembly that attaches the Launch Escape System rocket motors to the Command Module.
- **Boost Protective Cover**—Hollow conical structure that fit over the Command Module during launch. It protected the Command Module heat shield and windows during ascent through the atmosphere. It also protected the Command Module from rocket exhaust should the Launch Escape System have to be used.

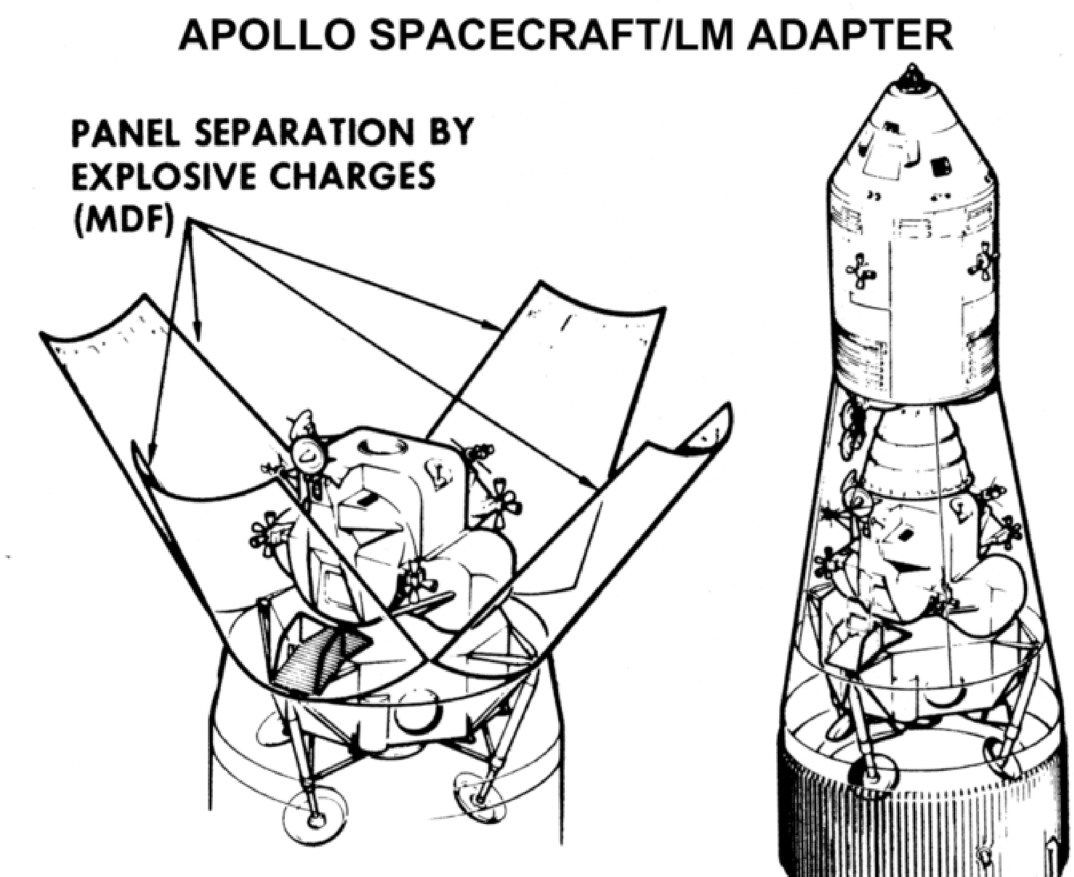
Specifications

- Length minus BPC: 32 ft 6 in (9.92 m)
- Length with BPC: 39 ft 5 in (12.02 m)
- Diameter: 2 ft 2 in (0.66 m)
- Total mass: 9,200 pounds (4,200 kg)
- Thrust: 155,000 lbf (689 kN)

Abort tests

- Pad Abort Test-1—Launch Escape System (LES) abort test from launch pad with Apollo Boilerplate BP-6.
- Pad Abort Test-2—LES pad abort test of near Block-I CM with Apollo Boilerplate B-23A.
- Little Joe II—In-air LES abort tests.

Spacecraft Lunar Module Adapter (SLA)



Apollo Spacecraft-to-LM Adapter

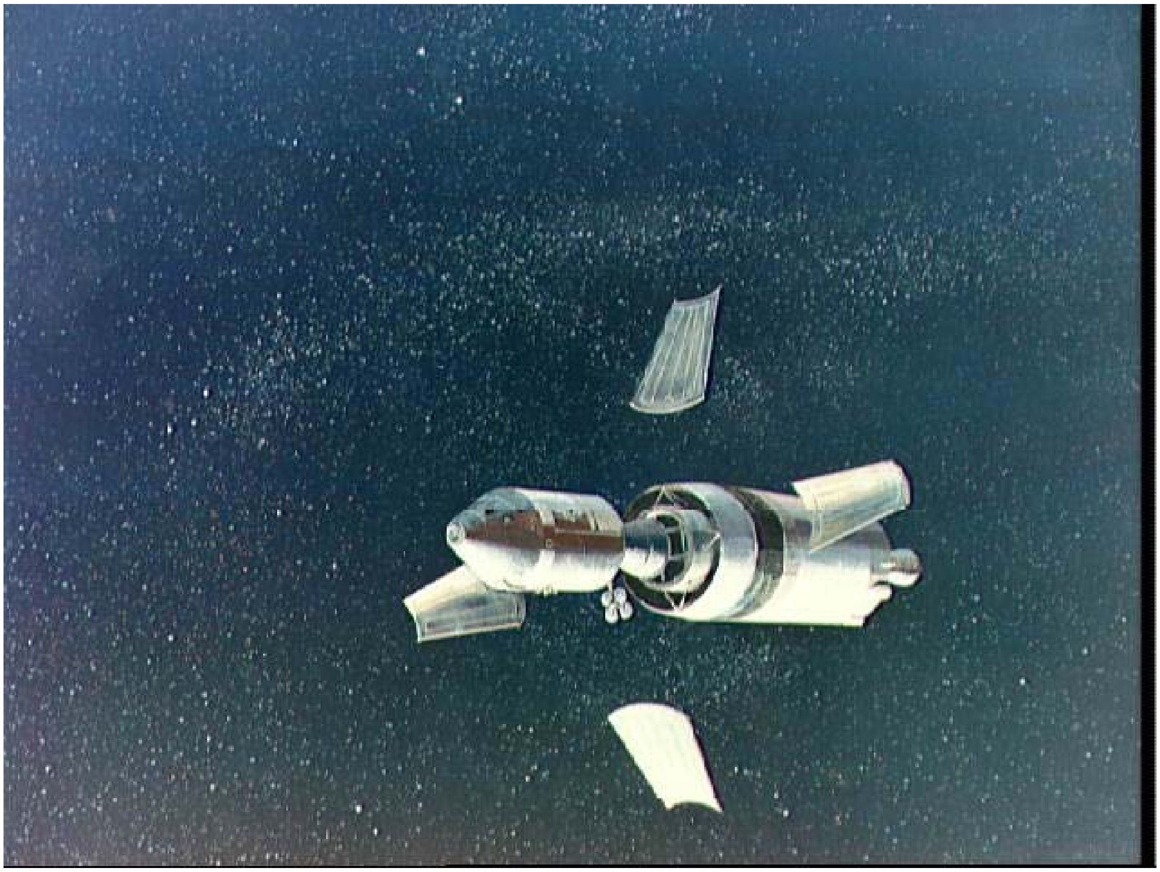
The Spacecraft Lunar Module Adapter (SLA) was a conical aluminum structure which supported the Service Module above the Saturn S-IVB rocket stage. It protected the Lunar Module (LM), the **Service Propulsion System** engine nozzle, and the launch vehicle to Service Module umbilical during launch and ascent through the atmosphere.

The SLA was composed of four fixed 7-foot-tall (2.1 m) panels bolted to the Instrument Unit on top of the S-IVB stage, which were connected via hinges to four 21-foot-tall (6.4 m) panels which would open from the top similar to flower petals.

The SLA was made from 1.7 inches (43 mm) thick aluminum honeycomb material. The exterior of the SLA was covered by a thin (0.03–0.2 inch or 0.76–5.1 millimetres) layer of cork and painted white to minimize thermal stresses during launch and ascent.

The Service Module was bolted to a flange at the top of the longer panels, and power to the SLA multiply-redundant pyrotechnics was provided by an umbilical. Because a failure to separate from the S-IVB stage could leave the crew stranded in orbit, the separation system used multiple signal paths, multiple detonators and multiple explosive charges where the detonation of one charge would set off another even if the detonator on that charge failed to function.

Once in space, the astronauts pressed the 'CSM/LV Sep' button on the control panel to separate the Command and Service Module (CSM) from the launch vehicle. Detonating cord was ignited around the flange between the Service Module and SLA, and along the joints between the four SLA panels, releasing the Service Module and blowing apart the connections between the panels. Dual-redundant pyrotechnic thrusters at the lower end of the SLA panels then fired to rotate them around the hinges at 30-60 degrees per second.



Artist's conception of SLA panel separation in space on the Apollo 8 mission

On the Apollo 7 flight the SLA panels were retained on the S-IVB, but concerns about collision between the CSM and the SLA panels when docking with the Lunar Module led to a decision that the Saturn V launches would release the panels during the separation process. When they opened to an angle of approximately 45 degrees the hinges connecting the moving panels to the fixed panels disengaged, and springs pushed the panels away from the S-IVB at a velocity of around five miles per hour. Hence by the time the astronauts had rotated the Command/Service Module through one hundred and eighty degrees in preparation for docking, the panels were a safe distance away with no chance of a collision occurring.

The Lunar Module was connected to the SLA at four points around the lower panels. After the astronauts docked the CSM to the LM, they blew charges to separate those connections and a guillotine severed the LM to Instrument Unit umbilical. After the charges fired, springs pushed the LM away from the S-IVB and the astronauts were free to continue their trip to the Moon.

Specifications

- Height: 28 ft (8.5 m)
- Apex Diameter: 12 ft 10 in (3.9 m) Service Module end

- Base Diameter: 21 ft 8 in (6.6 m) S-IVB end
- Weight: 4,050 lb (1,840 kg)
- Volume: 6,700 cu ft (190 m^3), 4,900 cu ft (140 m^3) usable

Abort modes

- Apollo abort modes
- Pad Abort Test-1 - Launch Escape System (LES) abort test from launch pad with Apollo Boilerplate BP-6.
- Pad Abort Test-2 - LES pad abort test of near Block-I CM with Apollo Boilerplate B-23A.

Space Shuttle Orbiter

Space Shuttle orbiter

The *Discovery* orbiter approaches the ISS on STS-121

Operator	NASA
Mission type	Orbiter
Satellite of	Earth
Launch vehicle	Space Shuttle Solid Rocket Booster
Launch site	Kennedy Space Center
Homepage	Space Shuttle Home

The **Space Shuttle orbiter** is the orbital spacecraft of the Space Shuttle program operated by NASA, the space agency of the United States. The orbiter is a reusable winged "space-plane", a mixture of rockets, spacecraft, and aircraft. This space-plane can carry crews and payloads into Earth orbit, perform on-orbit operations, then re-enter the atmosphere and land as a glider, returning her crew and any on-board payload to the Earth.

A total of six Orbiters were built for flight: *Atlantis*, *Challenger*, *Columbia*, *Discovery*, *Endeavour* and *Enterprise*. All were built by the southern California based Rockwell International company. The first Orbiter to fly, *Enterprise*, took her maiden flight in 1977. Built solely for unpowered atmospheric test flights and landings, her take-off was from the back of a modified Boeing-747 cargo plane, the Shuttle Carrier Aircraft, while the remaining Orbiters were built for orbital space flights, launched vertically as part of the full Space Shuttle package.

Columbia was the first Orbiter to launch into space as a Space Shuttle, in 1981. The first launches of *Challenger*, *Discovery*, and finally *Atlantis*, followed in 1983, 1984 and 1985 respectively. In 1986, *Challenger* was destroyed in an accident after launch. *Endeavour* was built as *Challenger's* replacement, and was first launched in 1992. In 2003, *Columbia* was destroyed during re-entry, leaving just three remaining Orbiters. Two were to be used for the last time in flights during 2010, *Atlantis* in May, *Discovery* in November. *Endeavour* is scheduled to make its final flight in January 2011.

In addition to their crews and payloads, the reusable Space Shuttle Orbiter carries most of the Space Shuttle System's liquid-fueled rocket propulsion system, but both the liquid hydrogen fuel and the liquid oxygen oxidizer for her three main rocket engines is fed from an external cryogenic propellant tank, and there are also two reusable large solid-fueled rocket boosters that help to lift both the Orbiter and her external propellant tanks during approximately the first two minutes of her ascent into outer space.

Description

Space Shuttle cockpit

Attitude control system

The Space Shuttle Orbiter resembles an aircraft in her design, with a standard-looking fuselage and two double-delta wings, both swept at an angle of 81 degrees at their inner leading edges and 45 degrees at their outer leading edges. The vertical stabilizer of the Orbiter has a leading edge that is swept back at a 45-degree angle. There are four elevons mounted at the trailing edges of the delta wings, and the combination rudder and speed brake is attached at the trailing edge of the vertical stabilizer. These, along with a movable body flap, control the Orbiter during her later stages of descent through the atmosphere and her landing.

Overall, the Space Shuttle Orbiter is roughly the same size as a McDonnell Douglas DC-9 airliner.

The Reaction Control System (RCS) is composed of 44 small liquid-fueled rocket thrusters and their very sophisticated computerized (fly-by-wire) flight control system, which utilizes computationally-intensive digital Kalman Filtering. This control system carries out the usual attitude control along the pitch, roll, and yaw axes during all of the flight phases of launching, orbiting, and re-entry. This system also executes any needed orbital maneuvers, including all changes in the orbit's altitude, orbital plane, and eccentricity. These are all operations that require a lot more power and energy than mere attitude control.

The forward rockets of the Reaction Control System, located near the nose of the Space Shuttle Orbiter, include 12 primary and two vernier RCS rockets. The aft RCS engines are located in the two Orbital Maneuvering System (OMS) pods at the rear of the Orbiter, and these include 12 primary and two vernier RCS engines in each pod. The RCS system provides the fine-pointing control of the Orbiter, and the RCS is used for the maneuvering during the rendezvous, docking, and undocking maneuvering with the International Space Station, or formerly with the Russian Mir space station. The RCS also controls the attitude of the Orbiter during most of its re-entry into the Earth's atmosphere - until the air becomes dense enough that the elevons and the rudder become effective.

Pressurised cabin

The Orbiter astronaut's crew cabin consists of three levels: the flight deck, the mid-deck, and the utility area. The uppermost of these is the flight deck, in which sit the Space Shuttle's commander and co-pilot, with up to two mission specialists seated behind them. The mid-deck, which is below the flight deck, has three more seats for the rest of the crew members.

The galley, toilet, sleep locations, storage lockers, and the side hatch for entering and exiting the Orbiter are also located on the mid-deck, as well as the airlock. The airlock has an additional hatch into the Payload Bay. This airlock allows two astronauts, wearing their Extravehicular Mobility Unit (EMU) space suits, to depressurize before a walk in space (EVA), and also to repressurize and re-enter the Orbiter at the conclusion of the EVA.

Propulsion

Three Space Shuttle Main Engines (SSMEs) are mounted on the Orbiter's aft fuselage in the pattern of an equilateral triangle. These three liquid-fueled engines can be swiveled 10.5 degrees vertically and 8.5 degrees horizontally during the rocket-powered ascent of the Orbiter in order to change the direction of their thrust. Hence, they steer the entire Space Shuttle, as well as providing her rocket thrust towards orbit. The aft of the fuselage also houses three auxiliary power units (APU). The APUs burn hydrazine to provide hydraulic pressure for all of the hydraulic system, including the ones that point the three main liquid-fueled rocket engines, under computerized flight control. The hydraulic pressure generated is also used to control all of the Orbiter's "aerosurfaces" (the elevons, rudder, air brake, etc.), to deploy the landing gear of the Orbiter, and to open and close the cargo bay's large main doors.

Two Orbital Maneuvering System (OMS) thusters are mounted in two separate pods in the Orbiter's aft fuselage, located between the SSMEs and the vertical stabilizer of the Orbiter. The OMS engines provide significant thrust for coarse orbital maneuvers, including insertion, circularization, transfer, rendezvous, deorbit, abort to orbit, and to abort once around.

Thermal protection

The Thermal Protection System (TPS) covers the outside of the Orbiter, protecting it from the cold soak of -121 °C (-250 °F) in space to the 1649 °C (3000 °F) heat of re-entry.

Structure

The orbiter structure is made primarily from aluminium alloy, although the engine thrust structure is made from titanium alloy. The windows are made of aluminum silicate glass and fused silica glass, and comprise an internal pressure pane, a 1.3-inch-thick (33 mm) optical pane, and an external thermal pane. The windows are tinted with the same ink used to make American banknotes.

Landing gear

The Space Shuttle Orbiter has three sets of landing gear (wheels, brakes, steering motors) which emerge downwards through doors in the Orbiter's heat shield. Once lowered, these cannot be retracted during flights, since that is never necessary - and also providing for this capability would only add to the weight load of the landing gear on the Orbiter. Furthermore, since any premature extension of the landing gear would very likely be catastrophic (since it opens through the heat shield layers), this lowering of the landing gear can only be manually activated, and never by any automatic system, such as a computer.

Lack of navigational lights

The Space Shuttle Orbiter carries neither anti-collision lights, navigational lights, nor landing lights, because she always lands in areas that have been specially-cleared by both the Federal Aviation Administration and the Air Force. The Orbiter nearly always lands at either Edwards Air Force Base (California) or near to the Patrick Air Force Base (Florida). Similar special clearances (no-fly zones) are also in effect at potential emergency-landing sites for the Orbiter, such as in Spain and in West Africa during all launches. Thus far, only one Orbiter landing has been carried out elsewhere, at an airfield in New Mexico, when the weather was unacceptable both in Florida and at Edwards Air Force Base.

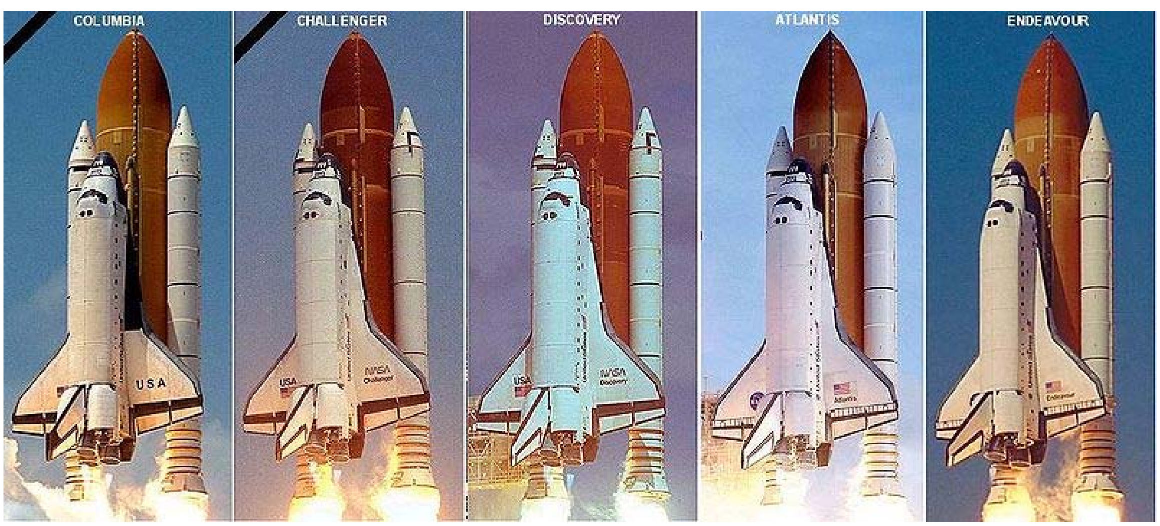
When any Orbiter landing is carried out at night, the runway is always strongly illuminated with light from floodlights and spotlights on the ground, making landing lights on the Orbiter unnecessary and also an unneeded spaceflight weight load.

Shuttle Orbiter Specifications

- Length: 122.17 ft (37.24 m)
- Wingspan: 78.06 ft (23.79 m)
- Height: 58.58 ft (17.25 m)
- Empty Weight: 151,205 lb (68,585 kg); 172,000 lb (78018 kg) with SSME installed
- Gross Liftoff Weight: 240,000 lb (109,000 kg)
- Maximum Landing Weight: 230,000 lb (104,000 kg)
- Main Engines: Three Rocketdyne Block two-A SSMEs, each with a sea-level thrust of 393,800 pounds-force (1.75 meganewtons)
- Maximum Payload: 55,250 pounds (25,060 kg)
- Payload Bay dimensions: 15 ft by 60 ft (4.6 m by 18.3 m)
- Operational Altitude: 100 to 520 nautical miles (190 to 960 km)
- Speed: 25,404 feet/sec (7,743 meters/sec, 27,875 km/hour, 17,321 m.p.h.)
- Cross-range capability: 1,085 nautical miles (2,010 km)
- Crew: six to eight (Commander, Pilot, four to six Mission Specialists, Payload Specialists, or passengers to/from space stations). Two astronauts (the Flight Commander and the Pilot) is the minimum number of crewmen.
- Crew Compartment Space: 2,325 cu ft (65.8 m^3) (With internal airlock) or 2,625 cu ft (74.3 m^3) (With external airlock inside the payload bay)

The orbiter's maximum glide ratio/lift-to-drag ratio varies considerably with speed, ranging from 1:1 at hypersonic speeds, 2:1 at supersonic speeds, and reaching 4.5:1 at subsonic speeds during her approach and landing.

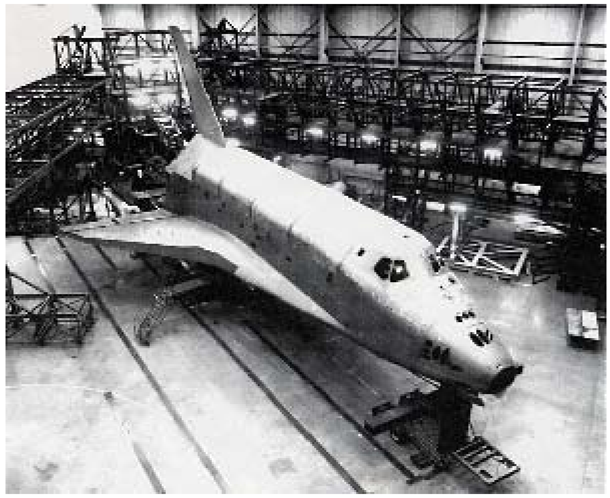
Fleet



Shuttle launch profiles. From left to right: *Columbia*, *Challenger*, *Discovery*, *Atlantis*, and *Endeavour*.

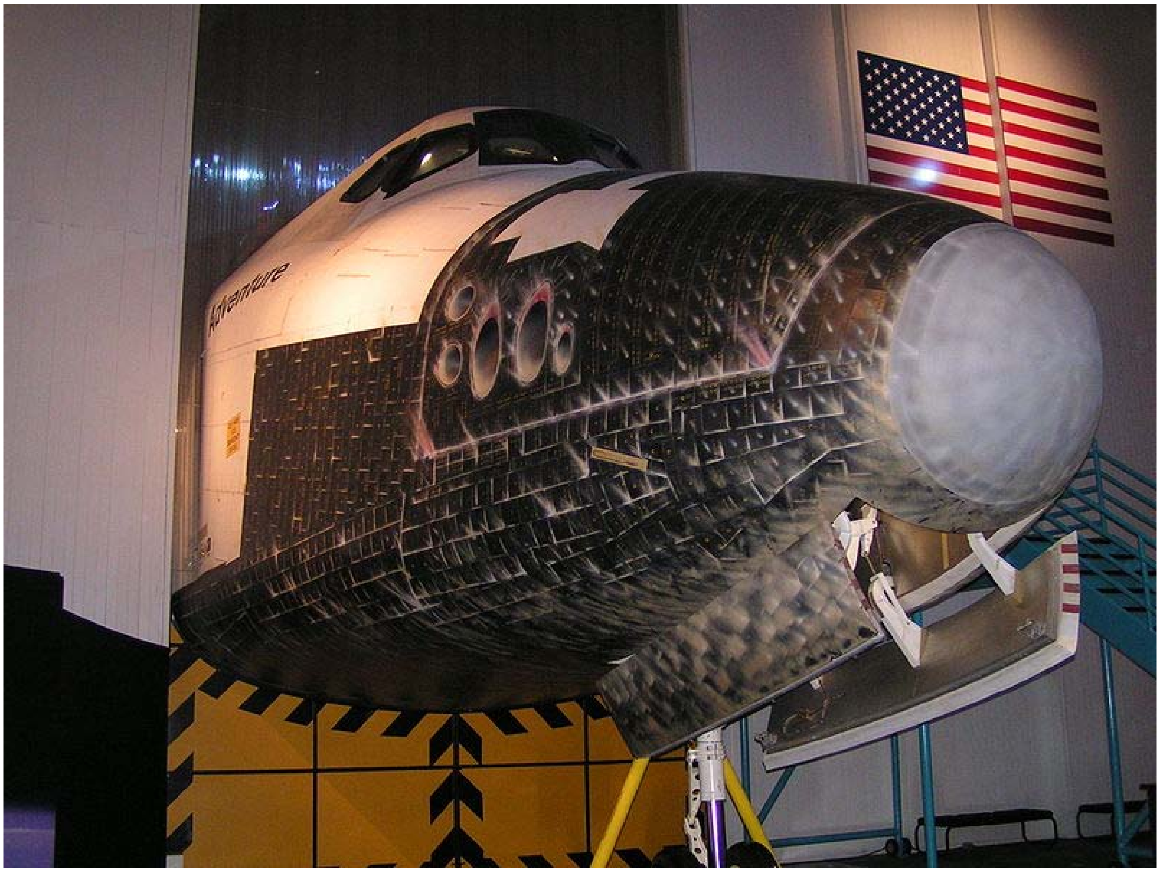
Individual Space Shuttle Orbiters are named in honor of antique sailing ships of the navies of the world, and they are also numbered using the NASA Orbiter Vehicle Designation system. While all of the Orbiters are externally practically identical, they have minor differences in their interiors. New equipment for the Orbiters is installed in the same order that they are undergoing maintenance work, and the newer Orbiters were constructed by Rockwell International, under NASA supervision, with some more advanced, lighter in weight, structural elements. Thus, the newer Orbiters, such as the *Atlantis* and the *Endeavour*, have slightly-more cargo capacity than the other ones did.

Test Articles		
Number	**Name**	**Notes**
OV-095	-	Shuttle Avionics Integration Laboratory replica for avionic system testing and training
OV-098 (honorary)	*Pathfinder*	Orbiter Simulator for moving and handling tests
MPTA-098	-	Testbed for propulsion and fuel delivery systems
STA-099	-	Structural test article used for stress and thermal testing, later became *Challenger*
OV-101	*Enterprise*	First atmospheric free flight October 26, 1977. Used for approach and landing tests, not suitable for spaceflight
Orbiters		
Number	**Name**	**Notes**
OV-099	*Challenger*	First launched April 4, 1983. Destroyed after her take-off on January 28, 1986
OV-102	*Columbia*	First launched April 12, 1981. Destroyed during her re-entry on February 1, 2003
OV-103	*Discovery*	First launched on August 30, 1984
OV-104	*Atlantis*	First launched on October 3, 1985
OV-105	*Endeavour*	First launched on May 7, 1992



Challenger while in service as structural test article STA-099

- The *Enterprise* was a prototype designed to test Space Shuttle behavior in atmospheric flight. She is currently on display at the Smithsonian's National Air and Space Museum Steven F. Udvar-Hazy Center at Dulles International Airport.
- The *Columbia* first launched on April 12, 1981. On February 1, 2003, the *Columbia* burned and disintegrated during her re-entry during her 28th spaceflight.
- The *Challenger* first launched on April 4, 1983. On January 28, 1986 she exploded and disintegratred 73 seconds after her launch on her 10th mission.
- The *Discovery* first launched on August 30, 1984. She has flown on 35 missions, and she is still flightworthy today. She was NASA's Return to Flight vehicle, following the accidental destruction of the *Challenger* and the *Columbia*. The *Discovery* is scheduled to fly her last mission in November 2010.
- The *Atlantis* first launched on October 3, 1985. She has flown 30 spaceflights and was officially retired from service in May 2010.
- The *Endeavour* first launched on May 7, 1992. She has flown 22 spaceflights, and she is still flightworthy today. She is tentively scheduled to be retired from service in January 2011.



Adventure on display at Space Center Houston

In addition to the test articles and orbiters produced for use in the Shuttle program, there are also various mock-ups on display throughout the world:

- *Space Shuttle Explorer*, a full-scale replica of an orbiter at the Kennedy Space Center visitor's complex
- *Space Shuttle Adventure*, a full-scale replica of an orbiter mid-deck and flight deck at Space Center Houston
- *Space Shuttle America*, a full-scale replica of a space shuttle for a theme park attraction since disassembled and removed
- *Space Shuttle Pathfinder*, an actual full-scale mock-up of the space shuttle originally built and used to test clearance and various ground operations; currently displayed at Space Camp in Huntsville, Alabama

Flight statistics

Shuttle	Flights	Flight days	Orbits	Longest flight	First flight		Most recent flight		Mir/ISS docking
					STS	Date	STS	Date	
Columbia †	28	300d 17h	4,808	17d 15h	STS-1	Apr	STS-	Jan 16,	0 / 0

		46m 42s		53m 18s		12, 1981	107 †	2003	
Challenger †	10	62d 07h 56m 15s	995	08d 05h 23m 33s	STS-6	Apr 04, 1983	STS-51-L †	Jan 28, 1986	0 / 0
Discovery	38	352d 04h 01m 27s	5,002	15d 02h 48m 08s	STS-41-D	Aug 30, 1984	STS-131	Apr 05, 2010	1 / 11
Atlantis	32	293d 18h 29m 37s	4,648	13d 20h 12m 44s	STS-51-J	Oct 03, 1985	STS-132	May 14, 2010	7 / 11
Endeavour	24	280d 09h 39m 44s	4,429	16d 15h 08m 48s	STS-49	May 07, 1992	STS-130	Feb 08, 2010	1 / 10
Total	**132**	**1289d 09h 52m 48s**	**20,022**						**9 / 32**

Shenzhou (spacecraft)

Shenzhou

A model of the Shenzhou spacecraft

Operator CNSA

Mission type	Orbiter
Satellite of	Earth
Launch vehicle	Long March 2F launch vehicle
Launch site	Jiuquan Satellite Launch Center

Shenzhou is a spacecraft developed and operated by the People's Republic of China to support its manned spaceflight program. The name is variously translated as "Divine Craft," "Divine Vessel of the Gods," "Magic Boat" or similar, and is identically pronounced, though differently written, with a literary name for China (神州 ; literally "Divine Land"). Its design resembles the Russian Soyuz spacecraft, but it is larger in size and all-new in construction. Moreover, unlike the Soyuz, the orbital module of the Shenzhou is equipped with its own propulsion, solar power, and control systems, allowing autonomous flight. The first launch was on November 19, 1999 and the first manned launch was on October 15, 2003. In March 2005, an asteroid was named 8256 Shenzhou in honor of the spacecraft.

History

China's first efforts at human spaceflight started in 1968 with a projected launch date of 1973. Although China did launch an unmanned satellite in 1970 and has maintained an active unmanned program since, this attempt was canceled due to lack of funds and political interest.

The current Chinese human spaceflight program was authorized on April 1, 1992 as Project 921/1, with work beginning on January 1, 1993. The initial plan had three phases:

- Phase 1 would involve launch of two unmanned versions of the manned spacecraft, followed by the first Chinese manned spaceflight, by 2002.
- Phase 2 would run through 2007, and involve a series of flights to prove the technology, conduct rendezvous and docking operations in orbit, and operate an 8-tonne spacelab using the basic spacecraft technology.
- Phase 3 would involve orbiting of a 20-ton space station in the 2010-2015 period, with crews being shuttled to it using the eight-ton manned spacecraft.

The chief designers of the Shenzhou include Qi Faren and Wang Yongzhi.

The first four unmanned test flights happened in 1999, 2001, and 2002. These were followed by manned launches on October 15, 2003, October 12, 2005, and September 25, 2008. It would be launched on the Long March 2F from the Jiuquan Satellite Launch Center. The command center for missions is the Beijing Aerospace Command and Control Center.

The first unmanned flight of the spacecraft was launched on November 19, 1999 after which **Project 921/1** was renamed **Shenzhou**, a name reportedly chosen by Jiang Zemin. A series of three additional unmanned flights ensued. The Shenzhou reentry modules used to date are 13 percent larger than Soyuz reentry modules, and it is expected that later crafts will be designed to carry a crew of four instead of Soyuz's three, although physical limitations on astronaut size, as experienced with earlier incarnations of Soyuz, will likely apply.

While the Shenzhou orbital module could be used for military reconnaissance there appears to be no military reason for incorporating such as system in a manned mission, as China could use purely unmanned satellites for these purposes. The experience during the 1960s of both the United States with the Manned Orbiting Laboratory and the Soviet Union with the Almaz space station suggests that the military usefulness of human spaceflight is quite limited and that practically all military uses of space are much more effectively performed by unmanned satellites. Yet, the nature of space exploration, with different nations trying successively to achieve the same goals (e.g., the original "space race," current efforts to duplicate GPS and GLONASS with Galileo), implies that China may well be walking down this route as others have before them.

The fifth launch, Shenzhou 5, was the first to carry a human (Yang Liwei) and occurred at 9:00 CST (UTC +8) on October 15, 2003.

Missions launched

Launch of Shenzhou 5 in 2003

- Shenzhou 1 - November 19, 1999 - unmanned test flight
- Shenzhou 2 - January 9, 2001 - carried animals
- Shenzhou 3 - March 25, 2002 - carried a test dummy
- Shenzhou 4 - December 29, 2002 - carried a test dummy and several science experiments
- Shenzhou 5 - October 15, 2003 - 14 Earth orbits carrying Yang Liwei
- Shenzhou 6 - October 12, 2005 - five day mission with Fei Junlong and Nie Haisheng
- Shenzhou 7 - September 25, 2008 - three man crew with Zhai Zhigang, Liu Boming, and Jing Haipeng; spacewalk performed by two crew members

Planned missions

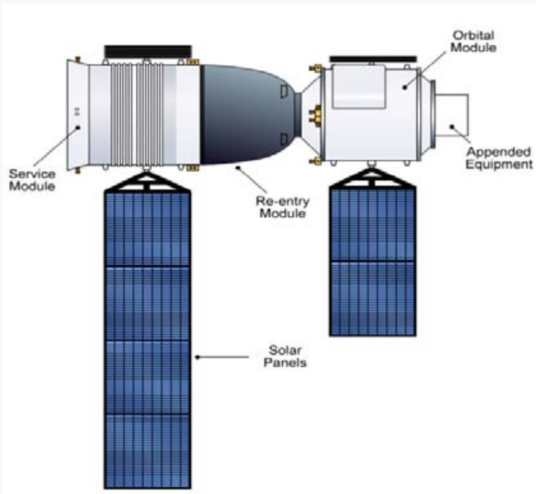
- Shenzhou 8 - 2011 (?) - unmanned mission, will rendezvous and dock with Tiangong 1.
- Shenzhou 9 - 2011 (?) - unmanned mission, will dock with Tiangong 1 after Shenzhou 8.
- Shenzhou 10 - 2011 (?) - three person crew, will dock with Tiangong 1 after Shenzhou 8 and Shenzhou 9 to form a space station or space laboratory.
- Shenzhou 11 - 2012 (?) - manned mission carrying the second space laboratory crew to Tiangong 2.

This is similar to the process used by the Soviet Union in their early Soyuz program which was intended to test procedures for future lunar flights.

Shenzhou spacecraft

Shenzhou spacecraft		
 *Shenzhou* model.		
Description		
Role:	Manned spacecraft	
Crew:	three	
Dimensions		
Height:	9.25 m	30.34 ft
Diameter:	2.8 m	9.10 ft
Volume:	14.00 m³	494.4 ft³
Rocket engines		
Main Engine (N_2O_4/MMH):	10000 N	2248 lbf ea
Performance		
Endurance:	20 days	
Apogee:	324 km	201 mi

Perigee:	196 km	121.8 mi
Inclination:	42.5 degrees	
Spacecraft delta v:	380 m/s	1,240 ft/s
Modules		



Modular design of *Shenzhou* spacecraft

The Shenzhou spacecraft resembles Soyuz, although it is substantially larger, and unlike the Soyuz, it features a powered orbital module capable of autonomous flight.

The similarity in outward appearance between Shenzhou and Soyuz arises partially from basic constraints on space flight. Like Soyuz, Shenzhou consists of three modules: a forward orbital module, a reentry module in the middle, and an aft service module. This division is based on the principle of minimizing the amount of material to be returned to Earth. Anything placed in the orbital or service modules does not require heat shielding, and this greatly increases the space available in the spacecraft without increasing weight as much as it would if those modules were also able to withstand reentry. Thus both Soyuz and Shenzhou have more living area with less weight than the Apollo CSM.

Complete Spacecraft Data

Total Mass: 7,840 kg
Length: 9.25 m
Diameter: 2.80 m
Span: 17.00 m

Orbital module

The orbital module contains space for experiments, crew-serviced or operated equipment, and in-orbit habitation. Without docking systems, Shenzhou 1-6 carried different kinds of payload on the top of their orbital modules for scientific experiments.

Unlike the Soyuz, the Shenzhou orbital module is also equipped with its own propulsion, and control systems, allowing autonomous flight. It is possible for Shenzhou to leave an orbital module in orbit for redocking by a later spacecraft, something which the Soyuz cannot do since the hatch enabling it to function as an airlock is part of its reentry module. In the future it is possible that the orbital module(s) could also be left behind on the planned Chinese project 921/2 space station as additional station modules. The fact that China has yet to deploy a space station (e.g., something equivalent to Salyut such as a module that has been re-docked with after deployment) implies an equivalent stage of progress to Russia pre-1970.

In the unmanned test flights launched to date, the orbital module of each Shenzhou was left functioning on orbit for several days after the reentry modules return, and the Shenzhou 5 orbital module continued to operate for six months after launch.

Orbital module data

Design Life: 200 days.
Length: 2.80 m (9.10 ft).
Basic Diameter: 2.25 m (7.38 ft).
Maximum Diameter: 2.25 m (7.38 ft).
Span: 10.40 m (34.10 ft).
Habitable Volume: 8.00 m^3.
Mass: 1,500 kg (3,300 lb).
RCS Coarse No x Thrust: 16 x 5 N.
RCS Propellants: Hydrazine.
Electrical System: Solar panels, 12.24 m^2.
Electric System: 0.50 average kW.
Electric System: 1.20 kWh.

Reentry module

The reentry module is located in the middle section of the spacecraft and contains seating for the crew. It is the only portion of Shenzhou which returns to Earth's surface. Its shape is a compromise between maximizing living space while allowing for some aerodynamic control upon reentry.

Reentry module data

Crew Size: 3.
Design Life: 20 days.
Length: 2.50 m (8.20 ft).
Basic Diameter: 2.52 m (8.26 ft).
Maximum Diameter: 2.52 m (8.26 ft).
Habitable Volume: 6.00 m^3.
Mass: 3,240 kg (7,140 lb).
Heat Shield Mass: 450 kg (990 lb)

RCS Coarse No x Thrust: 8 x 150 N.
RCS Propellants: Hydrazine

Service module

The aft service module contains life support and other equipment required for the functioning of Shenzhou. Two pairs of solar panels, one pair on the service module, the other pair on the orbital module, have a total area of over 40 m² (430 ft²), indicating average electrical power over 1.5 kW (*Soyuz* have 1.0 kW).

Service module data

Design Life: 20 days.
Length: 2.94 m (9.65 ft).
Basic Diameter: 2.50 m (8.20 ft).
Maximum Diameter: 2.80 m (9.10 ft).
Span: 17.00 m (55.00 ft).
Mass: 3,000 kg (6,600 lb).
RCS Coarse No x Thrust: 8 x 150 N.
RCS Fine No x Thrust: 16 x 5 N.
RCS Propellants: N2O4/MMH, unified system with main engine.
Main Engine: 4 x 2500 N.
Main Engine Thrust: 10.000 kN (2,248 lbf).
Main Engine Propellants: N2O4/MMH.
Main Engine Propellants: 1,000 kg (2,200 lb).
Main Engine Isp: 290 sec. L/D Hypersonic: 0.30.
Electrical System: Solar panels, 24.48 + 12.24 m², 36.72 m² total.
Electric System: 1.00 average kW.
Electric System: 2.40 kWh.

Shenzhou "space laboratory module"

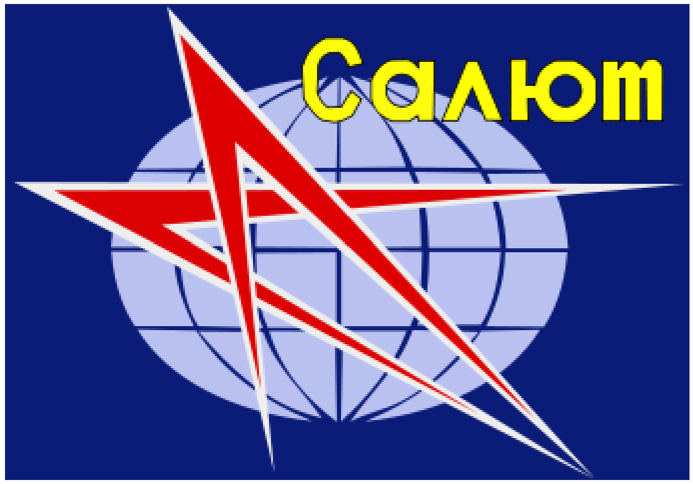
It has been stated by some sources that Shenzhou 8 would be an "8-ton small space laboratory" or "8-ton space station," and Shenzhou 9 and Shenzhou 10 will dock with it; but at 29 Sept. 2008, Zhang Jianqi, Vice Director of China manned space engineering, declared in an interview of China Central Television it is Tiangong 1 (i.e. not Shenzhou 8) that will be the 8-ton "target vehicle," and Shenzhou 8, Shenzhou 9 and Shenzhou 10 will all be spaceships to dock with Tiangong 1 in turn.
According to China Daily (2008-09-29) Zhang Bainan, chief designer of the spacecraft system of China's manned space program, has declared that Shenzhou 8 will be a final, improved version of earlier Shenzhou spacecraft.

Chapter- 5

Space Stations

Salyut program

Salyut 7, the final Salyut station to be launched, as seen from the departing Soyuz T-13 spacecraft



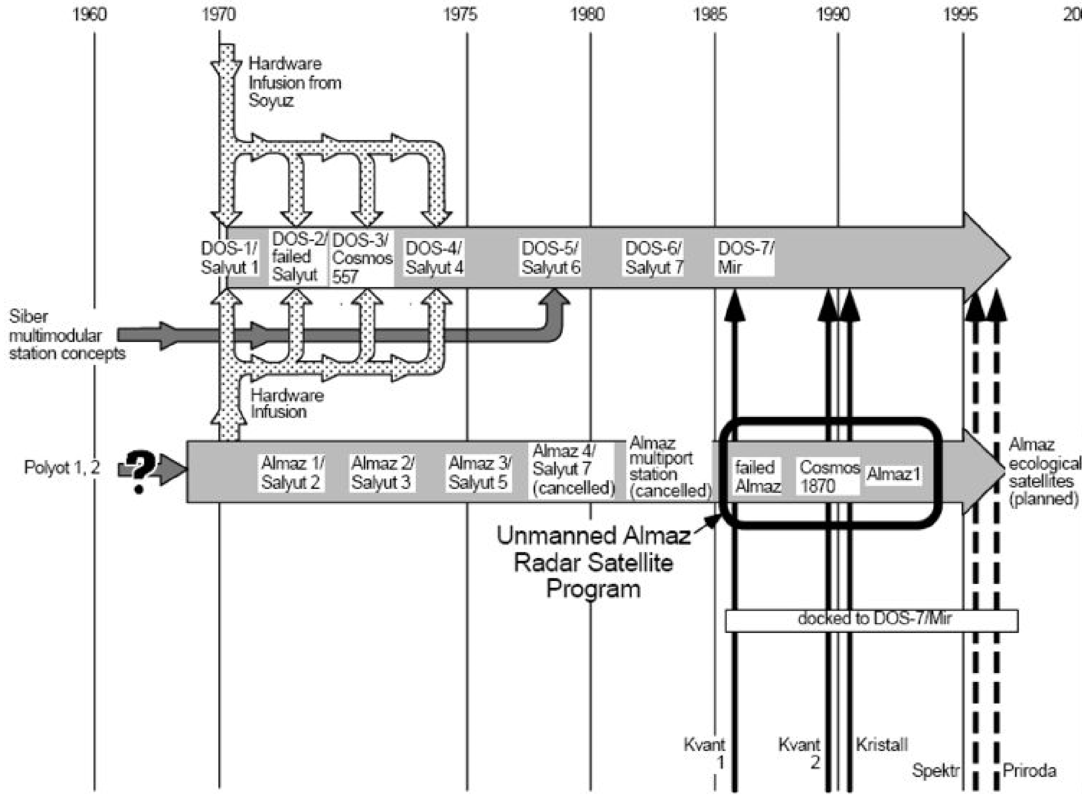
Salyut Program insignia

The **Salyut program** was the first space station program undertaken by the Soviet Union, which consisted of a series of nine single-module space stations launched over a period of eleven years from 1971 to 1982. Intended as a project to carry out long-term research into the problems of living in space and a variety of astronomical, biological and Earth-resources experiments, the program allowed space station technology to evolve from the engineering development stage to long-term research outposts in space. Ultimately, experience gained from the Salyut stations went on to pave the way for multimodular space stations such as *Mir* and the International Space Station, with each of those stations possessing a Salyut-derived core module at its heart.

The program consisted of a series of six scientific research stations and three military reconnaissance stations, the latter being launched as part of the highly secretive Almaz program. Salyut broke several spaceflight records, including several mission duration records, the first ever orbital handover of a space station from one crew to another, and various spacewalk records. By the time the program concluded, in 1991, it had seen space station technology evolve from basic, single-docking port stations to complex, multi-ported orbital outposts with impressive scientific capabilities, whose technological legacy continues to the present day.

Stations

A model of a Salyut 7 space station, with a Soyuz spacecraft and a Progress resupply spacecraft docked at each end. The display is in front of one of the pavilions of the Exhibition of Soviet National Economic Achievement



Development of the Soviet/Russian space stations and derivatives. Light gray arrows trace the evolution of space stations and satellites derived from space station hardware. Dark gray arrows trace the influence of concepts on later flown hardware. The stippled arrow leads from the Soyuz Programs chart (figure 1-1). Solid black arrows indicate modules joined to Mir, while dashed black arrows stand for modules to be added to Mir in the near future. These arrows lead from the Station Modules and Tug Programs chart

The program was composed of **DOS (Durable Orbital Station)** civilian stations and **OPS (Orbital Piloted Station)** military stations. All were adapted from Vladimir Chelomei's original **Almaz OPS** spaceframe. For the military **Orbital Piloted Stations** modifications were small, and related to the rear docking port for Soyuz spacecraft. For the civilian **DOS Orbital Space Station** changes were great, with extra solar panels, rear and front docking ports for Soyuz spacecraft, TKS spacecraft and modules.

Salyut 1

Salyut 1 (DOS-1) (Russian: Салют-1; English: *Salute 1*) was launched April 19, 1971. It was the first space station to orbit Earth. Its first crew launched in Soyuz 10 but were unable to board it due to a failure in the docking mechanism; its second crew launched in Soyuz 11 and remained on board for 23 productive days. A pressure-equalization valve in the Soyuz 11 reentry capsule opened prematurely when the crew returned to Earth, killing all three. Salyut 1 reentered Earth's atmosphere October 11, 1971.

DOS-2

DOS-2 was launched on July 29, 1972. It was similar in design to Salyut 1. The second stage of its Proton rocket failed, which meant that it never reached orbit. It crashed into the Pacific Ocean.

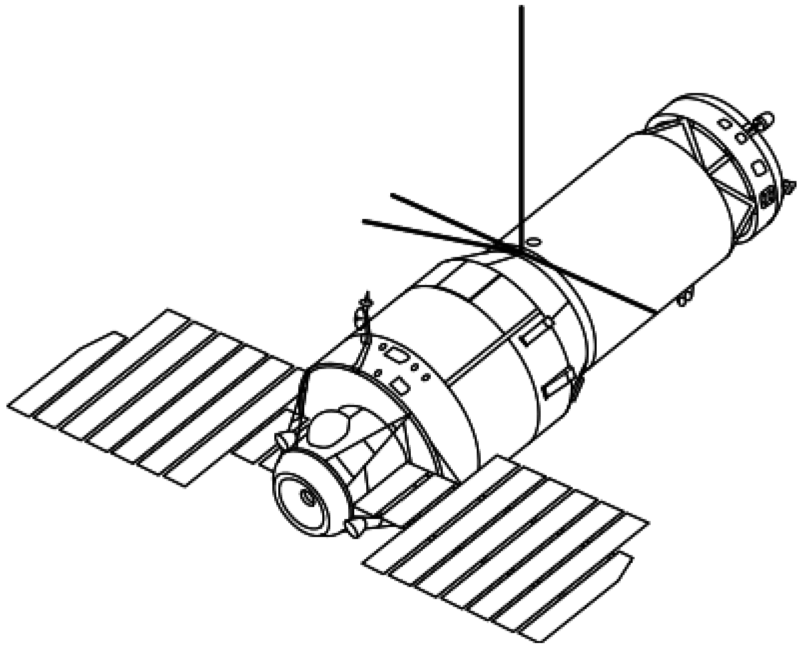
Salyut 2

Salyut 2 (OPS-1) (Russian: Салют-2; English: *Salute 2*) was launched April 4, 1973. It was not really a part of the same program as the other Salyut stations, instead being the highly classified prototype military space station Almaz. It was given the designation Salyut 2 to conceal its true nature. Despite its successful launch, within two days the as-yet-unmanned Salyut 2 began losing pressure and its flight control failed; the cause of the failure was likely due to shrapnel piercing the station when the discarded Proton rocket upper stage that had placed it in orbit later exploded nearby. On April 11, 1973, 11 days after launch, an unexplainable accident caused four solar panels to be torn loose from the space station cutting off all power to the space station. Salyut 2 re-entered on May 28, 1973.

Cosmos 557

The Salyut space station that Almaz had substituted for, designated **DOS-3**, was launched on May 11, 1973, three days before the launch of Skylab. Due to errors in the flight control system while out of the range of ground control, the station fired its orbit-correction engines until it consumed all of its fuel. Since the spacecraft was already in orbit and had been registered by Western radar, the Soviets disguised the launch as **"Cosmos 557"** and quietly allowed it to re-enter Earth's atmosphere and burn up a week later. It was revealed to have been a Salyut station only much later.

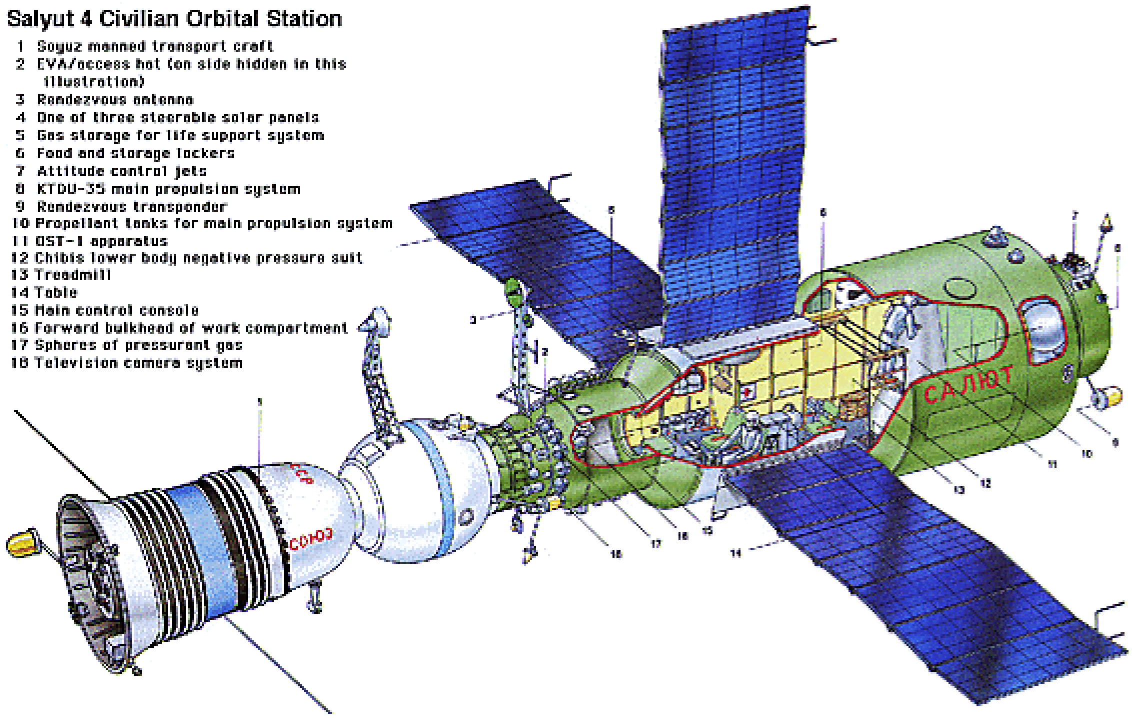
Salyut 3



OPS-2 (Salyut 3)

Salyut 3 (OPS-2) (Russian: Салют-3; English: *Salute 3*) was launched on June 25, 1974. It was another Almaz military space station, this one launched successfully. It tested a wide variety of reconnaissance sensors, returning a canister of film for analysis. On January 24, 1975 trials of the on-board 23 mm Nudelman aircraft cannon (other sources say it was a Nudelman NR-30 30 mm gun) were conducted with positive results at ranges from 3000 m to 500 m. Cosmonauts have confirmed that a target satellite was destroyed in the test. The next day, the station was ordered to deorbit. Only one of the three intended crews successfully boarded and manned the station, brought by Soyuz 14; Soyuz 15 attempted to bring a second crew but failed to dock. Nevertheless, it was an overall success. The station's orbit decayed, and it re-entered the atmosphere on January 24, 1975.

Salyut 4



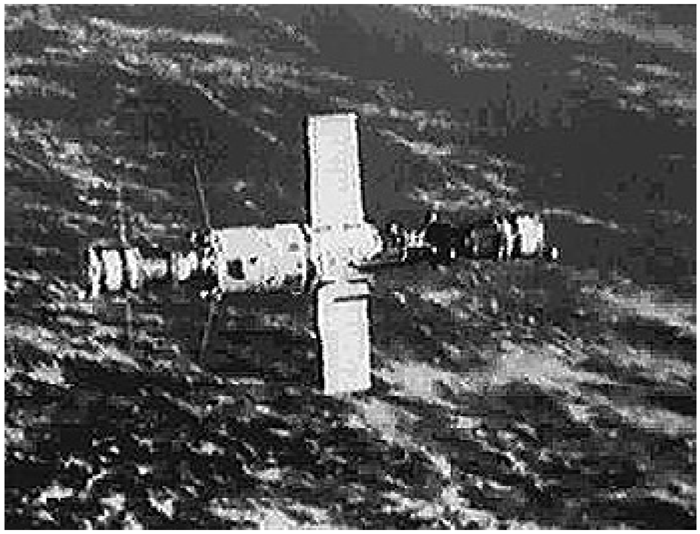
DOS-4 (Salyut 4)

Salyut 4 (DOS-4) (Russian: Салют-4; English: *Salute 4*) was launched on December 26, 1974. It was essentially a copy of the DOS-3, and unlike its ill-fated sibling it was a complete success. Two crews made stays aboard Salyut 4 (Soyuz 17 and Soyuz 18), including one of 63 days duration, and an unmanned Soyuz capsule (Soyuz 20) remained docked to the station for three months, proving the systems' long-term durability. Salyut 4 was deorbited February 2, 1977, and re-entered the Earth's atmosphere on February 3.

Salyut 5

Salyut 5 (OPS-3) (Russian: Салют-5; English translation *Salute 5*) was launched on June 22, 1976. It was the third and last Almaz military space station. Its launch and subsequent mission were both completed successfully, with three crews launching and two (Soyuz 21 and Soyuz 24) successfully boarding the craft for lengthy stays (the second crew on Soyuz 23 was unable to dock and had to abort). Salyut 5 reentered on August 8, 1977. Following Salyut 5 the Soviet Military decided that the tactical advantages were not worth the expense of the program and withdrew. The focus for the later missions was research and prestige.

Salyut 6



DOS-5 (Salyut 6) space station with two docked spacecraft

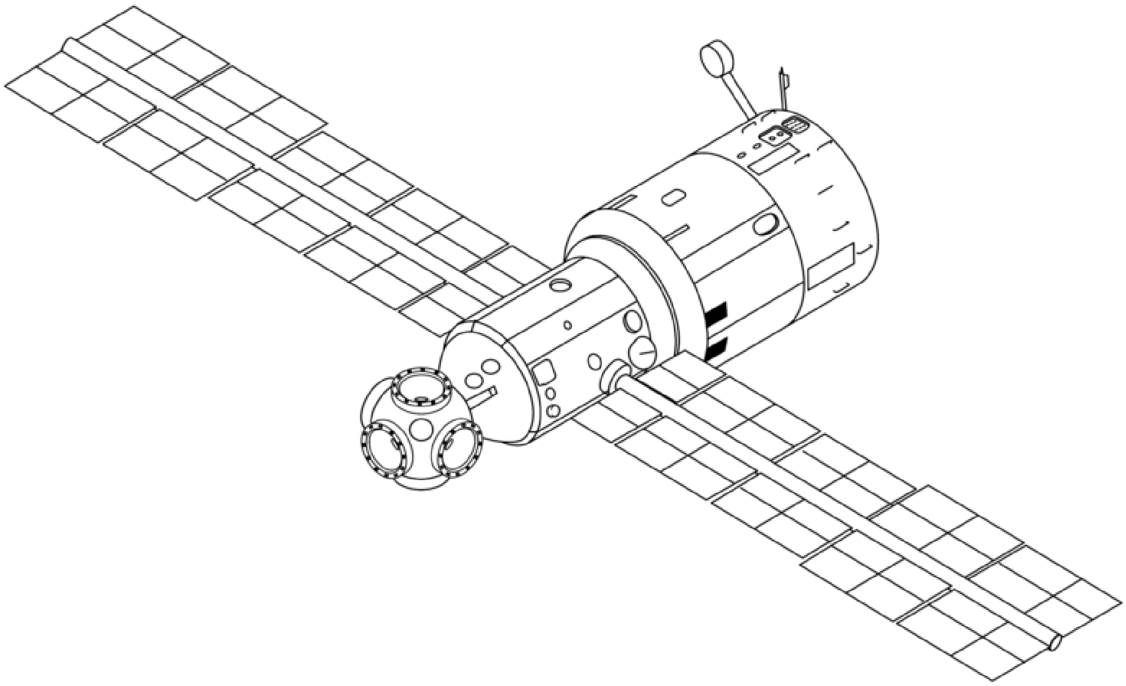
Salyut 6 (DOS-5) (Russian: Салют-6; English: *Salute 6*) was launched on September 29, 1977. Although it resembled the previous Salyut stations in overall design, it featured several revolutionary advances including a second docking port where an unmanned Progress cargo spacecraft could dock and refuel the station. From 1977 until 1982 Salyut 6 was visited by five long-duration crews and 11 short-term crews, including cosmonauts from Warsaw Pact countries. Some unconfirmed reports say the station was functionally capable of even more missions and years, but combating the ever-increasing mold in living quarters was becoming impossible, and in practice caused the retirement decision. The very first long-duration crew on Salyut 6 broke a record set on board Skylab, staying 96 days in orbit. The longest flight on board Salyut 6 lasted 185 days. The fourth Salyut 6 expedition deployed a 10-meter radio-telescope antenna delivered by a cargo ship. After Salyut 6 manned operations were discontinued in 1981, a heavy unmanned spacecraft called TKS and developed using hardware left from the canceled Almaz program was docked to the station as a hardware test. Salyut 6 was deorbited July 29, 1982.

Salyut 7

DOS-6 (Salyut 7) space station

Salyut 7 (DOS-6) (Russian: Салют-7; English: *Salute 7*) was launched on April 19, 1982. It was the back-up vehicle for Salyut 6 and very similar in equipment and capabilities, though several more advanced features were included. It was aloft for four years and two months, during which time it was visited by 10 crews constituting 6 main expeditions and 4 secondary flights (including French and Indian cosmonauts). Aside from the many experiments and observations made on Salyut 7, the station also tested the docking and use of large modules with an orbiting space station. The modules were called "Heavy Cosmos modules." They helped engineers develop technology necessary to build Mir. Salyut 7 deorbited on February 7, 1991.

DOS-7



DOS-7 (Mir Core Module)

It was planned that two other stations (**DOS-7** and **DOS-8**) would follow. These would be equipped with a total of four docking ports; two at either end of the station and an additional two ports on either side of docking sphere at the front of the station. **DOS-7** continued to be developed, becoming the Mir Core Module, featuring better computers and solar arrays, accommodations for two cosmonauts each having their own cabin and six docking ports.

DOS-8

DOS-8 (Zvezda (ISS module) module)

DOS-8 evolved into the Mir-2 project, intended to replace the Mir space station. Finally, it became the International Space Station Zvezda Service Module.

Skylab

Skylab

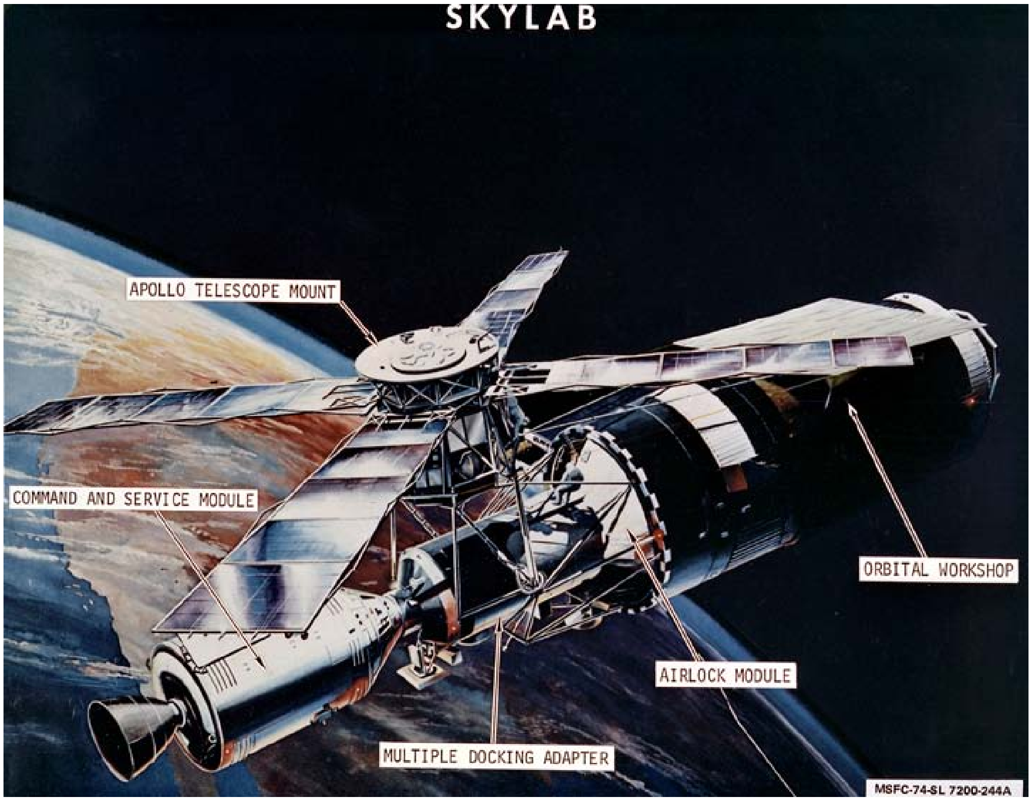
A view of Skylab from the departing Skylab 4 mission

	Station statistics
NSSDC ID	1973-027A
Call sign	Skylab
Crew	3
Launch	1973-05-14 17:30:00 UTC
Launch pad	LC-39A, Kennedy Space Center
Reentry	1979-07-11 16:37:00 UTC near Perth, Australia
Mass	77,088 kg (169,950 lb)
Pressurised volume	10,000 cu ft (283.17 m^3)
Perigee	269.7 mi (434.0 km)
Apogee	274.6 mi (441.9 km)
Orbital inclination	50°
Orbital period	93.4 min
Orbits per day	15.4

Days in orbit	2,249 days
Days occupied	171 days
Number of orbits	34,981
Distance travelled	~890,000,000 mi (1.43×10^9 km)

Statistics as of deorbit on 1979-07-11

Configuration



Skylab configuration with docked Apollo Command/Service Module

Skylab was the United States' first space station, and the second space station visited by a human crew. It was also the only space station NASA launched alone. The 100-ton space station was in Earth's orbit from 1973 to 1979 and it was visited by crews three times in 1973 and 1974.

Background

The exact origin of the project is difficult to pinpoint because a number of different but related proposals were floated by various NASA centers before Skylab itself was launched.

Early studies

A key event took place in 1959, when Wernher von Braun submitted his final Project Horizon plans to the U.S. Army. The overall goal of Horizon was to place a human on the Moon, a mission that would soon be taken over by the rapidly-forming NASA. Although concentrating on the Moon missions, von Braun also detailed an orbiting laboratory built out of a Horizon upper stage, an idea used for Skylab.

A number of NASA centers studied various space station designs in the early 1960s. Studies generally looked at platforms launched by the Saturn V, followed up by crews launched on Saturn IB using an Apollo Command and Service Module (CSM), or a Gemini capsule on a Titan II-C, the latter being much less expensive in the case where cargo was not needed. Proposals ranged from an Apollo-based station with two to three men, or a small "canister" for four men with Gemini capsules resupplying it, to a large, rotating station with 24 men and an operating lifetime of about five years.

Air Force competition

In September 1963, NASA and the Department of Defense (DoD) agreed to cooperate in building a space station. In December, the Air Force nonetheless announced Manned Orbital Laboratory (MOL), a small space station primarily intended for photo reconnaissance using large telescopes directed by a two-man crew. The station was the same diameter as a Titan II upper stage, and would be launched with the crew riding atop in a modified Gemini capsule with a hatch cut into the heat shield on the bottom of the capsule. MOL competed for funding with a NASA station for the next five years and caused changes to the NASA plans so they would resemble MOL less.

Development

Apollo Applications Program

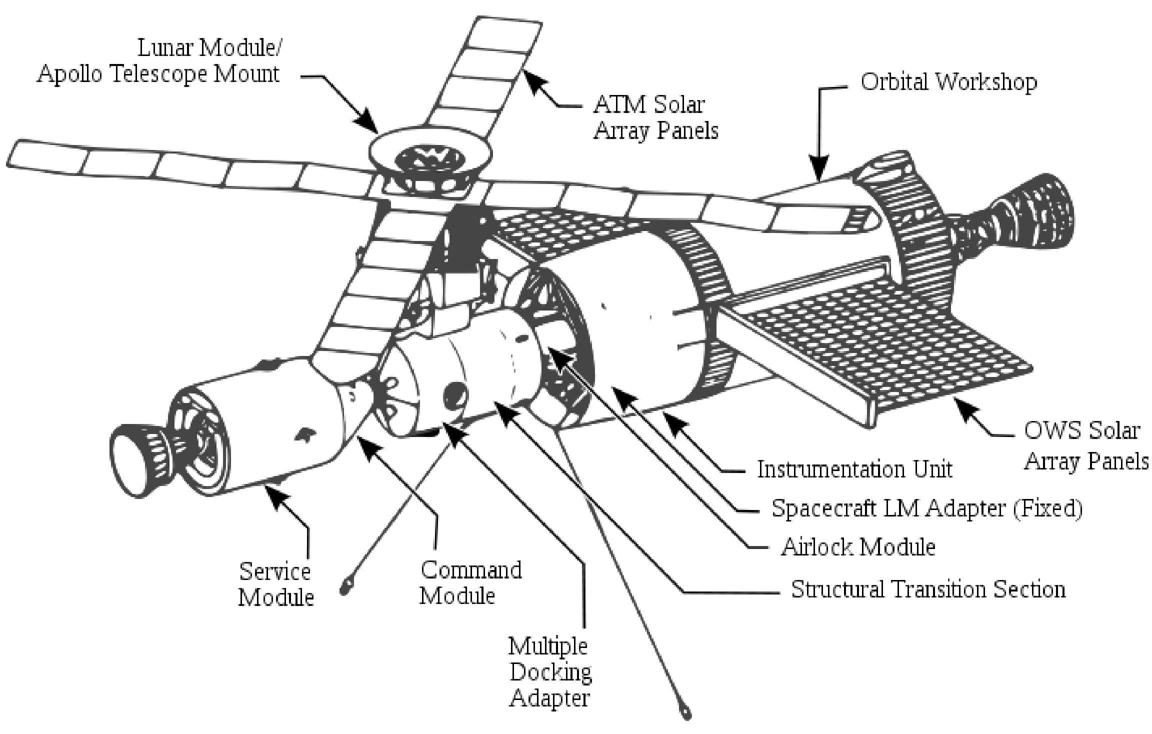
NASA management was concerned about, after landing on the moon, losing the 400,000 workers involved in Apollo. It set up the **Apollo Logistic Support System Office**, originally intended to study various ways to modify the Apollo hardware for scientific missions. The office initially proposed a number of projects for direct scientific study, including an extended-stay lunar mission which required two Saturn V launchers, a "lunar truck" based on the Lunar Module (LEM), a large manned solar telescope using an LEM as its crew quarters and small space stations using a variety of LEM or CSM-based hardware. Although it didn't look at the space station specifically, over the next two years the office would become increasingly dedicated to this role. In August 1965 the office was renamed, becoming the **Apollo Applications Program** (AAP).

As part of their general work, in August 1964 MSC presented studies on an expendable lab known as **Apollo "X"**, short for *Apollo Extension System*. "Apollo X" would have replaced the LEM carried on the top of the S-IVB stage with a small space station slightly larger than the CSM's service area, containing supplies and experiments for missions between 15 and 45 days' duration. Using this study as a baseline, a number of different mission profiles were looked at over the next six months.

Wet workshop

Von Braun proposed a more ambitious plan to build a much larger station. His design replaced the S-IVB stage of a complete Saturn V with an aeroshell, primarily as an adapter for the CSM on top. Inside the shell was a cylindrical equipment section slightly smaller in diameter than the CSM. On reaching orbit, the S-II booster would be vented to remove any remaining hydrogen fuel, then the equipment section would be slid into it via a large inspection hatch. The station filled the entire interior of the S-II stage's hydrogen tank, with the equipment section forming a "spine" and living quarters between it and the walls of the booster. This would have resulted in a very large 33-by-45-foot (10.1 by 13.7 m) living area. Power was to be provided by solar cells lining the outside of the S-II stage.

One problem with this proposal was that it required a dedicated Saturn V launch to fly the station. Engineers could not "piggyback" the station's launch on a lunar mission, which required a working S-IVB stage. At the time the design was being proposed, all of the then-contracted Saturn V's were already earmarked for Moon launches. Further work led to the idea of launching a smaller station based on the S-IVB instead, launching it on a surplus Saturn IB. Several planned Earth-orbit test missions for the LEM and CSM had been canceled, leaving a number of Saturn IB's free for use.



An early "wet workshop" version of Skylab

Since the Saturn I had a much lower throw weight capability, the S-IV stage could not be left empty; its thrust would be needed for the mission. This limitation led to the development of the wet workshop concept, which led naturally out of von Braun's idea of using an existing stage after its fuel had burned off. However, in this case the station was to be built out of the S-IVB stage itself, as opposed to the S-II below it. A number of S-IVB-based stations were studied at MSC, but even the earliest, from mid-1965, had much in common with the Skylab design that actually flew. An airlock was placed in the equipment area immediately below where the LEM sat on a Moon mission and a minimum amount of equipment was installed in the tank itself in order to avoid taking up too much fuel volume. After launch, a follow-up mission launched by a Saturn IB would carry up additional equipment in place of its LEM, including solar panels, an equipment section and docking adaptor, and various experiments. Douglas Aircraft, builder of the S-IVB stage, was asked to prepare proposals along these lines. The company had for several years been proposing stations based on the S-IV that the S-IVB replaced.

On 1 April 1966, MSC sent out contracts to Douglas, Grumman, and McDonnell for conversion of a S-IVB spent stage under the name **Saturn S-IVB spent-stage experiment support module** (SSESM). In May astronauts voiced concern over purging the stage's hydrogen tank in space. Nevertheless, in late July it was announced that the Orbital Workshop would be launched as a part of Apollo mission AS-209, originally one of the Earth-orbit CSM test launches, followed by two Saturn I/CSM crew launches, AAP-1 and AAP-2.

MOL remained AAP's chief competitor for funds although the two programs cooperated on technology. NASA considered flying experiments on MOL, or using its Titan IIIC booster instead of the much more-expensive Saturn IB, but decided that the Air Force station was not large enough and converting Apollo hardware for use with Titan would be too slow and too expensive. DoD canceled MOL in June 1969, however.

Dry workshop

Design work continued over the next two years, in an era of shrinking budgets. In August 1967 NASA announced that the lunar mapping and base construction missions examined by the AAP were being canceled. Only the Earth-orbiting missions remained, namely the Orbital Workshop and Apollo Telescope Mount solar observatory. Later several Moon missions were canceled as well, originally to be Apollo missions 18 through 20. The cancellation of these missions freed up three Saturn V boosters for the AAP program. Although this would have allowed them to develop von Braun's original S-II based mission, by this time so much work had been done on the S-IV based design that work continued on this baseline. With the extra power available, the wet workshop was no longer needed; the S-IC and S-II lower stages could launch a "dry workshop", with its interior already prepared, directly into orbit.

Habitability

Jack Lousma takes shower during Skylab 3 mission

A dry workshop simplified plans for the interior of the station. Industrial design firm Raymond Loewy/William Snaith recommended emphasizing habitability and comfort for the astronauts by, for example, providing a wardroom for meals and relaxation and a window to view the Earth and space, although astronauts who participated in Skylab planning were dubious about designers' focus on areas such as color schemes. Habitability had not previously been an area of concern when building spacecraft due to their small volume and brief mission durations, but Skylab missions would last for months. NASA sent a scientist on Jacques Piccard's *Ben Franklin* submarine in the Gulf Stream in July and August 1969 to learn how six people would live in an enclosed space for four weeks.

Astronauts were uninterested in watching movies on a proposed entertainment center or playing games, but did want books and individual music choices. Food was also important; early Apollo crews complained about its quality, and a NASA volunteer found living on the Apollo food for four days on Earth to be intolerable; its taste and composition, in the form of cubes and squeeze tubes, were unpleasant. Skylab food significantly improved on its predecessors by prioritizing habitability over scientific needs.

Each astronaut had a private sleeping area the size of a small walk-in closet with a curtain, sleeping bag, and locker. Designers also added a shower and a toilet; the latter was for both comfort and to obtain precise urine and feces samples for examination on Earth.

Operational history

On 8 August 1969, the McDonnell Douglas Corporation received a contract for the conversion of two existing S-IVB stages to the Orbital Workshop configuration. One of the S-IV test stages was shipped to McDonnell Douglas for the construction of a mock-up in January 1970. The Orbital Workshop was renamed "Skylab" in February 1970 as a result of a NASA contest. The actual stage that flew was the upper stage of the AS-212 rocket (the S-IVB stage). The mission computer used aboard Skylab was the IBM System/4Pi TC-1, a relative of the AP-101 Space Shuttle computers.

Launch of the modified Saturn V rocket carrying the Skylab space station

Skylab was launched 14 May 1973 by a Saturn V with the upper stage removed, but with the avionics remaining in the same position (different from the Saturn INT-21 rocket which could launch payloads not based on the S-IVB) into a 235 nautical mile (435 km) orbit. The launch is sometimes referred to as Skylab 1, or SL-1. Severe damage was sustained during launch and deployment, including the loss of the station's micrometeoroid shield/sun shade and one of its main solar panels. Debris from the lost micrometeoroid shield further complicated matters by pinning the remaining solar panel to the side of the station, preventing its deployment and thus leaving the station with a huge power deficit. The station underwent extensive repair during a spacewalk by the crew of the SL-2 mission, which launched on 25 May 1973 atop a Saturn IB. If the crew had failed to repair Skylab in time, the plastic insulation inside the station would have melted, releasing poisonous gas and making Skylab completely uninhabitable. They stayed in orbit with Skylab for 28 days. Two additional missions followed with the launch dates of 28 July 1973 (SL-3) and 16 November 1973 (SL-4) with mission durations of 59 and 84 days, respectively. The last Skylab crew returned to the Earth on 8 February 1974.

Operations in orbit

Skylab orbited Earth 2,476 times during the 171 days and 13 hours of its occupation during the three manned Skylab missions. Astronauts performed ten spacewalks totaling 42 hours 16 minutes. Skylab logged about 2,000 hours of scientific and medical experiments, 127,000 frames of film of the sun and 46,000 of the Earth. Solar experiments included photographs of eight solar flares, and produced valuable results that scientists stated would have been impossible to obtain with unmanned spacecraft. The existence of the Sun's coronal holes were confirmed because of these efforts. Many of the experiments conducted investigated the astronauts' adaptation to extended periods of microgravity.

Life in orbit

Each Skylab mission set a record for the amount of time astronauts spent in space. The station offered "a highly satisfactory living and working environment for crews." Although it had a dart set, playing cards, and other recreational equipment in addition to books and music players, the window became the most popular way to relax in orbit. Crews enjoyed taking a shower once a week but found drying themselves in weightlessness difficult. Although the toilet was noisy, both veteran astronauts—who had endured earlier missions' rudimentary waste-collection systems—and rookies complimented it.

Plans for reuse

Skylab was abandoned after the end of the SL-4 mission in February 1974. In 1977 and 1978, when NASA still believed the shuttle would be ready by 1979, it completed two studies on reusing the station. As of September 1978 the agency believed Skylab was safe for crews, with all major systems intact and operational. It still had 180 man-days of water and 420 man-days of oxygen, and astronauts could refill both; the station could hold up to about 600 to 700 man-days of drinkable water and 420 man-days of food.

The studies cited several benefits from reusing Skylab, which one called a resource worth "hundreds of millions of dollars" already in orbit. Since no more Saturn Vs existed, four to five shuttle flights and extensive space architecture would have beeen needed to build another station as large as Skylab's 12,400 cubic feet (350 m^3) volume. Its ample size—much greater than that of the shuttle alone or shuttle plus Spacelab—was enough with some modifications for up to seven astronauts of both sexes and experiments needing long duration in space; even a movie projector for recreation was possible.

Reuse proponents also said repairing and upgrading Skylab would provide information on the results of long-duration exposure to space for future stations. The most serious issue for reactivation was stationkeeping, as one of the gyroscopes had failed and the attitude control system needed refueling; they would need extra-vehicular activity (EVA) to fix or replace. The station had not been designed for extensive resupply. However, while plans had originally called for Skylab crews to perform only limited maintenance they successfully made major repairs during EVA, such as the SL-2 crew's deploying of the solar panel and the SL-4 crew's repair of the primary coolant loop. The SL-2 crew fixed one item during EVA by "hit[ting] it with the hammer."

Some studies also said beyond the opportunity for space construction and maintenance experience, reactivating the station would free up shuttle flights for other uses and reduce the need to modify the shuttle for long-duration missions. Even if the station were not manned again, went one argument, it would serve as a useful experimental platform.

Planned shuttle missions

The reactivation would have occurred in four phases:

1. An early Shuttle flight would boost Skylab to a higher orbit that would add five years of life. The shuttle might have pushed or towed the station, but attaching a booster—the Tele-operated Reboost System (TRS)—to the station was more likely based on astronauts' training for the task. Martin Marietta won the contract for the $26 million TRS, which contained about three tons of propellant, and began work in April 1978.
2. In two shuttle flights, Skylab would be refurbished. In January 1982, the first mission would attach a docking adapter and conduct repairs. In August 1983, a second crew would replace several system components.
3. In March 1984, shuttle crews would attach a solar-powered Power Expansion Package, refurbish scientific equipment, and conduct 30- to 90-day missions using the Apollo Telescope Mount and the earth resources experiments.
4. Over five years Skylab would be expanded to accommodate six to eight astronauts, with a new large docking/interface module, additional logistics modules, Spacelab modules and pallets, and an orbital vehicle space dock using the shuttle's external tank.

The first three phases would have required about $60 million in 1980s dollars, not including launch costs.

Abandonment and re-entry

Vanguard (T-AGM-19) seen here as a NASA Skylab tracking ship. Note the tracking radar and telemetry antennas.

After an 6.8 miles (10.9 km) boost by SL-4's Apollo CSM before its departure, Skylab was left in a parking orbit of 269 miles (433 km) by 283 miles (455 km) that was expected to last until at least the early 1980s based on estimates of the 11-year sunspot cycle that began in 1976. At the end of SL-4, only one Saturn IB rocket remained in the inventory—later used for Apollo-Soyuz Test Project—while all other Saturn IB and Saturn V rocket parts had been donated to museums. NASA began considering the risks from space station reentry as early as 1962, but decided to not incorporate a retrorocket system in Skylab due to cost and acceptable risk.

Solar activity

Greater-than-expected solar activity heated the outer layers of the Earth's atmosphere and thereby increased drag on Skylab. By late 1977 NORAD accurately forecast a reentry in mid-1979; a NOAA scientist criticized NASA for using an inaccurate model for the second most-intense sunspot cycle in a century, and for ignoring NOAA predictions published in 1976.

The reentry of the USSR's Cosmos 954 in January 1978 and the resulting radioactive debris in northern Canada drew more attention to Skylab's orbit. Although Skylab did not contain radioactive materials, the State Department warned NASA about diplomatic repercussions from station debris. Ground controllers re-established contact with Skylab in March 1978 and recharged its batteries. Although NASA worked on plans to reboost Skylab with the shuttle through 1978 and the TRS was almost complete, the agency gave up in December when it became clear that the shuttle would not be ready in time; its first flight, STS-1, did not occur until April 1981. Also rejected was a proposal to launch the TRS using one or two unmanned rockets.

Reentry

The largest fragment of Skylab recovered after its re-entry through Earth's atmosphere. It is on display at the United States Space & Rocket Center.

Skylab's demise was an international media event, with merchandising, wagering on time and place of re-entry, and nightly news reports. The *San Francisco Examiner* offered a $10,000 prize for the first piece of Skylab delivered to its offices; the competing *Chronicle* offered $200,000 if a subscriber suffered personal or property damage. NASA calculated that the odds of station re-entry debris hitting a human were 152 to 1—

although the odds of debris hitting a city of 100,000 or more were 7 to 1—and teams were ready to head to any country hit by debris and requesting help.

Ground controllers adjusted Skylab's orientation for ideal re-entry dynamics in the hours before reentry at approximately 16:37 UTC 11 July 1979. They aimed the station at a spot 810 miles (1,300 km) south southeast of Cape Town, South Africa. The station did not burn up as fast as NASA expected, however. Due to a 4% calculation error, debris landed southeast of Perth, Western Australia and was found between Esperance and Rawlinna, from 31° to 34°S and 122° to 126°E. The Shire of Esperance fined the United States $400 for littering, a fine which remained unpaid for 30 years. The fine was paid in April 2009, when radio show host Scott Barley of Highway Radio raised the funds from his morning show listeners and paid the fine on behalf of NASA.

17 years-old Stan Thornton found a few pieces of Skylab at his home in Esperance and caught the first flight to San Francisco, where he collected the *Examiner* prize. In a coincidence for the organizers, the annual Miss Universe pageant was scheduled to be held a few days later, on 20 July 1979 in Perth. A large piece of Skylab debris was displayed on the stage.

Unflown planned missions

Skylab 5

Skylab 5 would have been a short 20-day mission to conduct scientific experiments and boost Skylab into a higher orbit. Vance Brand (commander), Don Lind (command module pilot), and William B. Lenoir (science pilot) would have been the crew for this mission, with Brand and Lind being the prime crew for the never-flown Skylab Rescue flights. Brand and Lind also trained for a mission that would have aimed Skylab for a controlled deorbit.

Skylab B

A flight-quality backup Skylab was built. NASA considered using it for a second Skylab B station in May 1973 or later, but decided against it. Launching another Skylab with another Saturn V rocket would have been very costly, and it was decided to spend this money on the development of the Space Shuttle, instead. The backup is on display at the National Air and Space Museum in Washington, D.C.

A full-size training mock-up once used for astronaut training is located at the Lyndon B. Johnson Space Center visitor's center in Houston, Texas. Another full-size training mock-up, made from spare parts, has been rotting for years in a museum parking lot exposed to the elements at Huntsville, Alabama after it was moved outdoors to make way for an exhibit on the Russian space station MIR. This Skylab engineering mockup is currently being considered for restoration to the pristine condition it originally enjoyed inside the U.S. Space and Rocket Center.

Skylab mission designations

Robbins Medallions issued for Skylab Missions

The numeric identification of the manned Skylab missions is the cause of much confusion. Originally, the unmanned launch of Skylab and three manned missions were numbered **SL-1** through **SL-4**. During the preparations for the manned missions, some documentation was created with a different scheme -- **SLM-1** through **SLM-3** -- for those missions only. William Pogue credits Pete Conrad with asking the Skylab program director which scheme should be used for the mission patches, and the astronauts were told to use 1-2-3, not 2-3-4. By the time NASA administrators tried to reverse this decision, it was too late, as all the in-flight clothing had already been manufactured and shipped with the 1-2-3 mission patches.

Mission	Emblem	Commander	Pilot	Science Pilot	Launch date	Landing date	Duration (days)
Skylab 1 ***SL-1***		***unmanned launch of space station***			1973-05-14 17:30:00 UTC	1979-07-11 16:37:00 UTC	2248.96
Skylab 2 ***SL-2*** **(*SLM-1*)**		Pete Conrad	Paul Weitz	Joseph Kerwin	1973-05-25 13:00:00 UTC	1973-06-22 13:49:48 UTC	28.03
Skylab 3 ***SL-3*** **(*SLM-2*)**		Alan Bean	Jack Lousma	Owen Garriott	1973-07-28 11:10:50 UTC	1973-09-25 22:19:51 UTC	59.46

Skylab 4 ***SL-4*** **(*SLM-3*)**		Gerald Carr	William Pogue	Edward Gibson	1973-11-16 14:01:23 UTC	1974-02-08 15:16:53 UTC	84.04

Gallery

The waste management facilities in the backup Skylab at the National Air and Space Museum

An astronaut dines aboard the backup Skylab at the Smithsonian NASM

Mir

Mir

Mir on 26 September 1996 as seen from the departing Space Shuttle *Atlantis* during STS-79.

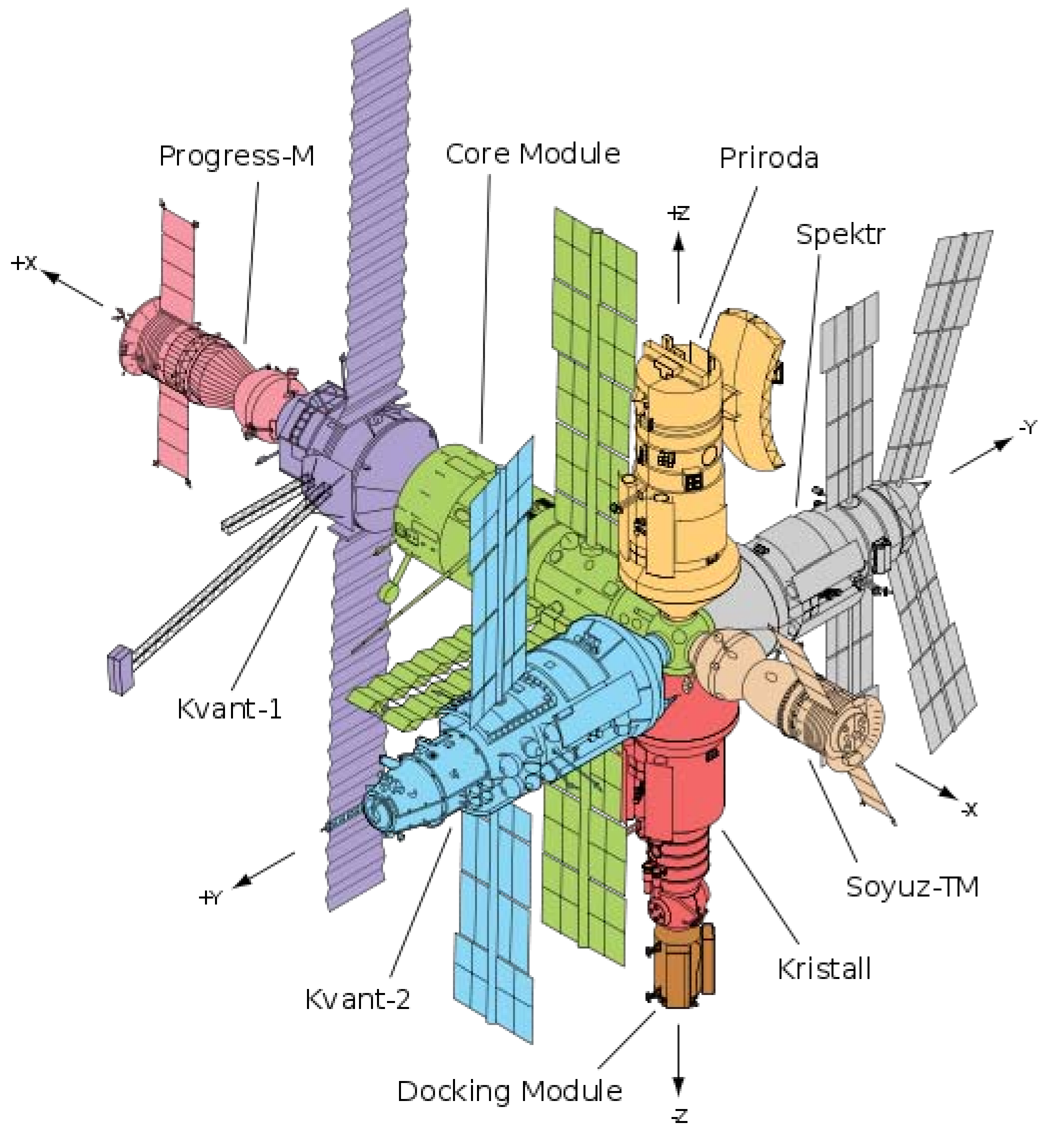
Mir insignia.

Station statistics

NSSDC ID	1986-017A
Call sign	*Mir*
Crew	3
Launch	1986–1996
Launch pad	LC-200/39, and LC-81/23, Baikonur Cosmodrome LC-39A, Kennedy Space Center
Reentry	23 March 2001 05:59 UTC
Mass	129,700 kg (285,940 lbs)
Length	31 m (101.7 ft) from *Priroda* to the docking module
Width	27.5 m (90.2 ft) from *Kvant*-2 to *Spektr*
Height	19 m (62.3 ft) from *Kvant*-1 to the core module
Pressurised volume	350 m^3
Perigee	354 km (189 nmi) AMSL $\bar{x}$
Apogee	374 km (216 nmi) AMSL $\bar{x}$
Orbital inclination	51.6 degrees
Average speed	7,700 m/s (27,700 km/h, 17,200 mph)
Orbital period	91.9 minutes $\bar{x}$
Orbits per day	15.7 $\bar{x}$
Days in orbit	5,519 days
Days occupied	4,592 days
Number of orbits	86,331

Statistics as of 23 March 2001

Configuration



Station elements as of May 1996.

Mir (Russian: Мир; lit. *Peace*, *World* or *Society*) was a Soviet and later Russian space station, operational in low Earth orbit from 1986 to 2001. With a greater mass than that of any previous space station, *Mir* was the first of the third generation type of space station, constructed from 1986 to 1996 with a modular design, and was the largest artificial satellite orbiting the Earth until its deorbit on 21 March 2001, a record now surpassed by the International Space Station (ISS). *Mir* served as a microgravity research laboratory in which crews conducted experiments in biology, human biology, physics, astronomy, meteorology and spacecraft systems, with an aim to develop technologies required for the permanent occupation of space. The station was the first consistently inhabited long-term research station in space, and was operated by a series of long-duration crews. The *Mir* programme currently holds the record for the longest uninterrupted human presence in space, at 9 years and 257 days, and for the longest single human spaceflight, of Valeri

Polyakov, at 437 days 18 hours. *Mir* was occupied for a total of twelve and a half years of its fifteen-year lifespan, having the capacity to support a resident crew of three and larger crews for short-term visits.

Following the success of the Salyut programme, *Mir* represented the next stage in the Soviet Union's space station programme. The first module of the station, known as the core module or base block, was launched in 1986, and was followed by six further modules, all being launched by Proton rockets (with the exception of the docking module). When complete, the station consisted of seven pressurised modules and several unpressurised components. Power was provided by several solar arrays mounted directly to the modules. The station was maintained at an orbit between 296 km (184 mi) and 421 km (262 mi) altitude and travelled at an average speed of 27,700 km/h (17,200 mph), completing 15.7 orbits per day.

The station was originally launched as part of the Soviet Union's manned spaceflight programme's effort to maintain a long-term research outpost in space, and, following the collapse of the USSR, was operated by the new Russian Federal Space Agency (RKA). As a result, the vast majority of the station's crew were Soviet or Russian, however, through a number of international collaborations, including Intercosmos, Euromir and the Shuttle-Mir Program, the station was made accessible to astronauts from North America, several western European nations and Japan, as well as cosmonauts from various eastern nations. The cost of the station was estimated by Yuri Koptev in 2001 as $4.3 billion over the lifetime of the station, including its development, assembly and orbital operation, making *Mir* the eleventh most expensive object ever constructed. The station was serviced by Soyuz spacecraft, Progress spacecraft and (during the Shuttle-*Mir* programme) US space shuttles, and was visited by astronauts and cosmonauts from 12 different nations.

Origins

Mir was authorized as part of the third generation of Soviet space systems in a February 17, 1976 decree to design an improved model of the Salyut DOS-17K space station. Four Salyut space stations had already been launched since 1971, with three more being launched during *Mir'*s development. It was planned that the base blocks (DOS-7 and DOS-8) would be equipped with a total of four docking ports; two at either end of the station as with the Salyut stations, and an additional two ports on either side of a docking sphere at the front of the station. By August 1978, this had evolved to the final configuration of one aft port and five ports in a spherical compartment at the forward end of the station.

It was originally planned that the ports would connect to 7.5 tonne modules derived from the Soyuz spacecraft. These modules would have used a Soyuz propulsion module, as in Soyuz and Progress, and descent module and orbital module would have been replaced with a long laboratory module. However, following a February 1979 governmental resolution, the program was consolidated with Vladimir Chelomei's manned Almaz military space station program. The docking ports were reinforced to accommodate 20 tonne space station modules based on the TKS spacecraft. NPO Energia was responsible for the overall space station, with work subcontracted to KB Salyut, due to ongoing work on the Energia launch vehicle and Salyut 7, Soyuz-T, and Progress spacecraft. KB Salyut began work in 1979, and drawings were released in 1982 and 1983. New systems incorporated into the station included the Salyut 5B digital flight control computer and gyrodyne flywheels (taken from Almaz), Kurs automatic rendezvous system, *Luch* satellite communications system, Elektron oxygen generators, and Vozdukh carbon dioxide scrubbers.

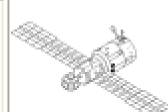
By early 1984 work on *Mir* had ground to a halt while all resources were being put into the Buran program in order to prepare the *Buran* space shuttle for flight testing. Funding was returned in early 1984 when Valentin Glushko was ordered by the Central Committee's Secretary for Space and Defense to orbit *Mir* by early 1986, in time for the 27th Communist Party Congress.

It was clear that the planned processing flow could not be followed and still make the 1986 launch date. It was decided on Cosmonaut's Day (April 12) to ship the flight model of the base block to the Baikonur cosmodrome and conduct the systems testing and integration there. The module arrived at the launch site on May 6, 1985. 1100 of 2500 cables required rework based on the results of tests to the ground test model at Khrunichev. In October the base block was rolled outside its cleanroom. The first launch attempt on February 16, 1986 was scrubbed when the spacecraft communications failed, but the second launch attempt, on February 19, 1986 at 21:28:23 UTC, was successful, meeting the political deadline.

Station structure

Pressurised modules

In its completed configuration, the space station consisted of seven different modules, each launched into orbit separately over a period of ten years by either Proton rocket or Space Shuttle.

<table>
<tr><th>Module</th><th>Soyuz</th><th>Launch date</th><th>Launch system</th><th>Nation</th><th>Isolated View</th><th>Station View</th></tr>
<tr><td rowspan="2">Mir
(Core Module)</td><td>N/A</td><td>19 February 1986</td><td>Proton-K</td><td>Soviet Union</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td colspan="4">The base block for the entire Mir complex, the core module provided the main living quarters for resident crews, environmental systems, provided early attitude control systems and contained the station's main engines. The module consisted of a stepped-cylinder main compartment and a spherical docking module to</td></tr>
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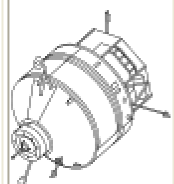
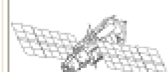
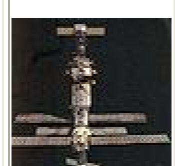
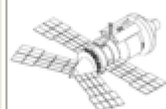
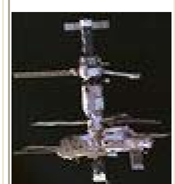
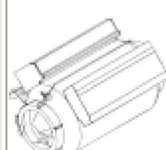
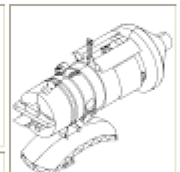
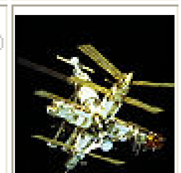
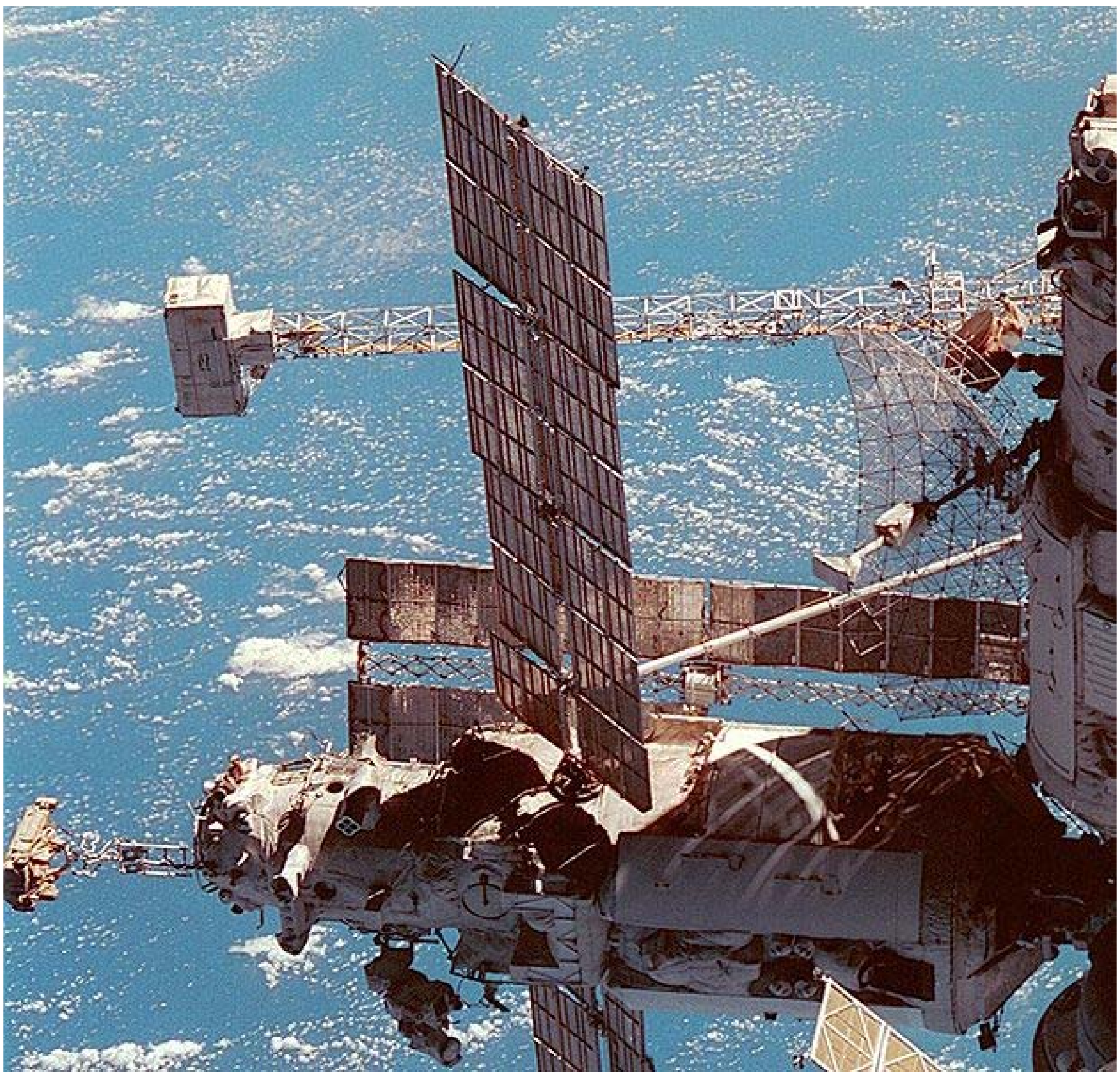
<tr><td></td><td colspan="4">which served as an airlock and provided ports to which four of the station's expansion modules were berthed, and to which a Soyuz or Progress spacecraft could dock. The module's aft port served as the berthing location for Kvant-1.</td><td></td><td></td></tr>
<tr><td rowspan="2">Kvant-1
(Astrophysics Module)</td><td>TM-2</td><td>31 March 1987</td><td>Proton-K</td><td>Soviet Union</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td colspan="4">The first expansion module to be launched, Kvant-1 consisted of two pressurized working compartments and one unpressurised experiment compartment. Scientific equipment included an X-ray telescope, an ultraviolet telescope, a wide-angle camera, high-energy X-ray experiments, an X-ray/gamma ray detector, and the Svetlana electrophoresis unit. The module also carried six gyrodines for attitude control, life support systems including an Elektron oxygen generator and Vozdukh carbon dioxide scrubber.</td></tr>
<tr><td rowspan="2">Kvant-2
(Augmentation Module)</td><td>TM-8</td><td>26 November 1989</td><td>Proton-K</td><td>Soviet Union</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td colspan="4">The first TKS based module, Kvant-2 was divided into three compartments; an EVA airlock, instrument/cargo compartment (which could function as a backup airlock), and instrument/experiment compartment. The module also carried a Soviet version of the Manned Maneuvering Unit for the Orlan space suit, a system for regenerating water from urine, a shower, the Rodnik water storage system and six gyrodines to augment those already located in Kvant-1. Scientific equipment included a high-resolution camera, spectrometers, X-ray sensors, the Volna 2 fluid flow experiment, and the Inkubator-2 unit which was used for hatching and raising quail.</td></tr>
<tr><td rowspan="2">Kristall
(Technology Module)</td><td>TM-9</td><td>31 May 1990</td><td>Proton-K</td><td>Soviet Union</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td colspan="4">Kristall, the fourth module, consisted of two main sections. The first was largely used for materials processing (via various processing furnaces), astronomical observations and housed a biotechnology experiment utilising the Aniur electrophoresis unit. The second section was a</td></tr>
</table>

	docking compartment, which featured two APAS-89 docking ports, initially intended for use with the Buran space shuttle programme, and eventually used during the Shuttle-*Mir* programme. The docking compartment also contained the Priroda 5 camera, used for Earth resources experiments. *Kristall* also carried six gyrodines for attitude control and to augment those already on the station, and two collapsible solar arrays.					
Spektr (Power Module)	TM-21	1 June 1995	Proton-K	Russia (Builder) US (Part Financier)		
	Spektr was the first of the three modules launched as part of the Shuttle-*Mir* programme, and served as the living quarters for American astronauts and housed NASA-sponsored experiments. The module was designed for remote observation of Earth's environment and contained atmospheric and surface research equipment, in addition to four solar arrays which generated approximately half of the station's electrical power. The module also featured a scientific airlock to expose experiments to the vacuum of space.					
Docking Module	TM-22	15 November 1995	Space Shuttle *Atlantis* (STS-74)	US		
	The Docking Module was designed to help simplify Space Shuttle dockings to *Mir*. Before the first shuttle docking mission (STS-71), the tedious task of moving the Kristall module had to be done to ensure there was sufficient clearance between the Shuttle and *Mir*'s solar arrays. The Docking Module provided enough clearance without the need to relocate *Kristall*. The module carried two identical APAS-89 docking ports. One was attached to the lateral port of *Kristall* and the other was open for shuttle dockings.					
Priroda (Earth Sensing Module)	TM-23	26 April 1996	Proton-K	Russia (Builder) US (Part Financier)		
	The seventh and final *Mir* module, *Priroda*'s					

	primary purpose was to conduct Earth resource experiments through remote sensing and to develop and verify remote sensing methods. The module's experiments were provided by twelve different nations, and covered microwave, visible, near infrared, and infrared spectral regions using both passive and active sounding methods. The module possessed both pressurised and unpressurised segments, and featured a large, externally mounted synthetic aperture radar dish.		

Unpressurised elements



The TRAVERS radar antenna, *Sofora* girder, VDU thruster block, SPK unit and a *Strela* crane, alongside *Kvant*-2 and *Priroda*.

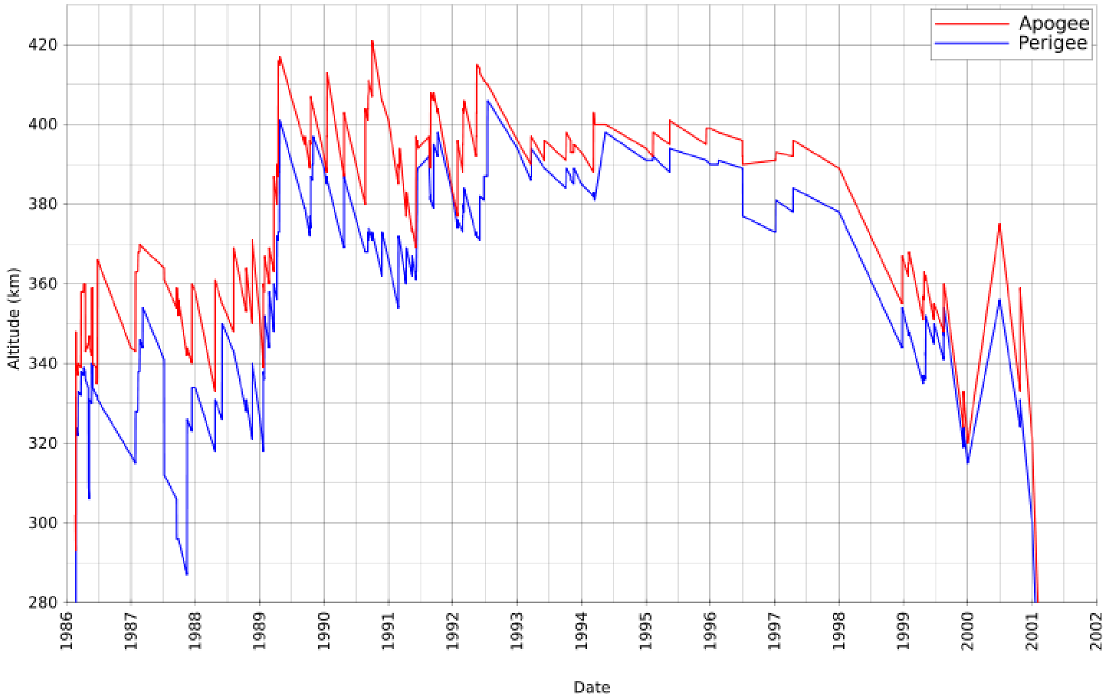
In addition to the pressurised modules, *Mir* featured a large number of external components. The largest component was the *Sofora* girder, a large scaffolding-link structure consisting of 20 segments which, when assembled, projected 14 metres from its mount on *Kvant*-1. A self-contained thruster block, referred to as the VDU, was mounted on the end of *Sofora* and was used to augment the roll-control thrusters on the core module in order to reduce the amount of propellant used to orientate the station, its increased distance from *Mir*'s axis leading to an 85% decrease in fuel consumption. A second girder, *Rapana*, was mounted aft of *Sofora* on *Kvant*-1. This girder, a scaled-down prototype of a structure intended to be used on *Mir*-2 to hold large parabolic dishes away from the main station structure, was 5 metres long and used as a mounting point for externally-mounted exposure experiments.

To assist in moving objects around the exterior of the station during EVAs, *Mir* featured two *Strela* cargo cranes mounted to the port and starboard sides of the core module, used for moving spacewalking cosmonauts and parts around the exterior of the station. The cranes consisted of telescopic poles assembled in sections, which measured around 6 feet when collapsed but, when extended using a hand crank, measured 46 feet long, meaning that all of the station's modules could easily be accessed during spacewalks.

Each module was also fitted with a number of external components specific to the experiments that were carried out within that module, the most obvious of which was the Travers antenna mounted to *Priroda*. This synthetic aperture radar consisted of a large dish-like framework mounted to the exterior of the module, with associated equipment within, and was used for Earth observations experiments, as was most of the other equipment on *Priroda*, including various radiometers and scan platforms. *Kvant*-2, too, featured a number of scan platforms, and was also fitted with a mounting bracket to which was mated the cosmonaut manoeuvring unit, or *Ikar*. This backpack was designed to assist cosmonauts in moving around the station and the planned *Buran* space shuttles, in a manner similar to the US Manned Maneuvering Unit, but in the end was only used once, during EO-5.

In addition to module-specific apparatus, *Kvant*-2, *Kristall*, *Spektr* and *Priroda* were equipped with a *Lyappa* arm, a robotic arm which, after the module had docked to the core module's forward port, grappled one of two fixtures positioned on the core module's docking node. The arriving module's docking probe was then retracted, and the arm raised the module so that it could be pivoted 90° for docking to one of the four radial docking ports.

Orbit control



Graph showing the changing altitude of *Mir* from 19 February 1986 until 21 March 2001

Mir was maintained in a near circular orbit with an average perigee of 354 km (220 mi) and an average apogee of 374 km (232 mi), travelling at an average speed of 27,700 km/h (17,200 mph), completing 15.7 orbits per day. As the station constantly lost altitude because of a slight atmospheric drag, it needed to be boosted to a higher altitude several times each year. This boost was generally performed by Progress resupply vessels, although during the Shuttle-*Mir* programme the task was performed by US Space Shuttles, and, prior to the arrival of *Kvant*-1, the engines on the core module could also accomplish the task.

The attitude (orientation) of the station was independently determined by a set of externally mounted sun, star and horizon sensors. The attitude knowledge is propagated between updates by rate sensors. Attitude control was maintained by a combination of two mechanisms; in order to hold a set attitude, a system of twelve control moment gyroscopes (CMGs, or 'gyrodynes') rotating at 10,000 rpm kept the station oriented, with six CMGs located in each of the *Kvant-1* and *Kvant-2* modules. When the attitude of the station needed to be changed, the gyrodynes were disengaged, thrusters (including those mounted directly to the modules, and the VDU thruster used for roll control mounted to the *Sofora* girder) used to establish the new attitude, and the CMGs reengaged. This was done fairly regularly dependent on experimental needs; for instance, Earth or astronomical observations required the instrument recording images to be continuously aimed at the target, and so the station was orientated to enable this. Conversely, materials processing experiments required the minimisation of movements aboard the station, and so *Mir* would be orientated in a gravity gradient attitude for stability. Prior to the arrival of the modules containing these gyrodynes, the station's attitude was controlled using thrusters located on the core module alone, and, in an emergency (such as following the collision with Progress M-34 in 1997), the thrusters on docked Soyuz spacecraft could be used to maintain the station's orientation.

Microgravity

At *Mir*'s orbital altitude, the gravity from the Earth was 88% of that at sea level. While the constant free fall of the station offered a perceived sensation of weightlessness, the environment onboard was not one of weightlessness or zero-gravity. The environment was, however, often described as microgravity. This state of perceived weightlessness was not perfect, however, being disturbed by four separate effects:

- The drag resulting from the residual atmosphere.
- Vibratory acceleration caused by mechanical systems and the crew on board the station.
- Orbital corrections by the on-board gyroscopes (which span at 10,000 rpm, producing vibrations of 166.67 Hz) or thrusters.
- The spatial separation from the real centre of mass of the station. Any part of *Mir* not at the exact centre of mass tended to follow its own orbit. However, as each point was physically part of the station, this is impossible, and so each component was subject to small accelerations from the forces which kept them attached to the station as it orbited. This is also called the tidal force.
- The differences in orbital plane between different locations aboard the station.

International cooperation

Intercosmos

The Intercosmos crest

The Intercosmos ("ИнтерКосмос" Interkosmos) was a space exploration program run by the Soviet Union to allow members from military forces of allied Warsaw Pact countries to participate in manned and unmanned space exploration missions. Participation was also made available to governments of sympathetic countries, such as France and India.

Only the last three of the program's fourteen missions consisted of an expedition to *Mir* but none resulted in an extended stay in the station.

- Muhammed Faris from Syria aboard Soyuz TM-3.
- Aleksandr Panayatov Aleksandrov from Bulgaria aboard Soyuz TM-5.
- Abdul Ahad Mohmand from Afghanistan aboard Soyuz TM-6.

Shuttle–*Mir* Program

The Shuttle–*Mir* insignia

In the early 1980s, NASA planned to launch a modular space station called *Freedom* as a counterpart to *Mir*, while the Soviets were planning to construct *Mir*-2 in the 1990s as a replacement for the station. Because of budget and design constraints, *Freedom* never progressed past mock-ups and minor component tests and, with the fall of the Soviet Union and the end of the Space Race, *Freedom* was nearly cancelled by the United States

House of Representatives. The post-Soviet economic chaos in Russia also led to the cancellation of *Mir*-2, though only after its base block, DOS-8, had been constructed. Similar budgetary difficulties were faced by other nations with space station projects, which prompted the American government to negotiate with European states, Russia, Japan, and Canada in the early 1990s to begin a collaborative project. In June 1992, American president George H. W. Bush and Russian president Boris Yeltsin agreed to cooperate on space exploration. The resulting *Agreement between the United States of America and the Russian Federation Concerning Cooperation in the Exploration and Use of Outer Space for Peaceful Purposes* called for a short, joint space program, with one American astronaut deployed to the Russian space station *Mir* and two Russian cosmonauts deployed to a Space Shuttle.

In September 1993, American Vice-President Al Gore, Jr., and Russian Prime Minister Viktor Chernomyrdin announced plans for a new space station, which eventually became the International Space Station. They also agreed, in preparation for this new project, that the United States would be heavily involved in the *Mir* program as part of an international project known as the Shuttle–*Mir* program. The project, sometimes called "Phase One", was intended to allow the United States to learn from Russian experience with long-duration spaceflight and to foster a spirit of cooperation between the two nations and their space agencies, the US National Aeronautics and Space Administration (NASA) and the Russian Federal Space Agency (Roskosmos). The project helped to prepare the way for further cooperative space ventures; specifically, "Phase Two" of the joint project, the construction of the International Space Station (ISS). The program was announced in 1993, the first mission started in 1994 and the project continued until its scheduled completion in 1998. Eleven Space Shuttle missions, a joint Soyuz flight and almost 1000 cumulative days in space for American astronauts occurred over the course of seven long-duration expeditions.

Life on board

Astronaut Jerry Linenger wears a respirator following a fire aboard *Mir*

Inside, the 100-ton *Mir* looked like a cramped labyrinth, crowded with hoses, cables and scientific instruments — as well as articles of everyday life, such as photos, children's drawings, books and a guitar. It commonly housed three crew members, but it sometimes supported as many as six for up to a month. Except for two short periods, *Mir* was continuously occupied until August 1999.

Air aboard the station has been described as 'very healthy, - it's not dry, it's not humid. Nothing smells.' by NASA astronaut John Blaha. He also describes that with the exception of the Priroda and Spektr which were added very recently, the station does look used, which is to be expected given it has been lived in for 10 to 11 years without being brought home and cleaned.

Blaha's account of the air quality aboard *Mir* contradicts sharply the concerns about air quality on the space station that Jerry Linenger relates in his book about his time on the facility. Linenger says that due to the age of the space station, the cooling system on board had developed a plethora of tiny leaks too small and numerous to be repaired, that permitted the constant release of coolant into the air on board making it unpleasant to breathe. He says that it was especially noticeable after he had made a space walk and become used to the clean air he had been breathing in his space suit. When he returned to the station and began breathing the air inside *Mir* again, he was deeply shocked by the intensity of the chemical smell and very worried about the possible negative health effects of breathing such heavily contaminated air.

Linenger also relates how life on board *Mir* was structured and lived according to the detailed itineraries provided by ground control. Every second on board was accounted for and all activities were timetabled. After some time working on *Mir* Linenger came to feel that the order in which his activities were allocated did not represent the most logical or efficient order possible for these activities. He decided to perform his tasks in an order that he felt enabled him to work more efficiently, be less fatigued, and suffer less from stress. Linenger noted that his comrades on *Mir* did not "improvise" in this way, and as a medical doctor he observed the effects of stress on his comrades that he believed was the outcome of following an itinerary without making modifications to it. Linenger noted that despite this, his comrades performed all their tasks in a supremely professional manner.

During the Shuttle–*Mir* programme, Russian cosmonauts were tasked with station upkeep and maintenance while the American astronauts conducted scientific experiment operations in the areas of human physiology, life science, microbiology, and materials science.

Astronaut Shannon Lucid, who set the record for longest stay in space by a woman while aboard *Mir* (surpassed by Sunita Williams 11 years later on the ISS), also commented about working aboard *Mir* saying "I think going to work on a daily basis on *Mir* is very similar to going to work on a daily basis on an outstation in Antarctica. The big difference with going to work here is the isolation, because you really are isolated. You don't have a lot of support from the ground. You really are on your own."

Two amateur radio call signs, U1MIR and U2MIR, were assigned to *Mir* in the late 1980s, allowing amateur radio operators on Earth to communicate with the cosmonauts.

Peter Rodney Llewellyn almost visited *Mir* in 1999 after promising US$100 million for the privilege.

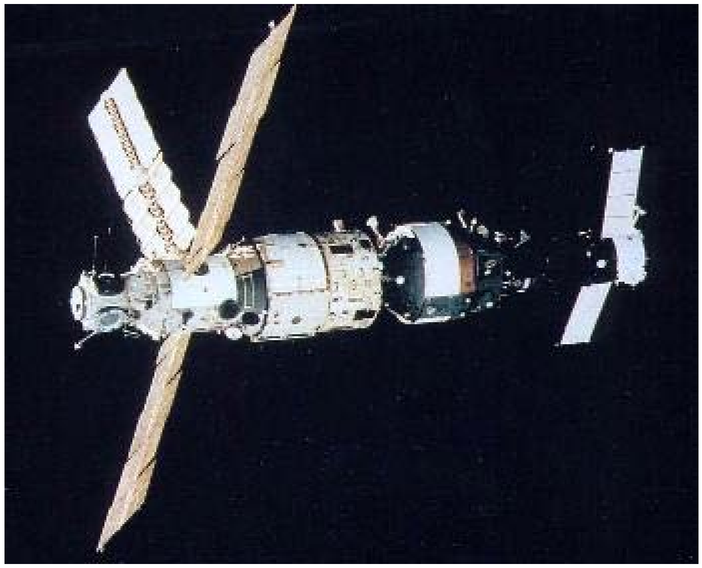
Station operations

Expeditions

Early existence

Due to the pressure to launch the station in such short order, mission planners were left without Soyuz spacecraft or modules to launch to the station at first. It was decided to launch Soyuz T-15 on a dual mission to both *Mir* and Salyut 7.

Leonid Kizim and Vladimir Solovyov first docked with the Mir space station on March 15, 1986. During their nearly 51-day stay on *Mir*, they brought the station online and checked its systems. They also unloaded two Progress spacecraft launched after their arrival, Progress-25 and Progress-26.



The base block with Kvant-1 and Soyuz TM-3

On May 5, 1986 they undocked from *Mir* for a day-long journey to Salyut 7. They spent 51 days there and gathered 400 kg of scientific material from Salyut 7 for return to *Mir*. While Soyuz T-15 was at Salyut 7, the unmanned Soyuz TM-1 arrived at the unoccupied *Mir* and remained for 9 days, testing the new Soyuz TM. Soyuz T-15 redocked with *Mir* on June 26 and delivered the experiments and 20 instruments, including a multichannel spectrometer. The EO-1 crew spent their last 20 days on *Mir* conducting Earth observations before returning to earth on July 16, 1986, leaving the new station unoccupied.

The second expedition to *Mir*, Mir EO-2, launched on Soyuz TM-2 on February 5, 1987. During their stay, the Kvant-1 module was launched on March 30, 1987. It was the first, experimental version of a planned series of '37K' modules scheduled to be launched to *Mir* on the Soviet Buran space shuttle. Kvant-1 was originally planned to dock with Salyut 7; however, due to technical problems during its development, it was reassigned for *Mir*. The module carried the first set of six gyroscopes for attitude control. The module also carried instruments for X-ray and ultraviolet astrophysical observation.

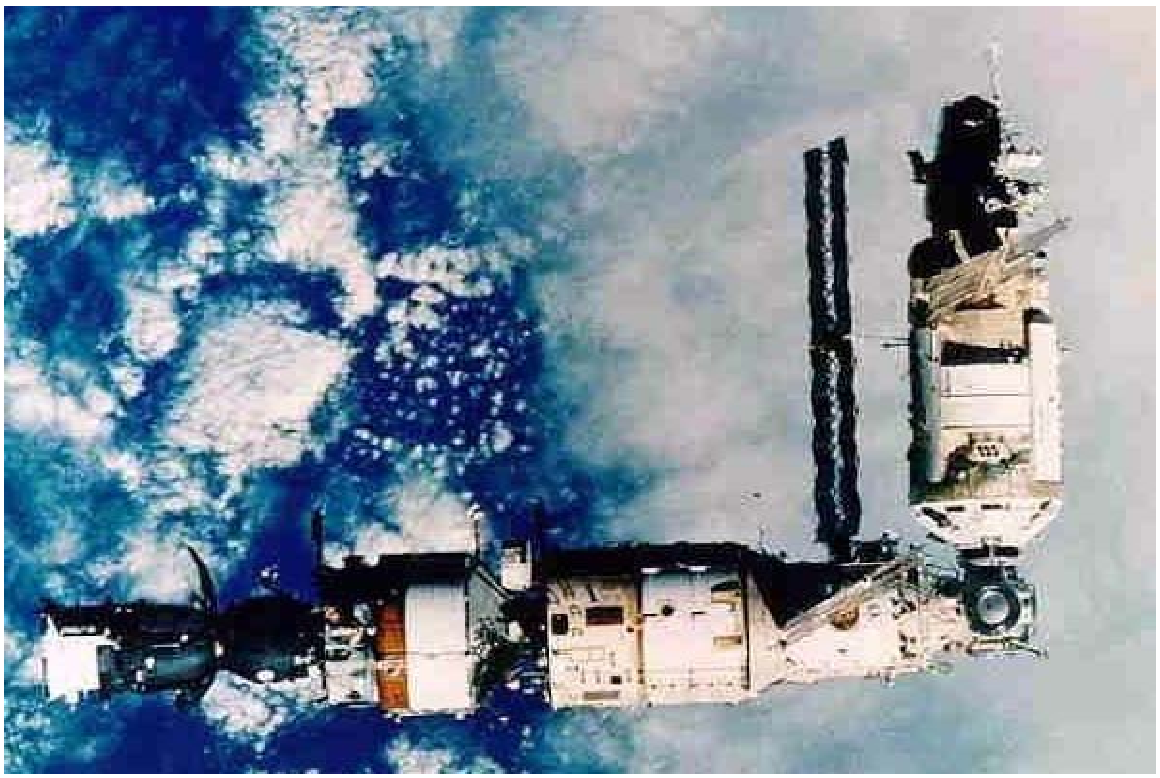
The initial rendezvous of the Kvant-1 module with *Mir* on April 5, 1987 was troubled by the failure of the onboard control system. After the failure of the second attempt to dock, the onboard cosmonauts, Yuri Romanenko and Aleksandr Laveykin, conducted a spacewalk to fix the problem. They found a trash bag between the module and the station, which prevented the docking. The bag was left in orbit after the departure of one of the cargo ships. They removed the bag and completed docking on April 12.

The Soyuz TM-2 launch was the beginning of a string of 6 Soyuz launches and three long-duration crews between February 5, 1987 and April 27, 1989. This time period also saw the first international visitors to the station, Muhammed Faris, Abdul Ahad

Mohmand and Jean-Loup Chrétien. With the departure of Mir EO-4 on Soyuz TM-7 April 27, 1989 the station was once again left unoccupied.

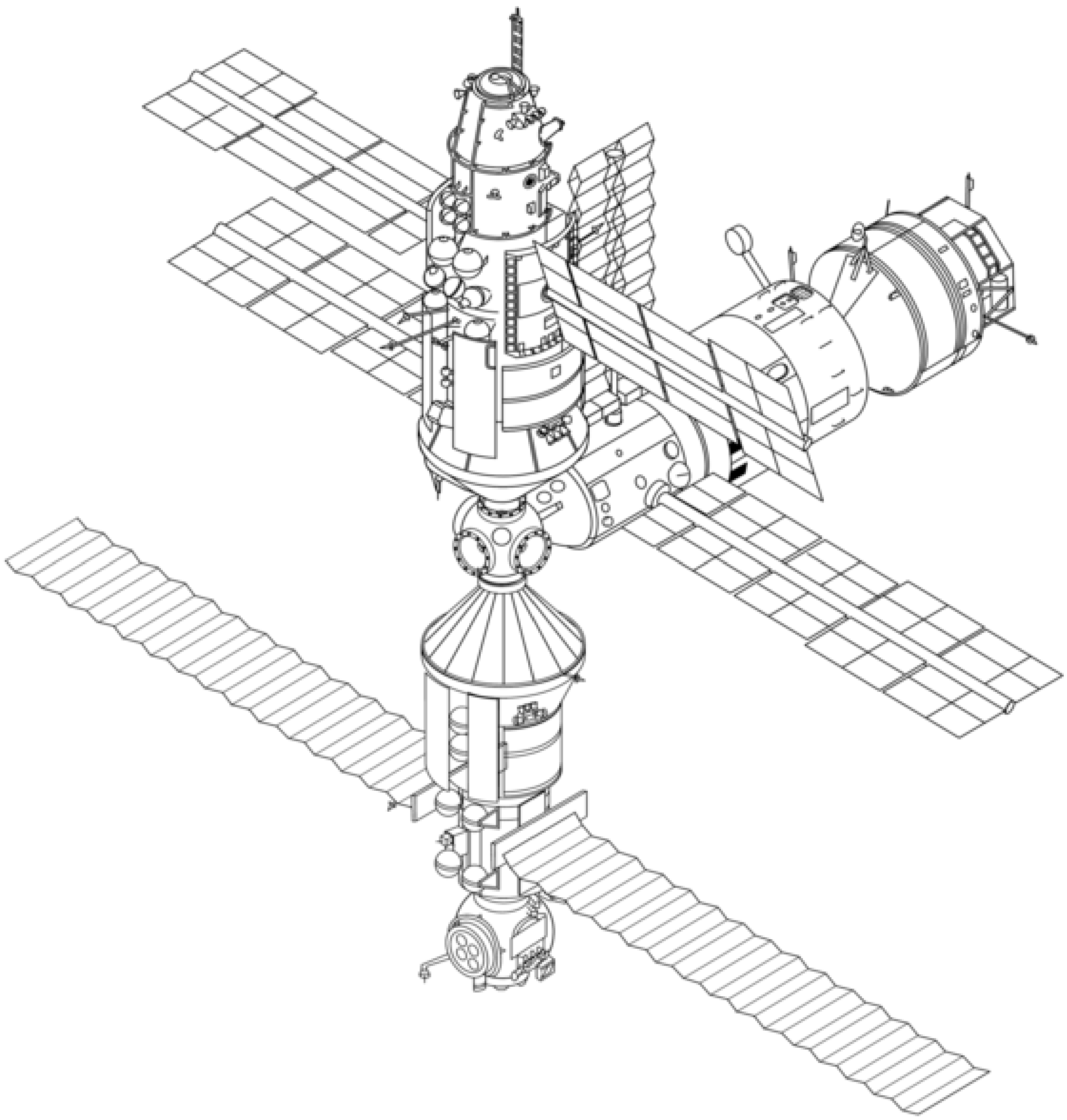
Second start

The launch of Soyuz TM-8 on September 5, 1989 marked the beginning of the longest human presence in space to date. It also marked the beginning of *Mir's* second expansion. The Kvant-2 and Kristall modules were now ready for launch. Alexander Viktorenko and Aleksandr Serebrov docked with *Mir* and brought the station out of its five-month hibernation. On September 29 the cosmonauts installed equipment in the docking system in preparation for the arrival of Kvant 2, the first of the 20-ton add-on modules based on the TKS spacecraft from the Almaz program



Mir following the arrival of Kvant-2 in 1989

After a delay of 40 days due to problems with a batch of computer chips, Kvant-2 was launched on November 26. After problems deploying the craft's solar array and with the automated docking systems on both Kvant-2 and *Mir*, Kvant-2 was docked manually on December 6. Kvant-2 added a second set of gyrodines to Mir. The module also carried the new life support systems for recycling water and generating oxygen on board *Mir*, reducing its dependence on resupply from the ground. Kvant-2 also featured a large airlock with a one-meter hatch. A special backpack unit, an equivalent of the U.S. Manned Maneuvering Unit, was located inside Kvant-2's airlock.



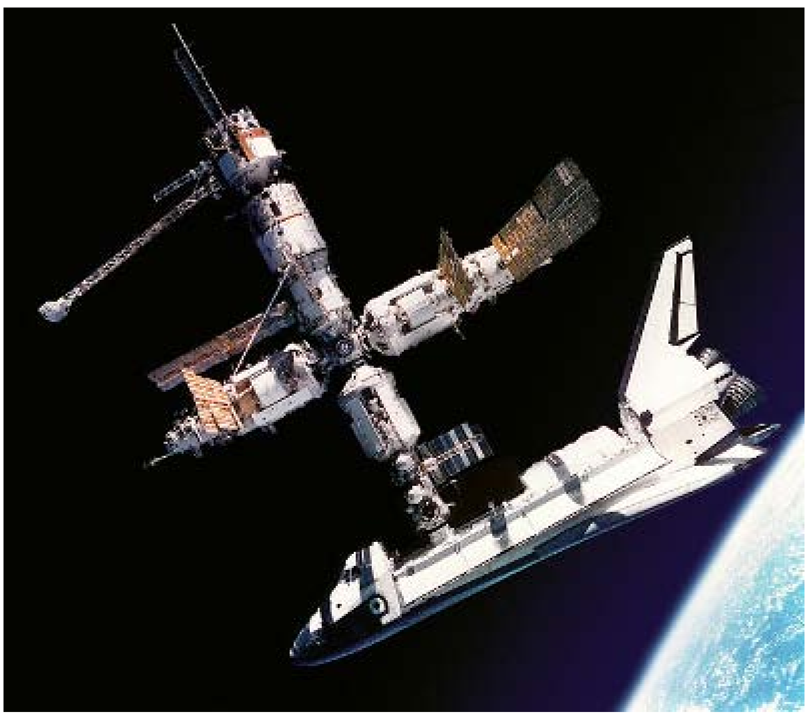
Mir's configuration after the arrival of Kristall in 1990

Soyuz TM-9 launched Mir EO-6 crew members Anatoly Solovyev and Aleksandr Balandin on February 11, 1990. While docking, the EO-5 crew on board *Mir* saw that 3 thermal blankets on the Soyuz-TM 9 were loose, potentially creating problems on reentry. It was decided that this would be manageable. Their stay on board *Mir* saw the addition of the Kristall module. The module was launched on May 31. The first docking attempt on June 6 was aborted due to an attitude control thruster failure. The Kristall module arrived at Mir's front port on June 10, and was relocated to the lateral port opposite Kvant-2 the next day, restoring the equilibrium of the complex. Due to the delay in the docking of Kristall, EO-6 was extended by 10 days to permit the activation of Kristall's systems, and to accommodate the EVA to repair the loose thermal blankets on Soyuz-TM 9.

The Kristall module contained a number of furnaces for the creation of crystals in micro-gravity. Also on board was biotechnology research equipment, including a small greenhouse for plant cultivation experiments. The unit was equipped with a source of light and a feeding system. The module also contained equipment for astronomy observations. The main feature, however, was the two APAS-89 Androgynous Peripheral Attach System docking ports designed to be compatible with the Buran shuttle. Although they were never used with a Buran Shuttle, they were later used with the American Space Shuttle.

The EO-7 relief crew arrived aboard Soyuz TM-10 on August 3, 1990. The new crew arrived at *Mir* with quail for Kvant-2's cages. A quail laid an egg en route to the station. It was returned to Earth, along with 130 kg of experiment results and industrial products, in Soyuz TM-9. Three more expeditions continued to visit *Mir* while tensions back on Earth grew. The Mir EO-10 crew launched aboard Soyuz TM-13 on October 2, 1991 was the last crew to launch from the USSR, and continued the occupation of *Mir* through the fall of the Soviet Union. The unlaunched modules, Spektr and Priroda, were not so lucky. The newly formed Russian Federal Space Agency was unable to finance them and they were put into storage, ending *Mir's* second expansion.

Shuttle–*Mir*



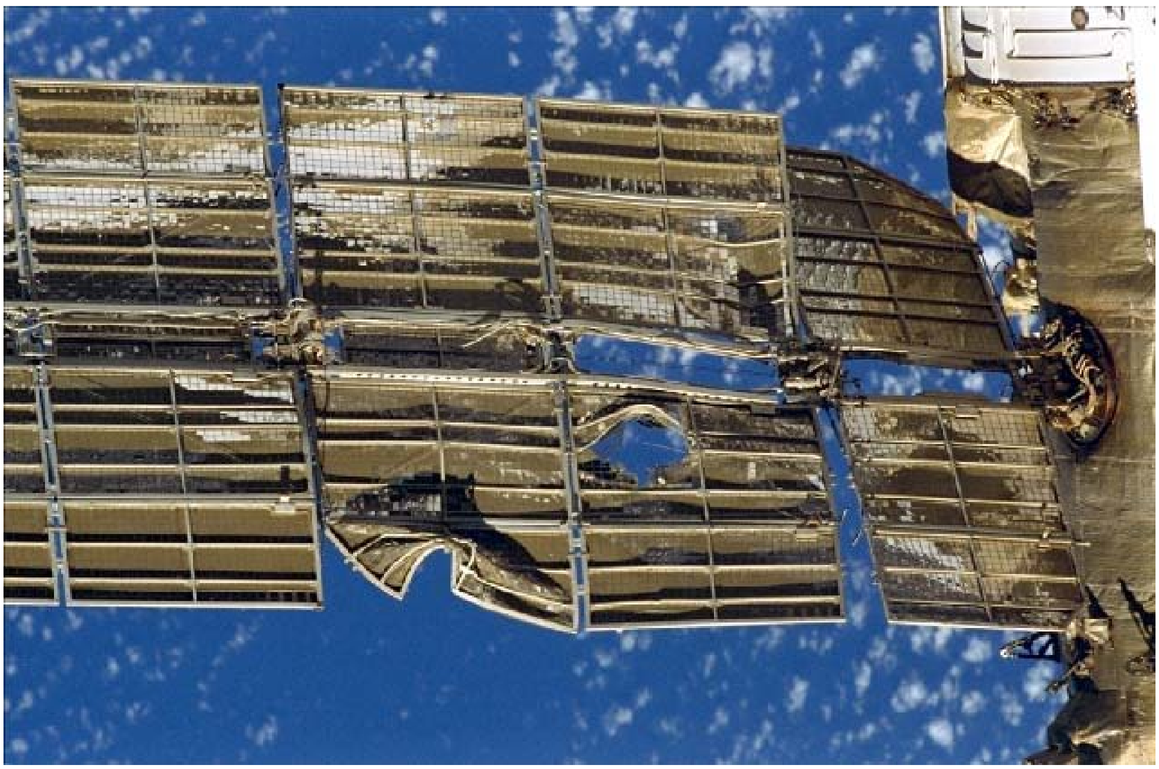
Space Shuttle *Atlantis* docked to *Mir* on STS-71

The US involvement in *Mir* brought new funds to the station. The most notable use of these was the completion and launch of the Spektr & Priroda modules and the construction of a docking module to make the process of docking the shuttle to the station easier.

In 1997 the crew of *Mir*, Linenger and the Russians Vasili Tsibliyev & Aleksandr Lazutkin faced several problems:

- The most severe fire ever aboard an orbiting spacecraft which was caused by a backup oxygen-generating device.
- Failures of various on board systems.
- Near collision with a Progress resupply cargo ship during a long-distance manual docking system test.
- Total loss of station electrical power and, as a result, attitude control, resulting in a slow, uncontrolled "tumble" through space.

Linenger was succeeded by Anglo-American astronaut Michael Foale, carried up by *Atlantis* on STS-84, alongside Russian mission specialist Elena Kondakova.



Damaged solar arrays on *Mir*'s *Spektr* module following a collision with an unmanned Progress spacecraft in September 1997.

Foale's increment proceeded fairly normally until June 25, when during the second test of the *Progress* manual docking system, TORU, the resupply ship collided with solar arrays on the *Spektr* module and crashed into the module's outer shell, holing the module and causing a depressurisation of the station, the first ever on-orbit depressurisation in the history of spaceflight. Only quick actions on the part of the crew, cutting cables leading to the module and closing *Spektr's* hatch, prevented the crew abandoning the station in their Soyuz lifeboat. Their efforts stabilised the station's air pressure, whilst the pressure in *Spektr*, containing many of Foale's experiments and personal effects, dropped to a vacuum. Fortunately, food, water and other vital supplies were stored in other modules, and remarkable salvage and replanning effort by Foale and the science community maximized the scientific return.

In an effort to restore some of the power and systems lost following the isolation of *Spektr* and to attempt to locate the leak, *Mir's* new commander Anatoly Solovyev and flight engineer Pavel Vinogradov carried out a risky salvage operation later in the mission, entering the empty module during a so-called "IVA" spacewalk, inspecting the condition of hardware and running cables through a special hatch from *Spektr's* systems to the rest of the station. Following these first investigations, Foale and Solovyev conducted a 6-hour EVA on the surface of *Spektr* to inspect the damage to the punctured module.

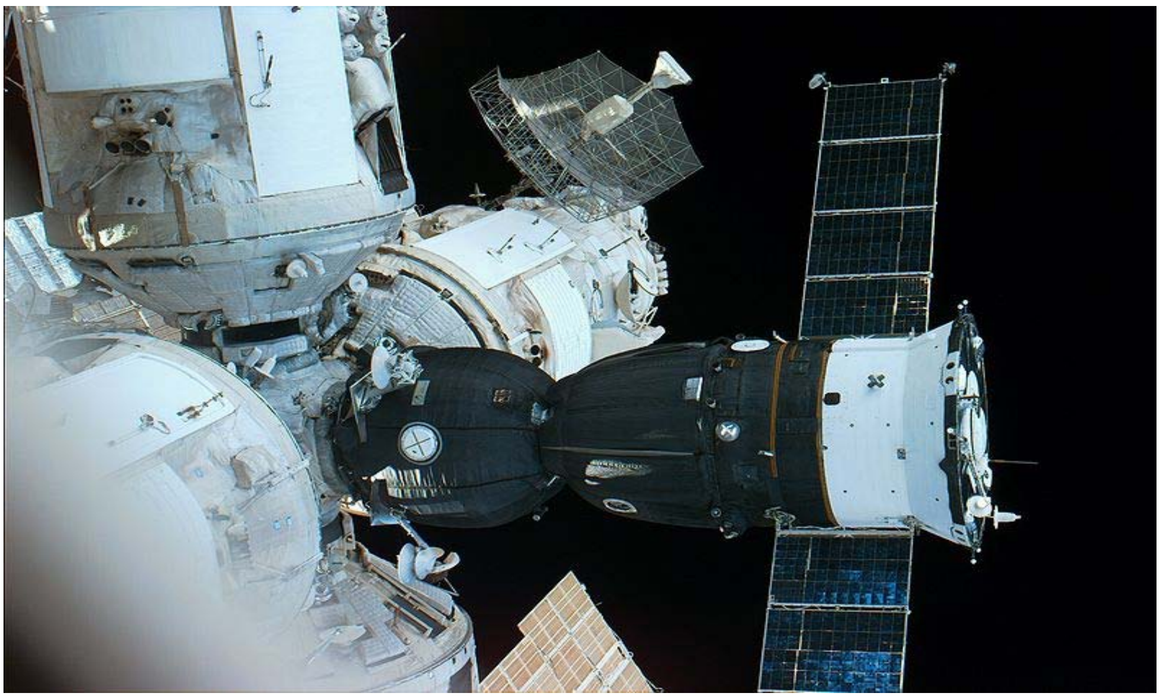
Final days and deorbit

Mir breaks up in Earth's atmosphere over the South Pacific on 23 March 2001

Near the end of its life, there were plans for private interests to purchase *Mir*, possibly for use as the first orbital television/movie studio. The privately-funded Soyuz TM-30 mission by MirCorp, launched on April 4, 2000, carried two crew members, Sergei Zalyotin and Alexandr Kaleri, to the station for two months to do repair work with the hope of proving that the station could be made safe. But this was to be the last manned mission to *Mir*. While Russia was optimistic about *Mir'*s future, its commitments to the International Space Station project left no funding to support the aging *Mir*.

Mir's deorbit was done in three stages. The first stage was waiting for atmospheric drag to decay Mir's orbit an average of 220 kilometers (137 mi). This began with the docking of Progress M1-5, a modified version of the Progress M carrying 2.5 times more fuel in place of supplies. The second stage was the transfer of the station into a 165 × 220 km (103 × 137 mi) orbit. This was achieved with two burns of the Progress M1-5's control engines at 00:32 UTC and 02:01 UTC on March 23, 2001. After a two-orbit pause, the third and final stage of *Mir*'s deorbit began with the burn of Progress M1-5's control engines and main engine at 05:08 UTC, lasting a little over 22 minutes. Reentry into Earth's atmosphere (100 km/60 mi) of the 15-year-old space station occurred at 05:44 UTC near Nadi, Fiji. Major destruction of the station began around 05:52 UTC and the unburned fragments fell into the South Pacific Ocean around 06:00 UTC.

Visiting spacecraft



A Soyuz spacecraft docked with *Mir* as seen from Space Shuttle *Atlantis*

Mir was primarily supported by the Russian Soyuz and Progress spacecraft. Soyuz craft provided manned access to and from the station, allowing for crew rotations, and also functioned as a lifeboat for the station, allowing for a relatively quick return to earth in the event of an emergency. The unmanned Progress cargo vehicles were only used to resupply the station and were incapable of surviving reentry.

It was anticipated that it would also be the destination for flights by the later-abandoned Buran space shuttle. The Kristall module even carried two APAS-89 Androgynous Peripheral Attach System docking ports designed to be compatible with the Buran shuttle. These were later used with the American Space Shuttle.

During the Shuttle-Mir Program, *Mir* was also supported by Space Shuttles, allowing American and other western astronauts to visit or stay long-term on the station. The visiting US shuttles used a modified docking collar originally designed for the Soviet Buran shuttle, mounted on a bracket intended for use with Space Station Freedom but this required the relocation of the Kristall module to ensure sufficient distance between the shuttle and Mir's solar arrays. In order to eliminate the need to move the module and retract solar arrays for clearance issues, a Docking Module was later added to the end of Kristall. The shuttles provided crew rotation of the American astronauts on station as well as carrying cargo to and from the station, performing some of the largest transfers of cargo of the time. With a space shuttle docked to Mir the temporary enlargements of living and working areas amounted to a complex that was the largest spacecraft in history at that time, with a combined mass of 250 tonnes (280 short tons).

Mission control centre

Safety aspects

Ageing systems and accidents

In the later years of the programme, particularly during the Shuttle-*Mir* programme, *Mir* suffered from various systems failures as the station aged. The station was originally designed to fly for five years but eventually flew for three times that length of time, and in the 1990s was showing its age—constant computer crashes, loss of power, uncontrolled tumbles through space and leaking pipes were an ever-present concern for crews. Various breakdowns of *Mir'*s Elektron oxygen-generating system were also a concern. These breakdowns led crews to become increasingly reliant on the backup *Vika* solid-fuel oxygen generator (SFOG) systems, responsible for the fire during the handover between EO-22 and EO-23.

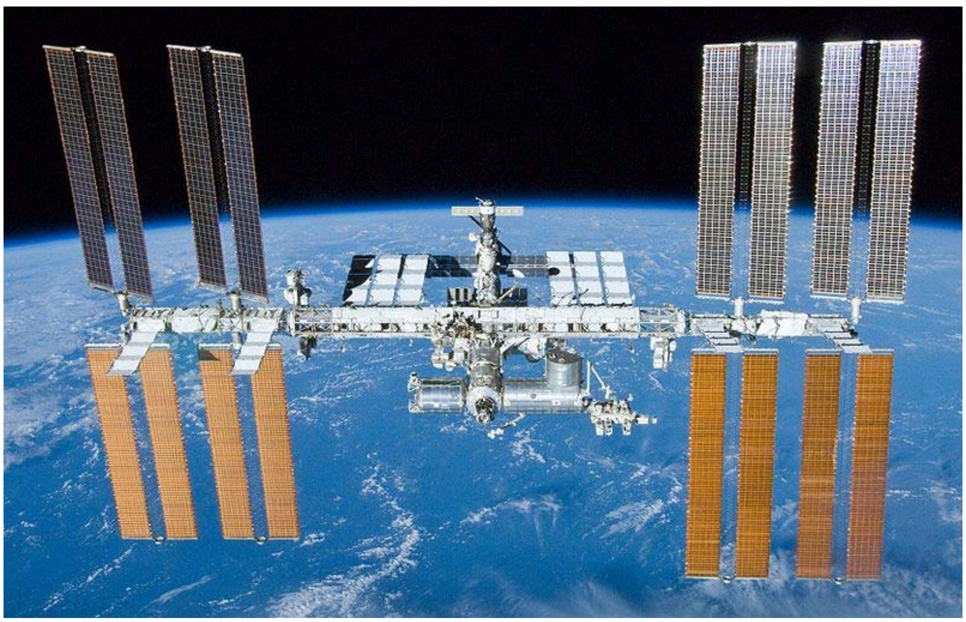
The *Vika* malfunction led to a fire which burned for, according to various sources, between 90 seconds and 14 minutes, and produced large amounts of toxic smoke that filled the station for around 45 minutes. This forced the crew to don respirators, but some of the respirator masks initially worn were broken. Fire extinguishers mounted on the walls of the modules were immovable. A similar incident had occurred on an earlier expedition, although in that case the *Vika* burned for only a few seconds. Now used aboard the ISS, the *Vika*s continue to be a problem.

The near-miss and collision incidents during EO-23 presented further safety issues. Both were caused by failure of the same piece of equipment, the TORU manual docking system, which was undergoing tests at the time. The tests were called in order to gauge the performance of long-distance docking in order to enable the cash-strapped Russians to remove the expensive *Kurs* automatic docking system from Progress spacecraft.

Chapter- 6

International Space Station

International Space Station



The International Space Station on 23 May 2010 as seen from the departing Space Shuttle *Atlantis* during STS-132.

ISS Insignia

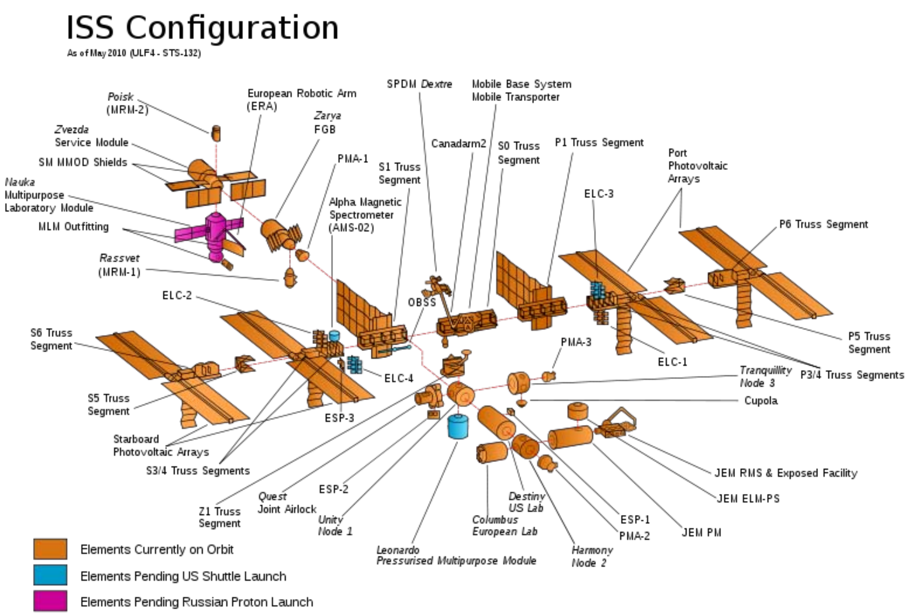
Station statistics

NSSDC ID	1998-067A
Call sign	*Alpha*
Crew	6
Launch	1998–2011
Launch pad	KSC LC-39, Baikonur LC-1/5 & LC-81/23
Mass	369,914 kg (815,520 lb)
Length	51 m (167.3 ft) from PMA-2 to *Zvezda*
Width	109 m (357.5 ft) along truss, arrays extended
Height	c. 20 m (c. 66 ft)

	nadir–zenith, arrays forward–aft (27 November 2009)
Pressurised volume	837 m^3 (29,561 cu ft)
Atmospheric pressure	101.3 kPa (29.91 inHg, 1 atm)
Perigee	347 km (187 nmi) AMSL (18 June 2010)
Apogee	360 km (194 nmi) AMSL (18 June 2010)
Orbital inclination	51.6 degrees
Average speed	7,706.6 m/s (27,743.8 km/h, 17,239.2 mph)
Orbital period	91 minutes
Days in orbit	4338 (6 October 2010)
Days occupied	3627 (6 October 2010)
Number of orbits	68091 (6 October 2010)
Orbital decay	2 km/month

Statistics as of 23 May 2010

Configuration



Station elements as of 18 May 2010

The **International Space Station** (**ISS**) is an internationally developed research facility that is being assembled in low Earth orbit. On-orbit construction of the station began in 1998 and is scheduled for completion by late 2011. The station is expected to remain in operation until at least 2015, and likely 2020. With a greater cross-sectional area than that of any previous space station, the ISS can be seen from Earth with the naked eye, and is by far the largest artificial satellite that has ever orbited Earth. The ISS serves as a research laboratory that has a microgravity environment in which crews conduct experiments in biology, chemistry, medicine, physiology and physics, as well as astronomical and meteorological observations. The station provides a unique environment for the testing of the spacecraft systems that will be required for missions to the Moon and Mars. The ISS is operated by Expedition crews of six astronauts and cosmonauts, with the station programme maintaining an uninterrupted human presence in space since the launch of Expedition 1 on 31 October 2000, a total of 9 years and 340 days. The programme is thus approaching the current record for uninterrupted human presence on a space station, set aboard *Mir*, of 3,644 days (8 days short of 10 years), with the ISS expected to take the record on 23 October 2010. As of 25 September 2010, the crew of Expedition 25 is aboard.

The ISS is a synthesis of several space station projects that include the American *Freedom*, the Soviet/Russian *Mir*-2, the European *Columbus* and the Japanese *Kibō*. Budget constraints led to the merger of these projects into a single multi-national programme. The ISS project began in 1994 with the Shuttle–*Mir* programme, and the first module of the station, *Zarya*, was launched in 1998 by Russia. Assembly continues, as pressurised modules, external trusses, and other components are launched by American space shuttles, Russian Proton rockets and Russian Soyuz rockets. As of May 2010, the station consists of fourteen pressurised modules and an extensive integrated truss structure (ITS). Power is provided by sixteen solar arrays mounted on the external truss, in addition to four smaller arrays on the Russian modules. The station is maintained at an orbit between 278 km (173 mi) and 460 km (286 mi) altitude, and travels at an average speed of 27,743.8 km/h (17,239.2 mph), completing 15.7 orbits per day.

Operated as a joint project between the five participant space agencies, the station's sections are controlled by mission control centres on the ground operated by the American National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), the Russian Federal Space Agency (RKA), the Japan Aerospace Exploration Agency (JAXA) and the Canadian Space Agency (CSA). The ownership and use of the space station is established in intergovernmental treaties and agreements that allow the Russian Federation to retain full ownership of its own modules in the Russian Orbital Segment, with the US Orbital Segment, the remainder of the station, allocated between the other international partners. The cost of the station has been estimated by ESA as €100 billion over 30 years, and, although estimates range from 35 billion dollars to 160 billion dollars, the ISS is believed to be the most expensive object ever constructed. The financing, research capabilities and technical design of the ISS programme have been criticised because of the high cost. The station is serviced by Soyuz spacecraft, Progress spacecraft, space shuttles, the Automated Transfer Vehicle and the H-II Transfer Vehicle, and has been visited by astronauts and cosmonauts from 15 different nations.

Purpose

The International Space Station (ISS) is an internationally developed satellite currently being assembled in Low Earth Orbit. Primarily a research laboratory, the ISS offers an advantage over spacecraft such as NASA's Space Shuttle because it is a long-term platform in the space environment, where extended studies are conducted. The presence of a permanent crew affords the ability to monitor, replenish, repair, and replace experiments and components of the spacecraft itself. Scientists on Earth have swift access to the crew's data and can modify experiments or launch new ones, benefits generally unavailable on specialised unmanned spacecraft.

Crews, who fly expeditions of several months duration, conduct scientific experiments each day (approximately 160 man-hours a week). As of the conclusion of Expedition 15, 138 major science investigations had been conducted on the ISS. Scientific findings, in fields from basic science to exploration research, are published every month.

The ISS provides a location in the relative safety of Low Earth Orbit to test spacecraft systems that will be required for long-duration missions to the Moon and Mars. This provides experience in the maintenance, repair, and replacement of systems on-orbit, which will be essential in operating spacecraft further from Earth. Mission risks are reduced, and the capabilities of interplanetary spacecraft are advanced.

Part of the crew's mission is educational outreach and international cooperation. The crew of the ISS provide opportunities for students on Earth by running student-developed experiments, making educational demonstrations, and allowing for student participation in classroom versions of ISS experiments, NASA investigator experiments, and ISS engineering activities. The ISS programme itself, with the international cooperation that it represents, allows 14 nations to live and work together in space, providing lessons for future multi-national missions.

Scientific research

Expedition 8 Commander and Science Officer Michael Foale conducts an inspection of the Microgravity Science Glovebox.

The ISS provides a platform to conduct experiments that require one or more of the unusual conditions present on the station. The primary fields of research include human research, space medicine, life sciences, physical sciences, astronomy and meteorology. The 2005 NASA Authorization Act designated the American segment of the International Space Station as a national laboratory with the goal of increasing the use of the ISS by other federal agencies and the private sector.

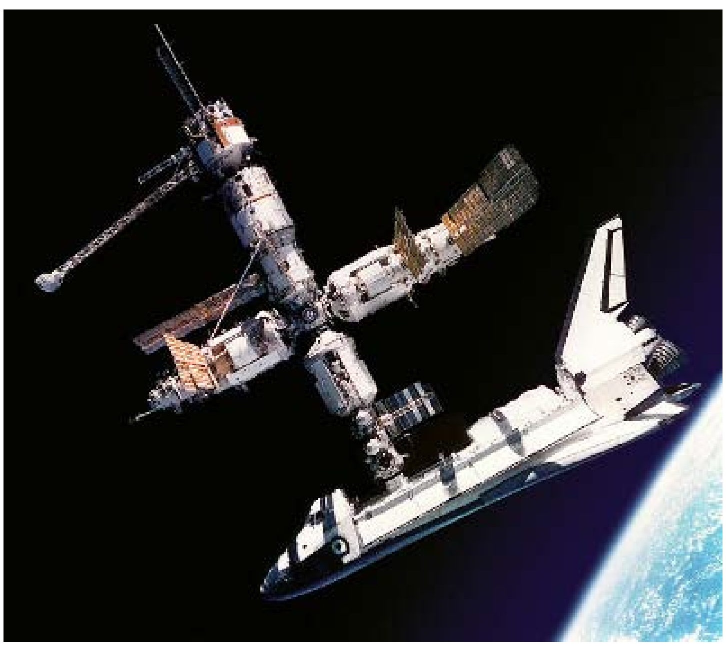
Research on the ISS improves knowledge about the effects of long-term space exposure on the human body. Subjects currently under study include muscle atrophy, bone loss, and fluid shift. The data will be used to determine whether space colonisation and lengthy human spaceflight are feasible. As of 2006, data on bone loss and muscular atrophy suggest that there would be a significant risk of fractures and movement problems if astronauts landed on a planet after a lengthy interplanetary cruise (such as the six-month journey time required to fly to Mars). Large scale medical studies are conducted aboard the ISS via the National Space and Biomedical Research Institute (NSBRI). Prominent among these is the Advanced Diagnostic Ultrasound in Microgravity study in which astronauts (including former ISS Commanders Leroy Chiao and Gennady Padalka) perform ultrasound scans under the guidance of remote experts. The study considers the diagnosis and treatment of medical conditions in space. Usually, there is no physician onboard the ISS and diagnosis of medical conditions is a challenge. It is anticipated that remotely guided ultrasound scans will have application on Earth in emergency and rural care situations where access to a trained physician is difficult.

Researchers are investigating the effect of the station's near-weightless environment on the evolution, development, growth and internal processes of plants and animals. In response to some of this data, NASA wants to investigate microgravity's effects on the growth of three-dimensional, human-like tissues, and the unusual protein crystals that can be formed in space.

The investigation of the physics of fluids in microgravity will allow researchers to model the behaviour of fluids better. Because fluids can be almost completely combined in microgravity, physicists investigate fluids that do not mix well on Earth. In addition, an examination of reactions that are slowed by low gravity and temperatures will give scientists a deeper understanding of superconductivity.

The study of materials science is an important ISS research activity, with the objective of reaping economic benefits through the improvement of techniques used on the ground. Other areas of interest include the effect of the low gravity environment on combustion, through the study of the efficiency of burning and control of emissions and pollutants. These findings may improve our knowledge about energy production, and lead to economic and environmental benefits. Future plans are for the researchers aboard the ISS to examine aerosols, ozone, water vapour, and oxides in Earth's atmosphere, as well as cosmic rays, cosmic dust, antimatter, and dark matter in the universe.

Origins



Space Shuttle *Atlantis* docked to *Mir* on STS-71, during the Shuttle-Mir Program

The International Space Station represents a union of several national space station projects that originated during the Cold War. In the early 1980s, NASA planned to launch a modular space station called *Freedom* as a counterpart to the Soviet *Salyut* and *Mir* space stations, while the Soviets were planning to construct *Mir*-2 in the 1990s as a replacement for *Mir*. Because of budget and design constraints, *Freedom* never progressed past mock-ups and minor component tests.

With the fall of the Soviet Union and the end of the Space Race, *Freedom* was nearly cancelled by the United States House of Representatives. The post-Soviet economic chaos in Russia led to the cancellation of *Mir*-2, though only after its base block, DOS-8, had been constructed. Similar budgetary difficulties were faced by other nations with space station projects, which prompted the American government to negotiate with European states, Russia, Japan, and Canada in the early 1990s to begin a collaborative project.

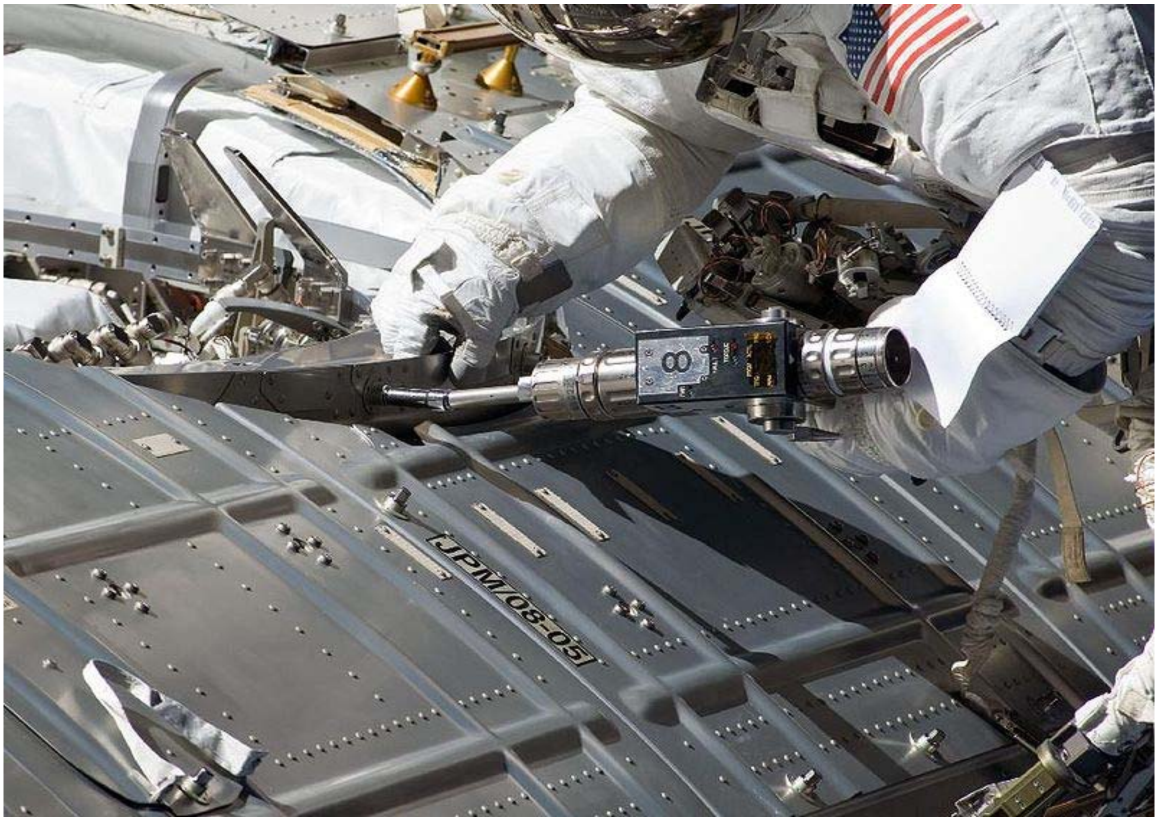
In June 1992 American president George H. W. Bush and Russian president Boris Yeltsin agreed to cooperate on space exploration. The resulting *Agreement between the United States of America and the Russian Federation Concerning Cooperation in the Exploration and Use of Outer Space for Peaceful Purposes* called for a short, joint space programme, with one American astronaut deployed to the Russian space station *Mir* and two Russian cosmonauts deployed to a Space Shuttle.

In September 1993, American Vice-President Al Gore, Jr., and Russian Prime Minister Viktor Chernomyrdin announced plans for a new space station, which eventually became the International Space Station. They also agreed, in preparation for this new project, that the United States would be heavily involved in the *Mir* programme as part of an agreement that later included Space Shuttle orbiters docking with *Mir*.

According to the plan, the International Space Station programme would combine the proposed space stations of all participant agencies: NASA's *Freedom*, the RSA's *Mir*-2 (with DOS-8 later becoming *Zvezda*), ESA's *Columbus*, and the Japanese *Kibō* laboratory. When the first module, *Zarya*, was launched in 1998, the station was expected to be completed by 2003. Delays have led to a revised estimated completion date of 2011.

Station structure

Assembly



Astronaut Ron Garan during an STS-124 ISS assembly spacewalk

Expedition 18 commander Michael Fincke's video tour of the habitable part of the ISS from January 2009

The assembly of the International Space Station, a major endeavour in space architecture, began in November 1998. Astronauts install each element using spacewalks. By 27 November 2009, they had completed 136, totalling 849 hours of extra-vehicular activity (EVA), all devoted to assembly and maintenance of the station. Twenty-eight of these spacewalks originated from the airlocks of docked Space Shuttles; the remaining 108 were launched from the station.

The first segment of the ISS, *Zarya*, was launched on 20 November 1998 on a Russian Proton rocket, followed two weeks later by *Unity*—the first of three node modules—which was launched aboard Space Shuttle flight STS-88. This bare two-module core of the ISS remained unmanned for the next one-and-a-half years. In July 2000 the Russian module *Zvezda* was added, allowing a maximum crew of three to occupy the ISS continuously. The first resident crew, Expedition 1, arrived in November 2000 on Soyuz TM-31, midway between the flights of STS-92 and STS-97. These two Space Shuttle flights each added segments of the station's Integrated Truss Structure, which provided the embryonic station with communications, guidance, electrical grounding (on Z1), and power via solar arrays located on the P6 truss.

Over the next two years the station continued to expand. A Soyuz-U rocket delivered the *Pirs* docking compartment. The Space Shuttles *Discovery*, *Atlantis*, and *Endeavour* delivered the *Destiny* laboratory and *Quest* airlock, in addition to the station's main robot arm, the *Canadarm2*, and several more segments of the Integrated Truss Structure.

The expansion schedule was interrupted by the destruction of the Space Shuttle *Columbia* on STS-107 in 2003, with the resulting hiatus in the Space Shuttle programme halting station assembly until the launch of *Discovery* on STS-114 in 2005.

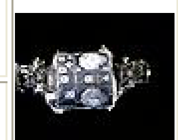
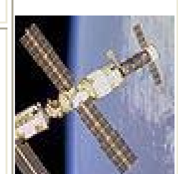
The official resumption of assembly was marked by the arrival of *Atlantis*, flying STS-115, which delivered the station's second set of solar arrays. Several more truss segments and a third set of arrays were delivered on STS-116, STS-117, and STS-118. As a result of the major expansion of the station's power-generating capabilities, more pressurised modules could be accommodated, and the *Harmony* node and *Columbus* European laboratory were added. These were followed shortly after by the first two components of *Kibō*. In March 2009, STS-119 completed the Integrated Truss Structure with the installation of the fourth and final set of solar arrays. The final section of *Kibō* was delivered in July 2009 on STS-127, followed by the Russian *Poisk* module. The third node, *Tranquility*, was delivered in February 2010 during STS-130 by the Space Shuttle *Endeavour*, alongside the Cupola, closely followed in May 2010 by the penultimate Russian module, *Rassvet*, delivered by Space Shuttle *Atlantis* on STS-132.

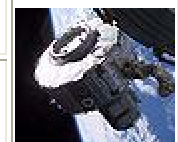
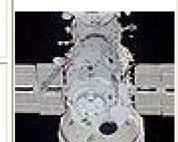
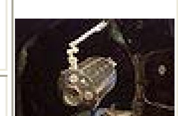
As of May 2010, the station consisted of fourteen pressurised modules and the complete Integrated Truss Structure. Still to be launched is the Pressurized Multipurpose Module *Leonardo*, the Russian Multipurpose Laboratory Module *Nauka* and a number of external components, including the European Robotic Arm and Alpha Magnetic Spectrometer (AMS-02). Assembly is expected to be completed by 2011, by which point the station will have a mass in excess of 400 metric tons (440 short tons).

Pressurised modules

When completed, the ISS will consist of sixteen pressurised modules with a combined volume of around 1,000 cubic metres (35,000 cu ft). These modules include laboratories, docking compartments, airlocks, nodes and living quarters. Thirteen of these components are already in orbit, with the remaining three awaiting launch. Each module was or will be launched either by the Space Shuttle, Proton rocket or Soyuz rocket.

<table>
<tr><th>Module</th><th>Assembly mission</th><th>Launch date</th><th>Launch system</th><th>Nation</th><th>Isolated View</th></tr>
<tr><td rowspan="2">Zarya

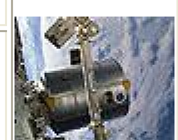
(lit. 'dawn')
(FGB)</td><td>1A/R</td><td>20 November 1998</td><td>Proton-K</td><td>Russia (Builder)
USA (Financier)</td><td rowspan="2"></td></tr>
<tr><td colspan="4">The first component of the ISS to be launched, Zarya provided electrical power, storage, propulsion, and guidance during initial assembly. The module now serves as a storage compartment, both inside the pressurised section and in the externally mounted fuel tanks.</td></tr>
<tr><td rowspan="2">Unity
(Node 1)</td><td>2A</td><td>4 December 1998</td><td>Space Shuttle Endeavour, STS-88</td><td>USA</td><td rowspan="2"></td></tr>
<tr><td colspan="4">The first node module, connecting the American section of the station to the Russian section (via PMA-1), and providing berthing locations for the Z1 truss, Quest airlock, Destiny laboratory and Tranquility node.</td></tr>
<tr><td rowspan="2">Zvezda
(lit. 'star')
(Service Module)</td><td>1R</td><td>12 July 2000</td><td>Proton-K</td><td>Russia</td><td rowspan="2"></td></tr>
<tr><td colspan="4">The station's service module, which provides the main living quarters for resident crews, environmental systems and attitude & orbit control. The module also provides docking locations for Soyuz spacecraft, Progress spacecraft and the Automated Transfer Vehicle, and its addition rendered the ISS permanently habitable for the first time.</td></tr>
<tr><td rowspan="2">Destiny
(US Laboratory)</td><td>5A</td><td>7 February 2001</td><td>Space Shuttle Atlantis, STS-98</td><td>USA</td><td rowspan="2"></td></tr>
<tr><td colspan="4">The primary research facility for US payloads aboard the ISS, Destiny is intended for general experiments. The module houses 24 International Standard Payload Racks, some of which are used for environmental systems and crew daily living equipment, and features a 51-centimetre (20 in)</td></tr>
</table>

	optically perfect window, the largest such window ever produced for use in space. *Destiny* also serves as the mounting point for most of the station's Integrated Truss Structure.				
Quest (Joint Airlock)	7A	12 July 2001	Space Shuttle *Atlantis*, STS-104	USA	
	The primary airlock for the ISS, *Quest* hosts spacewalks with both US EMU and Russian Orlan spacesuits. *Quest* consists of two segments; the equipment lock, that stores spacesuits and equipment, and the crew lock, from which astronauts can exit into space.				
Pirs (lit. 'pier') (Docking Compartment)	4R	14 September 2001	Soyuz-U, Progress M-SO1	Russia	
	Pirs provides the ISS with additional docking ports for Soyuz and Progress spacecraft, and allows egress and ingress for spacewalks by cosmonauts using Russian Orlan spacesuits, in addition to providing storage space for these spacesuits.				
Harmony (Node 2)	10A	23 October 2007	Space Shuttle *Discovery*, STS-120	Europe (Builder) USA (Operator)	
	The second of the station's node modules, *Harmony* is the utility hub of the ISS. The module contains four racks that provide electrical power, bus electronic data, and acts as a central connecting point for several other components via its six Common Berthing Mechanisms (CBMs). The European *Columbus* and Japanese *Kibō* laboratories are permanently berthed to the module, and American Space Shuttle Orbiters dock with the ISS via PMA-2, attached to *Harmony*'s forward port. In addition, the module serves as a berthing port for the Italian Multi-Purpose Logistics Modules during shuttle logistics flights.				
Columbus (European Laboratory)	1E	7 February 2008	Space Shuttle *Atlantis*, STS-122	Europe	
	The primary research facility for European payloads aboard the ISS, *Columbus* provides a generic laboratory as well as facilities specifically designed for biology, biomedical research and fluid physics. Several mounting locations are				

<table>
<tr><td></td><td colspan="4">affixed to the exterior of the module, which provide power and data to external experiments such as the European Technology Exposure Facility (EuTEF), Solar Monitoring Observatory, Materials International Space Station Experiment, and Atomic Clock Ensemble in Space. A number of expansions are planned for the module to study quantum physics and cosmology.</td><td></td></tr>
<tr><td rowspan="2">Kibō Experiment Logistics Module (lit. 'hope' and 'wish' JEM–ELM)</td><td>1J/A</td><td>11 March 2008</td><td>Space Shuttle Endeavour, STS-123</td><td>Japan</td><td rowspan="2"></td></tr>
<tr><td colspan="4">Part of the Kibō Japanese Experiment Module laboratory, the ELM provides storage and transportation facilities to the laboratory with a pressurised section to serve internal payloads.</td></tr>
<tr><td rowspan="2">Kibō Pressurised Module (JEM–PM)</td><td>1J</td><td>31 May 2008</td><td>Space Shuttle Discovery, STS-124</td><td>Japan</td><td rowspan="2"></td></tr>
<tr><td colspan="4">Part of the Kibō Japanese Experiment Module laboratory, the PM is the core module of Kibō to which the ELM and Exposed Facility are berthed. The laboratory is the largest single ISS module and contains a total of 23 racks, including 10 experiment racks. The module is used to carry out research in space medicine, biology, Earth observations, materials production, biotechnology, and communications research. The PM also serves as the mounting location for an external platform, the Exposed Facility (EF), that allows payloads to be directly exposed to the harsh space environment. The EF is serviced by the module's own robotic arm, the JEM–RMS, which is mounted on the PM.</td></tr>
<tr><td rowspan="2">Poisk (lit. 'search') (Mini-Research Module 2)</td><td>5R</td><td>10 November 2009</td><td>Soyuz-U, Progress M-MIM2</td><td>Russia</td><td rowspan="2"></td></tr>
<tr><td colspan="4">One of the Russian ISS components, MRM2 will be used for docking of Soyuz and Progress ships, as an airlock for spacewalks and as an interface for scientific experiments.</td></tr>
<tr><td rowspan="2">Tranquility (Node 3)</td><td>20A</td><td>8 February 2010</td><td>Space Shuttle Endeavour, STS-130</td><td>Europe (Builder)
USA (Operator)</td><td rowspan="2"></td></tr>
<tr><td colspan="4">The third and last of the station's US nodes, Tranquility contains an advanced life support system to recycle waste</td></tr>
</table>

<table>
<tr><td></td><td colspan="4">water for crew use and generate oxygen for the crew to breathe. The node also provides four berthing locations for more attached pressurised modules or crew transportation vehicles, in addition to the permanent berthing location for the station's Cupola.</td><td></td></tr>
<tr><td rowspan="2">Cupola</td><td>20A</td><td>8 February 2010</td><td>Space Shuttle Endeavour, STS-130</td><td>Europe (Builder)
USA (Operator)</td><td rowspan="2"></td></tr>
<tr><td colspan="4">The Cupola is an observatory module that provides ISS crew members with a direct view of robotic operations and docked spacecraft, as well as an observation point for watching the Earth. The module comes equipped with robotic workstations for operating the SSRMS and shutters to protect its windows from damage caused by micrometeorites.</td></tr>
<tr><td rowspan="2">Rassvet
(lit. 'dawn')
(Mini-Research Module 1)</td><td>ULF4</td><td>14 May 2010</td><td>Space Shuttle Atlantis, STS-132</td><td>Russia</td><td rowspan="2"></td></tr>
<tr><td colspan="4">MRM1 is being used for docking and cargo storage aboard the station.</td></tr>
</table>

Scheduled to be launched

<table>
<tr><th>Module</th><th>Assembly mission</th><th>Launch date</th><th>Launch system</th><th>Nation</th><th>Isolated View</th></tr>
<tr><td rowspan="2">Leonardo
(Pressurized Multipurpose Module)</td><td>ULF5</td><td>NET 1 November 2010</td><td>Space Shuttle Discovery, STS-133</td><td>Italy (Builder)
USA (Operator)</td><td rowspan="2"></td></tr>
<tr><td colspan="4">The Leonardo PMM will house spare parts and supplies, allowing longer times between resupply missions and freeing space in other modules, particularly Columbus. The PMM was created by converting the Italian Leonardo Multi-Purpose Logistics Module into a module that could be permanently attached to the station. The arrival of the module will mark the completion of the US Orbital Segment.</td></tr>
<tr><td rowspan="2">Nauka
(lit. 'science')
(Multipurpose Laboratory Module)</td><td>3R</td><td>c. December 2011</td><td>Proton-M</td><td>Russia</td><td rowspan="2"></td></tr>
<tr><td colspan="4">The MLM will be Russia's primary research module as part of the ISS and will be used for general microgravity experiments, docking, and cargo logistics. The module</td></tr>
</table>

	provides a crew work and rest area, and will be equipped with a backup attitude control system that can be used to control the station's attitude. Based on the current assembly schedule, the arrival of *Nauka* will complete construction of the Russian Orbital Segment and it will be the last major component added to the station.	

Cancelled modules

The prototype X-38 lifting body, the cancelled ISS Crew Return Vehicle

Several modules planned for the station have been cancelled over the course of the ISS programme, whether for budgetary reasons, because the modules became unnecessary, or following a redesign of the station after the 2003 *Columbia* disaster. The cancelled modules include:

- The US Centrifuge Accommodations Module for experiments in varying levels of artificial gravity.
- The US Habitation Module, which would have served as the station's living quarters. The sleep stations are now spread throughout the station.
- The US Crew Return Vehicle would have served as the station's lifeboat; a service now provided by one Soyuz spacecraft for every three crew members aboard.

- The US Interim Control Module and ISS Propulsion Module were intended to replace functions of *Zvezda* in case of a launch failure.
- The Russian Universal Docking Module, to which the cancelled Russian Research modules and spacecraft would have docked.
- The Russian Science Power Platform would have provided the Russian Orbital Segment with a power supply independent of the ITS solar arrays.
- Two Russian Research Modules that were planned to be used for scientific research.

Unpressurised elements

Astronaut Stephen K. Robinson anchored to the end of Canadarm2 during STS-114

In addition to the pressurised modules, the ISS features a large number of external components. The largest component is the Integrated Truss Structure (ITS), to which the station's main solar arrays and thermal radiators are mounted. The ITS consists of ten separate segments forming a structure 108.5 m (356 ft) long.

The Alpha Magnetic Spectrometer (AMS), a particle physics experiment, is scheduled to be launched on STS-134 in 2011, and will be mounted externally on the ITS. The AMS will measure cosmic rays and look for evidence of dark matter and antimatter.

The ITS serves as a base for the main remote manipulator system called the Mobile Servicing System (MSS). This consists of the Mobile Base System (MBS), the Canadarm2, and the Special Purpose Dexterous Manipulator. The MBS rolls along rails built into some of the ITS segments to allow the arm to reach all parts of the US segment of the station. The MSS is due to have its reach increased by an Orbiter Boom Sensor System, scheduled for installation during the STS-133 mission.

Two other remote manipulator systems are present in the station's final configuration. The European Robotic Arm, which will service the Russian Orbital Segment, will be launched alongside the Multipurpose Laboratory Module. The JEM RMS, which services the JEM Exposed Facility, was launched on STS-124 and is attached to the JEM Pressurised Module. In addition to these robotic arms, there are two Russian *Strela* cargo cranes used for moving spacewalking cosmonauts and parts around the exterior of the Russian Orbital Segment.

The station in its complete form will have several smaller external components, such as the three External Stowage Platforms (ESPs), launched on STS-102, STS-114 and STS-118, which are used to store spare parts. Four ExPRESS Logistics Carriers (ELCs) will allow experiments to be deployed and conducted in the vacuum of space, and will provide the necessary electricity and computing to process experimental data locally. ELCs 1 and 2 were delivered on STS-129 in November 2009, and ELCs 3 and 4 are scheduled for delivery on STS-134 in November 2010 and STS-133 in September 2010. There are two exposure facilities mounted directly to laboratory modules: the JEM Exposed Facility serves as an external 'porch' for the Japanese Experiment Module complex, and a facility on the European *Columbus* laboratory provides power and data connections for experiments such as the European Technology Exposure Facility and the Atomic Clock Ensemble in Space.

Power supply

The ISS in 2001, showing the solar arrays on *Zarya* and *Zvezda*, in addition to the US P6 solar arrays

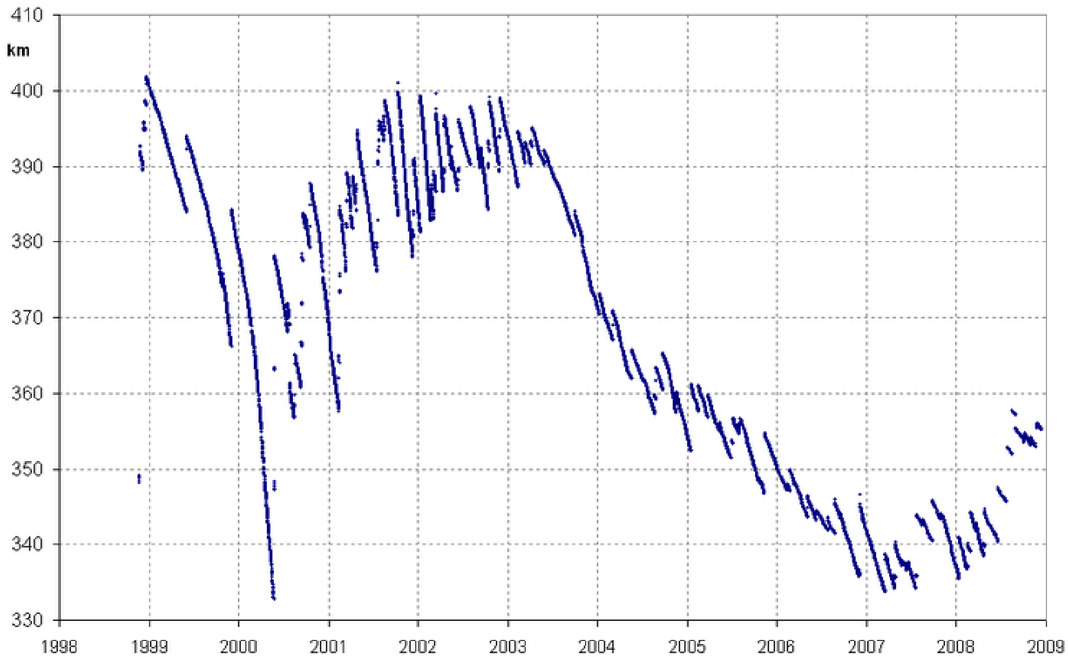
Photovoltaic (PV) arrays power the ISS. The Russian segment of the station, like the space shuttle and most aircraft, uses 28 volt DC partly provided by four solar arrays mounted directly to *Zarya* and *Zvezda*. The rest of the station uses 130-180 V DC from the US PV array arranged as four wing pairs. Each wing produces nearly 32.8 kW.

Power is stabilised and distributed at 160 V DC and converted to the user-required 124 V DC. The higher distribution voltage allows smaller, lighter conductors. The two station segments share power with converters, essential since the cancellation of the Russian Science Power Platform made the Russian Orbital Segment dependent on the US arrays.

The station uses rechargeable nickel-hydrogen batteries for continuous power during the 35 minutes of every 90 minute orbit that it is eclipsed by the Earth. The batteries are recharged on the day side of the earth. They have a 6.5 year lifetime (over 37,000 charge/discharge cycles) and will be regularly replaced over the anticipated 20-year life of the station.

The US solar arrays normally track the sun to maximise power generation. Each array is about 375 m^2 (450 yd^2) in area and 58 metres (63 yd) long. In the complete configuration, the solar arrays track the sun by rotating the *alpha gimbal* once per orbit while the *beta gimbal* follows slower changes in the angle of the sun to the orbital plane. The Night Glider mode aligns the solar arrays parallel to the velocity vector at night to reduce the significant aerodynamic drag at the station's relatively low orbital altitude.

Orbit control



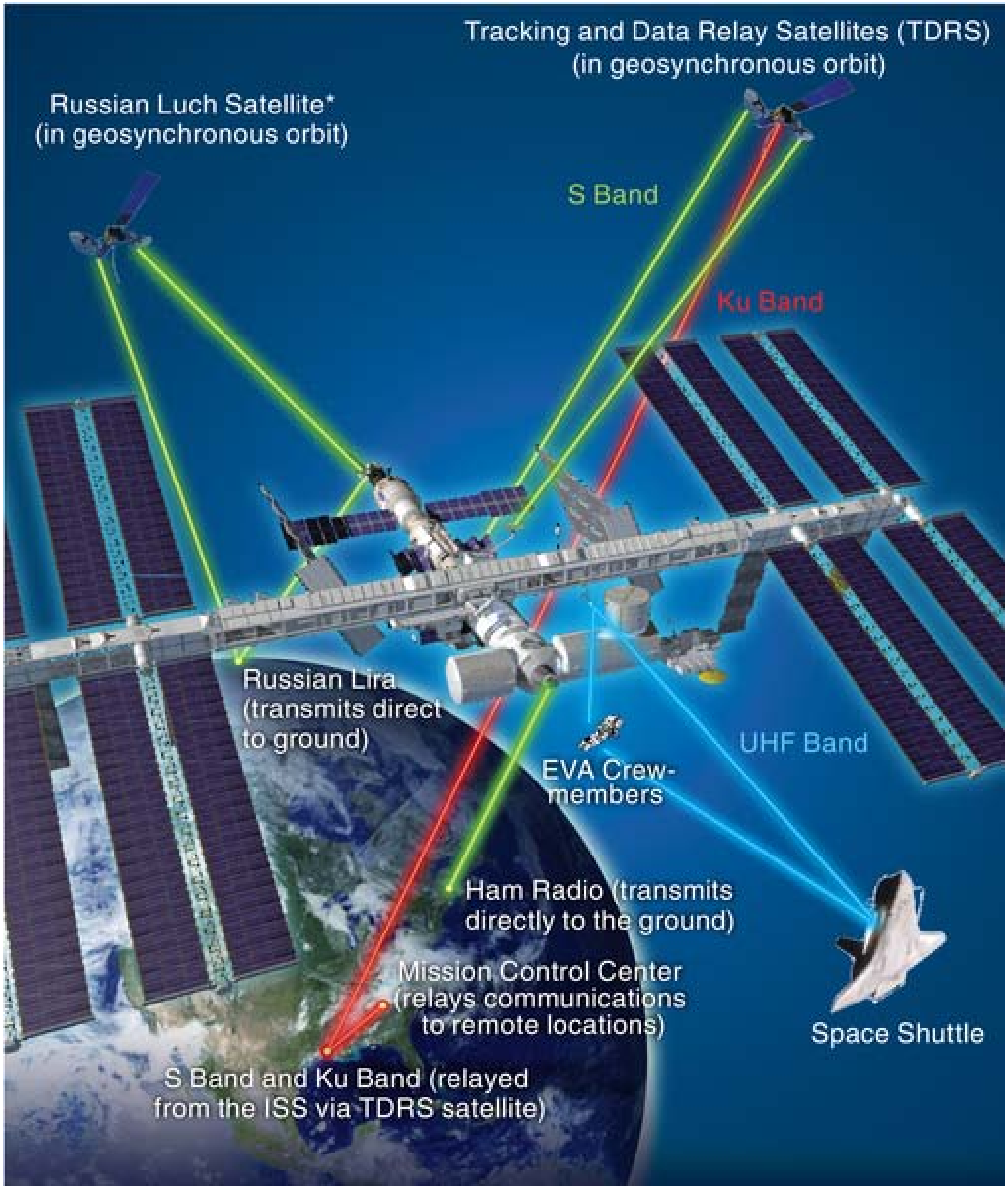
Graph showing the changing altitude of the ISS from November 1998 until January 2009

The ISS is maintained in a near circular orbit with a minimum mean altitude of 278 km (173 mi) and a maximum of 460 km (286 mi). It travels at an average speed of 27,724 kilometres (17,227 mi) per hour, and completes 15.7 orbits per day. The normal maximum altitude is 425 km (264 mi) to allow Soyuz rendezvous missions. As the ISS constantly loses altitude because of a slight atmospheric drag, it needs to be boosted to a higher altitude several times each year. This boost can be performed by the station's two main engines on the *Zvezda* service module, a docked space shuttle, a Progress resupply vessel, or by ESA's ATV. It takes approximately two orbits (three hours) for the boost to a higher altitude to be completed.

In December 2008 NASA signed an agreement with the Ad Astra Rocket Company which may result in the testing on the ISS of a VASIMR plasma propulsion engine. This technology could allow station-keeping to be done more economically than at present. The station's navigational position and velocity, or state vector, is independently established using the US Global Positioning System (GPS) and a combination of state vector updates from Russian Ground Sites and the Russian GLONASS system.

The attitude (orientation) of the station is independently determined by a set of sun, star and horizon sensors on *Zvezda* and the US GPS with antennas on the S0 truss and a receiver processor in the US lab. The attitude knowledge is propagated between updates by rate sensors. Attitude control is maintained by either of two mechanisms; normally, a system of four control moment gyroscopes (CMGs) keeps the station oriented, with *Destiny* forward of *Unity*, the P truss on the port side, and *Rassvet* on the Earth-facing (nadir) side. When the CMG system becomes 'saturated'—when the set of CMGs exceed their operational range or cannot track a series of rapid movements—they can lose their ability to control station attitude. In this event, the Russian attitude control system is designed to provide desaturating thruster firings, taking over automatically whilst the CMG system is reset. This automatic attitude control safing has only occurred once, during Expedition 10. When a space shuttle is docked to the station, it can also be used to maintain station attitude. This occurs during portions of every mated shuttle ISS mission. Shuttle control was used exclusively during STS-117 as the S3/S4 truss was installed.

Communications



The communications systems used by the ISS
* Luch satellite not currently in use.

Radio communications provide telemetry and scientific data links between the station and Mission Control Centres. Radio links are also used during rendezvous and docking procedures and for audio and video communication between crewmembers, flight controllers and family members. As a result, the ISS is equipped with internal and external communication systems used for different purposes.

The Russian Orbital Segment communicates directly with the ground via the *Lira* antenna mounted to *Zvezda*. The *Lira* antenna also has the capability to use the *Luch* data relay satellite system. This system, used for communications with *Mir*, fell into disrepair during the 1990s, and as a result is no longer in use, although two new *Luch* satellites—*Luch*-5A and *Luch*-5B—are planned for launch in 2011 to restore the operational capability of the system. Another Russian communications system is the Voskhod-M, which enables internal telephone communications between *Zvezda*, *Zarya*, *Pirs*, *Poisk* and the USOS, and also provides a VHF radio link to ground control centres via antennas on *Zvezda*'s exterior.

The US Orbital Segment (USOS) makes use of two separate radio links mounted in the Z1 truss structure: the S band (used for audio) and Ku band (used for audio, video and data) systems. These transmissions are routed via the US Tracking and Data Relay Satellite System (TDRSS) in geostationary orbit, which allows for almost continuous real-time communications with NASA's Mission Control Center (MCC-H) in Houston. Data channels for the Canadarm2, European *Columbus* laboratory and Japanese *Kibō* modules are routed via the S band and Ku band systems, although the European Data Relay Satellite System and a similar Japanese system will eventually complement the TDRSS in this role. Communications between modules are carried on an internal digital wireless network.

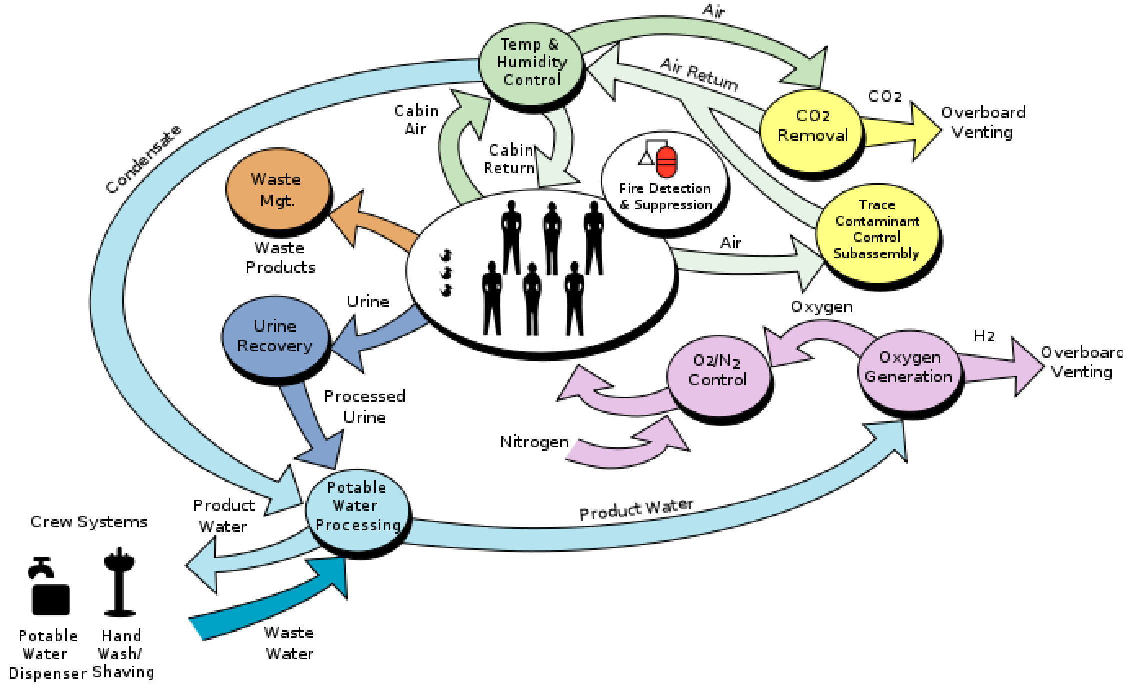
UHF radio is used by astronauts and cosmonauts conducting EVAs. UHF is employed by other spacecraft that dock to or undock from the station, such as Soyuz, Progress, HTV-II, ATV and the Space Shuttle (except the shuttle also makes use of the S band and Ku band systems via TDRSS), to receive commands from Mission Control and ISS crewmembers. Automated spacecraft are fitted with their own communications equipment; the ATV uses a laser attached to the spacecraft and equipment attached to *Zvezda*, known as the Proximity Communications Equipment, to accurately dock to the station.

Microgravity

At the station's orbital altitude, the gravity from the Earth is 88% of that at sea level. While the constant free fall of the ISS offers a perceived sensation of weightlessness, the environment onboard is not one of weightlessness or zero-gravity, instead often being described as microgravity. This state of perceived weightlessness is not perfect, however, being disturbed by four separate effects:

- The drag resulting from the residual atmosphere.
- Vibratory acceleration caused by mechanical systems and the crew on board the ISS.
- Orbital corrections by the on-board gyroscopes or thrusters.
- The spatial separation from the real centre of mass of the ISS. Any part of the ISS not at the exact centre of mass will tend to follow its own orbit. However, as each point is physically part of the station, this is impossible, and so each component is subject to small accelerations from the forces which keep them attached to the station as it orbits. This is also called the tidal force.
- The differences in orbital plane between different locations aboard the ISS.

Life support



The interactions between the components of the ISS Environmental Control and Life Support System (ECLSS)

The ISS Environmental Control and Life Support System (ECLSS) provides or controls atmospheric pressure, fire detection and suppression, oxygen levels, waste management and water supply. The highest priority for the ECLSS is the ISS atmosphere, but the system also collects, processes, and stores waste and water produced and used by the crew—a process that recycles fluid from the sink, toilet, and condensation from the air. The *Elektron* system aboard *Zvezda* and a similar system in *Destiny* generate oxygen aboard the station. The crew has a backup option in the form of bottled oxygen and Solid Fuel Oxygen Generation (SFOG) canisters. Carbon dioxide is removed from the air by the Vozdukh system in *Zvezda*. Other by-products of human metabolism, such as methane from the intestines and ammonia from sweat, are removed by activated charcoal filters.

The atmosphere on board the ISS is similar to the Earth's. Normal air pressure on the ISS is 101.3 kPa (14.7 psi); the same as at sea level on Earth. An Earth-like atmosphere offers benefits for crew comfort, and is much safer than the alternative, a pure oxygen atmosphere, because of the increased risk of a fire such as that responsible for the deaths of the Apollo 1 crew.

Sightings

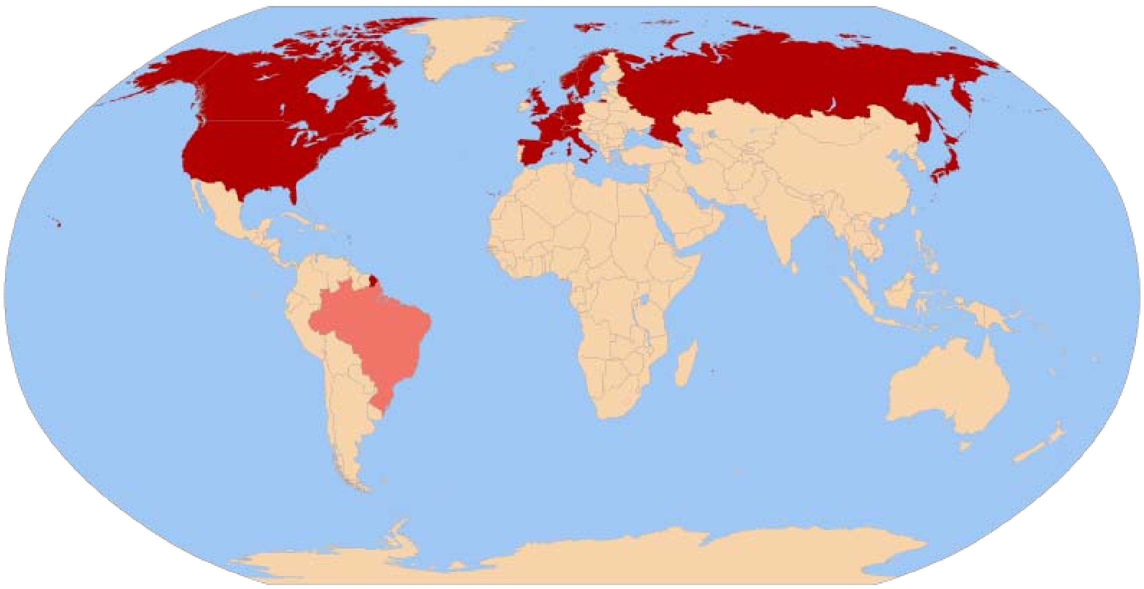
A January 2008 sighting of the International Space Station

Because of the size of the ISS (about that of an American football field) and the large reflective area offered by its solar panels, ground based observation of the station is possible with the naked eye if the observer is in the right location at the right time. In many cases, the station is one of the brightest naked-eye objects in the sky, although it is visible only for periods ranging from two to five minutes.

If the following conditions are fulfilled (assuming the weather is clear), the station will appear as a very bright object in the sky: The station must be above the observer's horizon, and it must pass within about 2,000 kilometres (1,200 mi) of the observation site (the closer the better). It must be dark enough at the observer's location for stars to be visible, and the station must be in sunlight rather than in the Earth's shadow. It is common for the third condition to begin or end during what would otherwise be a good viewing opportunity. In the evening, as the station moves further from the dusk, going from west to east it will appear to suddenly fade and disappear. In the reverse situation, it may suddenly appear in the sky as it approaches the dawn. With the station's maximum theoretical brightness at approximately magnitude -5.9 (with a typical maximum of -3.8), it is bright enough to be spotted during broad daylight conditions without optical aid.

Politics, utilisation and financing

Legal aspects



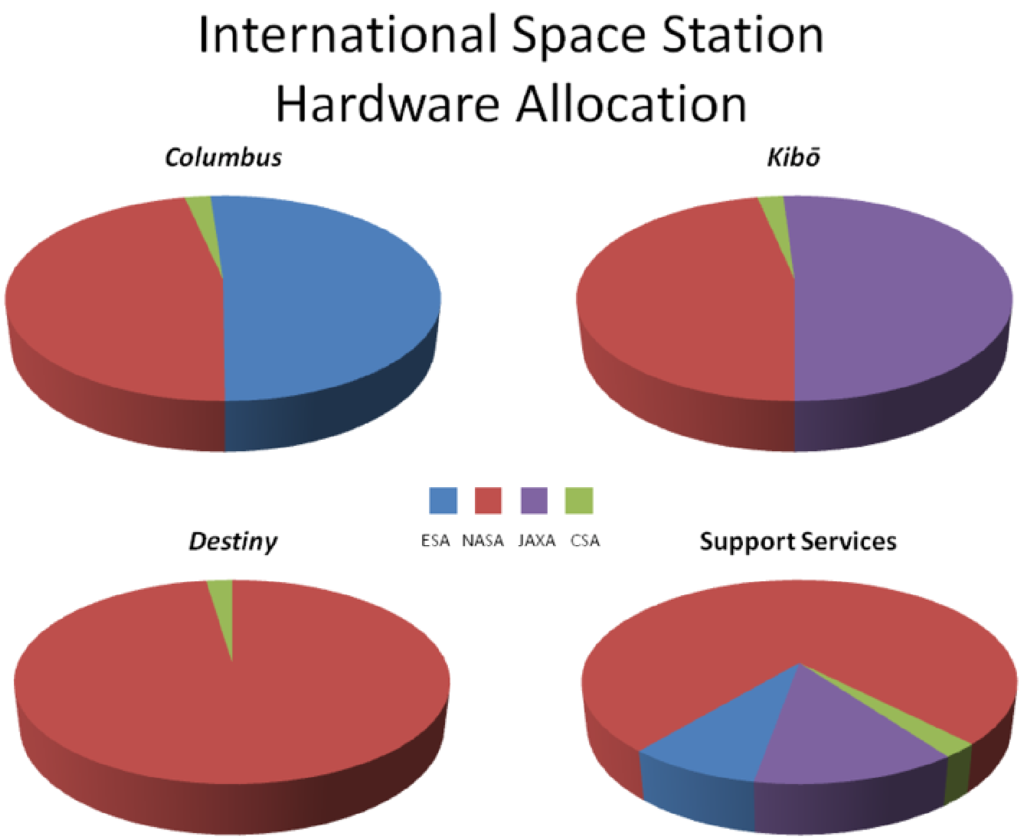
Primary contributing nations NASA contracted nations

The ISS is a joint project of several space agencies: the US National Aeronautics and Space Administration (NASA), the Russian Federal Space Agency (RKA), the Japan Aerospace Exploration Agency (JAXA), the Canadian Space Agency (CSA) and the European Space Agency (ESA).

As a multinational project, the legal and financial aspects are complex. Issues of concern include the ownership of modules, station utilisation by participant nations, and responsibilities for station resupply. Obligations and rights are established by the Space Station Intergovernmental Agreement (IGA). This international treaty was signed on 28 January 1998 by the primary nations involved in the Space Station project; the United States of America, Russian Federation, Japan, Canada and ten member states of the European Space Agency (Belgium, Denmark, France, Germany, Italy, The Netherlands, Norway, Spain, Sweden and Switzerland). A second layer of agreements was then achieved, called Memoranda of Understanding (MOU), between NASA and ESA, CSA, RKA and JAXA. These agreements are then further split, such as for the contractual obligations between nations, and trading of partners' rights and obligations. Use of the Russian Orbital Segment is also negotiated at this level.

In addition to these main intergovernmental agreements, Brazil joins as a bilateral partner of the United States by a contract with NASA to supply hardware. In return, NASA will provide Brazil with access to its ISS facilities on-orbit, as well as a flight opportunity for one Brazilian astronaut during the course of the ISS programme. Italy has a similar contract with NASA to provide comparable services, although Italy also takes part in the programme directly via its membership in ESA. China has reportedly expressed interest in the project, especially if it would be able to work with the RKA. However, as of 2009 China is not involved because of US objections. The heads of both the South Korean and Indian space agencies announced at the first plenary session of the 2009 International Astronautical Congress that their nations intend to join the ISS programme, with talks due to begin in 2010. The heads of agency also expressed support for extending ISS lifetime.

Utilisation rights



Allocation of American segment hardware utilisation between nations

The Russian part of the station is operated and controlled by the Russian Federation's space agency and provides Russia with the right to nearly one-half of the crew time for the ISS. The allocation of remaining crew time (three to four crew members of the total permanent crew of six) and hardware within the other sections of the station has been assigned as follows:

- *Columbus*: 51% for the ESA, 46.7% for NASA, and 2.3% for CSA.
- *Kibō*: 51% for the JAXA, 46.7% for NASA, and 2.3% for CSA.
- *Destiny*: 97.7% for NASA and 2.3% for CSA.

- Crew time, electrical power and rights to purchase supporting services (such as data upload and download and communications) are divided 76.6% for NASA, 12.8% for JAXA, 8.3% for ESA, and 2.3% for CSA.

Costs

The cost estimates for the ISS range from 35 billion to 160 billion dollars. ESA, the one agency which actually presents potential overall costs, estimates €100 billion for the entire station over 30 years. A precise cost estimate for the ISS is unclear, as it is difficult to determine which costs should be attributed to the ISS programme, or how the Russian contribution should be measured.

Criticism

Critics of the ISS contend that the time and money spent on the ISS could be better spent on other projects—whether they be robotic spacecraft missions, space exploration, investigations of problems on Earth, colonisation of Mars, or just tax savings. Some critics, such as Robert L. Park, argue that little scientific research was convincingly planned for the ISS, and that the primary feature of a space-based laboratory, its microgravity environment, can be studied less expensively with a "vomit comet".

The research capabilities of the ISS have been criticised, particularly following the cancellation of the ambitious Centrifuge Accommodations Module, which, alongside other equipment cancellations, means scientific research performed on the station is generally limited to experiments which do not require any specialised apparatus. For example, in the first half of 2007, ISS research dealt primarily with human biological responses to living and working in space, covering topics like kidney stones, circadian rhythm, and the effects of cosmic rays on the nervous system. Other criticisms hinge on the technical design of the ISS, including the high inclination of the station's orbit, which leads to a higher cost for US-based launches to the station.

In response to some of these comments, advocates of manned space exploration say that criticism of the ISS project is short-sighted, and that manned space research and exploration have produced billions of dollars' worth of benefits. NASA has estimated that the indirect economic return from spin-offs of human space exploration has been many times the initial public investment, although this estimate is based on the Apollo Program and was made in the 1970s. A review of the claims by the Federation of American Scientists argued that NASA's rate of return from spin-offs is actually very low, except for aeronautics work that has led to aircraft sales.

End of mission and deorbit plans

NASA planned to deorbit the ISS in the first quarter of 2016. However, the plan to end the ISS programme in 2015, as determined in 2004 by then-President George W. Bush, has been rejected by the current Obama administration. With the new budget announced on 1 February 2010, the administration aims to extend the lifetime through 2020. The

Augustine Commission, which reviewed NASA's human space flight program, recommended in its final report of 23 October 2009 the extension of the ISS programme to at least 2020. In particular, Leroy Chiao, a former space station commander and space shuttle astronaut who sat on the advisory panel, stated in a CNN interview: "You've got all of these different countries working together on this common project in space. And if we go ahead and stop [...] it is going to break up that framework. The different countries around the world will lose confidence in the US as a leader in space exploration." NASA officials received confirmation from the Obama administration on the future direction of the ISS in particular and the human spaceflight programme in general on 1 February 2010, with a budget proposing an extension to the ISS programme until at least 2020, with talks between ISS partners suggesting that the station could conceivably remain operational until 2025 or 2028.

The Multilateral Coordination Board (MCB) of the ISS international partners, in a videoconference on 21 September 2010, learned that the Japanese and Russian governments have approved operation continuing to 2020. The Canadian Space Agency (CSA) and the European Space Agency (ESA) are working with their governments to confirm consensus on extending operations beyond 2016, while NASA continues working with the US Congress on extension plans.

NASA has the responsibility to deorbit the ISS. Although *Zvezda* has a propulsion system used for station-keeping, it is not powerful enough for a controlled deorbit. Options for controlled deorbit of the ISS include the use of a modified European ATV or a specially constructed deorbit vehicle. According to a 2009 report, RKK Energia is considering methods to remove from the station some modules of the Russian Orbital Segment when the end of mission is reached and use them as a basis for a new station, known as the Orbital Piloted Assembly and Experiment Complex. The modules under consideration for removal from the current ISS include the Multipurpose Laboratory Module (MLM), currently scheduled to be launched at the end of 2011, with other Russian modules which are currently planned to be attached to the MLM until 2015, although still currently unfunded. Neither the MLM nor any additional modules attached to it would have reached the end of their useful lives in 2016 or 2020. The report presents a statement from an unnamed Russian engineer who believes that, based on the experience from *Mir*, a thirty-year life should be possible, except for micrometeorite damage, because the Russian modules have been built with on-orbit refurbishment in mind.

Life on board

Crew schedule

The time zone used on board the ISS is Coordinated Universal Time (UTC). The windows are covered at night hours to give the impression of darkness because the station experiences 16 sunrises and sunsets a day. During visiting space shuttle missions, the ISS crew will mostly follow the shuttle's Mission Elapsed Time (MET), which is a flexible time zone based on the launch time of the shuttle mission. Because the sleeping periods between the UTC time zone and the MET usually differ, the ISS crew often has to adjust its sleeping pattern before the space shuttle arrives and after it leaves to shift from one time zone to the other in a practice known as sleep shifting.

A typical day for the crew begins with a wake-up at 06:00, followed by post-sleep activities and a morning inspection of the station. The crew then eats breakfast and takes part in a daily planning conference with Mission Control before starting work at around 08:10. The first scheduled exercise of the day follows, after which the crew continues work until 13:05. Following a one-hour lunch break, the afternoon consists of more exercise and work before the crew carries out its pre-sleep activities beginning at 19:30, including dinner and a crew conference. The scheduled sleep period begins at 21:30. In general, the crew works 10 hours per day on a weekday, and 5 hours on Saturdays, with the rest of the time their own for relaxation, games or work catch-up.

Sleeping in space

Astronaut Peggy Whitson in the doorway of a sleeping rack in the *Destiny* laboratory

The station provides crew quarters for each member of permanent Expedition crews, with two 'sleep stations' in the Russian Orbital Segment and four more, due to be installed in *Tranquility*, currently spread around the USOS. The American quarters are private, approximately person-sized soundproof booths. A crewmember can sleep in them in a tethered sleeping bag, listen to music, use a laptop, and store personal effects in a large drawer or in nets attached to the module's walls. The module also provides a reading lamp, a shelf and a desktop. Visiting crews have no allocated sleep module, and attach a sleeping bag to an available space on a wall—it is possible to sleep floating freely through the station, but this is generally avoided because of the possibility of bumping into sensitive equipment. It is important that crew accommodations are well ventilated. Otherwise, astronauts can wake up oxygen deprived and gasping for air, because a bubble of their own exhaled carbon dioxide has formed around their heads.

Hygiene

The ISS does not feature a shower, although it was planned as part of the now cancelled Habitation Module. Instead, crewmembers wash using a water jet and wet wipes, with soap dispensed from a toothpaste tube-like container. Crews are also provided with rinseless shampoo and edible toothpaste to save water.

There are two space toilets on the ISS, both of Russian design, located in *Zvezda* and *Tranquility*. These Waste and Hygiene Compartments use a fan-driven suction system similar to the Space Shuttle Waste Collection System. Astronauts first fasten themselves to the toilet seat, which is equipped with spring-loaded restraining bars to ensure a good seal. A lever operates a powerful fan and a suction hole slides open: the air stream carries the waste away. Solid waste is collected in individual bags which are stored in an aluminium container. Full containers are transferred to Progress spacecraft for disposal. Liquid waste is evacuated by a hose connected to the front of the toilet, with anatomically correct “urine funnel adapters” attached to the tube so both men and women can use the same toilet. Waste is collected and transferred to the Water Recovery System, where it is recycled back into drinking water.

Food and drink

The crews of STS-127 and Expedition 20 enjoy a meal inside *Unity*

Most of the food eaten by station crews is frozen, refrigerated or canned. Menus are prepared by the astronauts, with the help of a dietitian, before the astronauts' flight to the station. As the sense of taste is reduced in orbit because of fluid shifting to the head, spicy food is a favourite of many crews. Each crewmember has individual food packages and cooks them using the onboard galley, which features two food warmers, a refrigerator, and a water dispenser that provides both heated and unheated water. Drinks are provided in dehydrated powder form, and are mixed with water before consumption. Drinks and soups are sipped from plastic bags with straws, while solid food is eaten with a knife and fork, which are attached to a tray with magnets to prevent them floating away. Any food which does float away, including crumbs, must be collected to prevent it from clogging up the station's air filters and other equipment.

Exercise

The most significant adverse effects of long-term weightlessness are muscle atrophy and deterioration of the skeleton, or spaceflight osteopenia. Other significant effects include fluid redistribution, a slowing of the cardiovascular system, decreased production of red blood cells, balance disorders, and a weakening of the immune system. Lesser symptoms include loss of body mass, nasal congestion, sleep disturbance, excess flatulence, and puffiness of the face. These effects begin to reverse quickly upon return to the Earth.

Astronaut Sunita "Suni" Williams is attached to the TVIS treadmill with bungee cords aboard the International Space Station

To prevent some of these adverse physiological effects, the station is equipped with two treadmills (including the COLBERT), the aRED (advanced Resistive Exercise Device) which enables various weightlifting exercises, and a stationary bicycle; each astronaut spends at least two hours per day exercising on the equipment. Astronauts use bungee cords to strap themselves to the treadmill. Researchers believe that exercise is a good countermeasure for the bone and muscle density loss that occurs when humans live for a long time without gravity.

Station operations

Expeditions

Each permanent station crew is given a sequential expedition number. Expeditions have an average duration of half a year, and they commence following the official handover of the station from one Expedition commander to another. Expeditions 1 through 6 consisted of three person crews, but the *Columbia* accident led to a reduction to two crew members for Expeditions 7 to 12. Expedition 13 saw the restoration of the station crew to three, and the station has been permanently staffed as such since. While only three crew members are permanently on the station, several expeditions, such as Expedition 16, have consisted of up to six astronauts or cosmonauts, who are flown to and from the station on separate flights.

On 27 May 2009, Expedition 20 began. Expedition 20 was the first ISS crew of six. Before the expansion of the living volume and capabilities from STS-115 the station could only host a crew of three. Expedition 20's crew was lifted to the station in two separate Soyuz-TMA flights launched at two different times (each Soyuz-TMA can hold only three people): Soyuz TMA-14 on 26 March 2009 and Soyuz TMA-15 on 27 May 2009. However, the station would not be permanently occupied by six crew members all year. For example, when the Expedition 20 crew (Roman Romanenko, Frank De Winne and Bob Thirsk) returned to Earth in November 2009, for a period of about two weeks only two crew members (Jeff Williams and Max Surayev) were aboard. This increased to five in early December, when Oleg Kotov, Timothy Creamer and Soichi Noguchi arrived on Soyuz TMA-17. It decreased to three when Williams and Surayev departed in March 2010, and finally returned to six in April 2010 with the arrival of Soyuz TMA-18, carrying Aleksandr Skvortsov, Mikhail Korniyenko and Tracy Caldwell Dyson.

The International Space Station is the most-visited spacecraft in the history of space flight. As of 24 November 2009, it had received 266 visitors (185 different people). *Mir* had 137 visitors (104 different people).

Visiting spacecraft

The Space Shuttle *Endeavour* approaching the ISS during STS-118

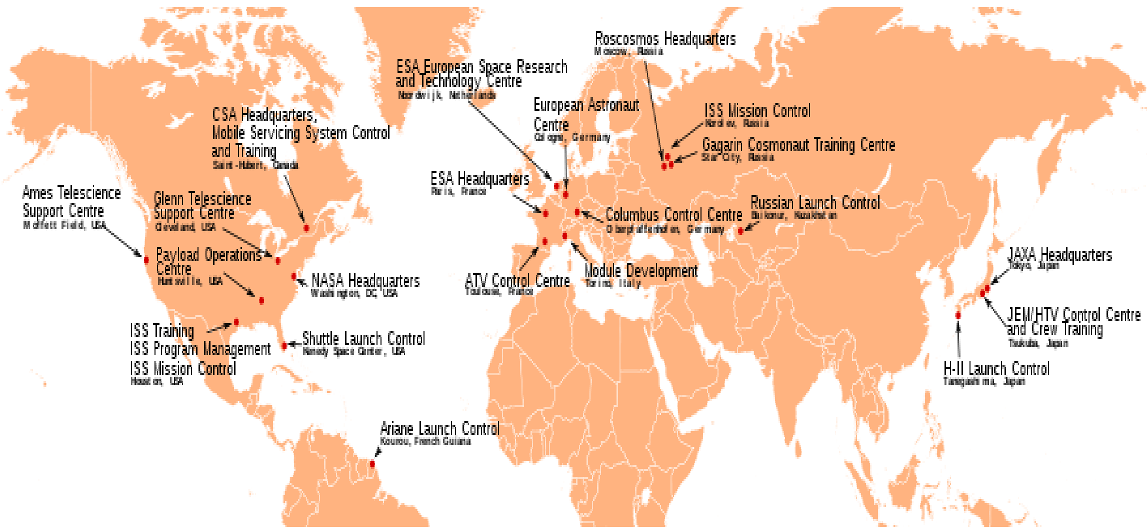
Spacecraft from four different space agencies visit the ISS, serving a variety of purposes. The Automated Transfer Vehicle from the European Space Agency, the Russian Roskosmos Progress spacecraft and the HTV-II from the Japan Aerospace Exploration Agency have provided resupply services to the station. In addition, Russia supplies a Soyuz spacecraft used for crew rotation and emergency evacuation, which is replaced every six months. Finally, the US services the ISS through its Space Shuttle programme, providing resupply missions, assembly and logistics flights, and crew rotation. As of 27 November 2009, there have been 20 Soyuz, 35 Progress, 1 ATV, 1 HTV and 31 Space Shuttle flights to the station. Expeditions require, on average, 2,722 kg of supplies, and as of 27 November 2009, crews had consumed a total of around 19,000 meals. Soyuz crew rotation flights and Progress resupply flights visit the station on average two and three times respectively each year, with the ATV and HTV planned to visit annually from 2010 onwards.

Following the retirement of the Space Shuttle, a number of other spacecraft are expected to fly to the station. Two, the Orbital Sciences Cygnus and SpaceX Dragon, will fly under NASA's Commercial Orbital Transportation Services and Commercial Resupply Services contracts, delivering cargo to the station until at least 2015. In addition, the Orion spacecraft, developed as a Space Shuttle replacement as part of NASA's Constellation Programme, was retasked by President Barack Obama on 15 April 2010 to provide lifeboat services to the station. The spacecraft had until that point been entirely cancelled under the US 2011 fiscal year budget.

As of 25 September 2010, there are three spacecraft docked with the ISS:

Spacecraft	Mission	Docking port	Date docked (UTC)
Soyuz TMA-19	Expedition 24/Expedition 25	*Rassvet*	17 June 2010 21:21
Progress M-05M	ISS Progress 37	*Pirs*	1 May 2010 18:30
Progress M-07M	ISS Progress 39	*Zvezda* aft	12 September 2010 11:58

Mission control centres



Space centres involved with the ISS programme

The components of the ISS are operated and monitored by their respective space agencies at control centres across the globe, including:

- NASA's Mission Control Center at Lyndon B. Johnson Space Center in Houston, Texas, serves as the primary control facility for the US segment of the ISS and also controls the Space Shuttle missions that visit the station.
- NASA's Payload Operations and Integration Center at Marshall Space Flight Center in Huntsville, Alabama, serves as the centre that coordinates all payload operations in the US Segment.
- Roskosmos's Mission Control Center at Korolyov, Moscow, controls the Russian Orbital Segment of the ISS, in addition to individual Soyuz and Progress missions.
- ESA's Columbus Control Centre at the German Aerospace Centre (DLR) in Oberpfaffenhofen, Germany, controls the European *Columbus* research laboratory.

- ESA's ATV Control Centre, at the Toulouse Space Centre (CST) in Toulouse, France, controls flights of the unmanned European Automated Transfer Vehicle.
- JAXA's JEM Control Centre and HTV Control Centre at Tsukuba Space Centre (TKSC) in Tsukuba, Japan, are responsible for operating the Japanese Experiment Module complex and all flights of the unmanned Japanese HTV-II respectively.
- CSA's MSS Control at Saint-Hubert, Quebec, Canada, controls and monitors the Mobile Servicing System, or Canadarm2.

Safety aspects

Anomalies

Since construction started, the ISS programme has had to deal with several major incidents, unexpected problems and failures. These incidents have impacted the station's assembly timeline, led to periods of reduced capabilities and, in some cases, could have forced abandonment of the station for safety reasons, had these problems not been resolved.

The first major impact to station operations came with the Space Shuttle *Columbia* disaster on 1 February 2003 (during STS-107), which resulted in a two-and-a-half-year suspension of the US Space Shuttle programme, followed by another one-year suspension following STS-114 (because of continued foam shedding on the external tank). This halted station assembly plans and reduced the station's operational capabilities, as, due to a lack of logistics, caretaker crews of just two astronauts were launched from Expedition 7 until Expedition 12. The *Columbia* disaster was followed by a number of smaller issues aboard the station, including an air leak from the USOS in 2004, the venting of smoke from an *Elektron* oxygen generator in 2006, and the failure of the computers in the ROS in 2007 during STS-117 which left the station without thruster, *Elektron*, *Vozdukh* and other environmental control system operations, the root cause of which was found to be condensation inside the electrical connectors leading to a short-circuit.

These issues with internal station equipment were then followed by a spate of issues with external components; during STS-120 on 2007, following the relocation of the P6 truss and solar arrays, it was noted during the redeployment of the array that it had become torn and was not deploying properly. An emergency EVA was carried out by Scott Parazynski, assisted by Douglas Wheelock, to repair the array, an activity which was considerably more dangerous than most EVAs due to the short planning time and the risk of electric shock from the arrays themselves. The issues with the array were followed in the same year by problems with the starboard Solar Alpha Rotary Joint (SARJ), which rotates the arrays on the starboard side of the station. Excessive vibration and high-current spikes in the array drive motor were noted, resulting in a decision to substantially curtail motion of the starboard SARJ until the cause was understood. Inspections during EVAs on STS-120 and STS-123 showed extensive contamination from metallic shavings and debris in the large drive gear and confirmed damage to the large metallic race ring at the heart of the joint, and so the joint was locked to prevent further damage. Repairs to the joint were carried out during STS-126 with lubrication of both joints and the replacement 11 of 12 trundle bearings on the joint.

More recently, problems have been noted with the station's engines and cooling. In 2009, the engines on *Zvezda* were issued an incorrect command which caused excessive vibrations to propagate throughout the station structure which persisted for over two minutes. While no damage to the station was immediately reported, some components may have been stressed beyond their design limits. Further analysis confirmed that the station was unlikely to have suffered any structural damage, and it appears that "structures will still meet their normal lifetime capability". Further evaluations are under way. 2009 also saw damage to the S1 radiator, one of the components of the station's cooling system. The problem was first noticed in Soyuz imagery in September 2008, but was not thought to be serious. The imagery showed that the surface of one sub-panel has peeled back from the underlying central structure, possibly due to micro-meteoroid or debris impact. It is also known that a Service Module thruster cover, jettisoned during an EVA in 2008, had struck the S1 radiator, but its effect, if any, has not been determined. On 15 May 2009 the damaged radiator panel's ammonia tubing was mechanically shut off from the rest of the cooling system by the computer-controlled closure of a valve. The same valve was used immediately afterwards to vent the ammonia from the damaged panel, eliminating the possibility of an ammonia leak from the cooling system via the damaged panel.

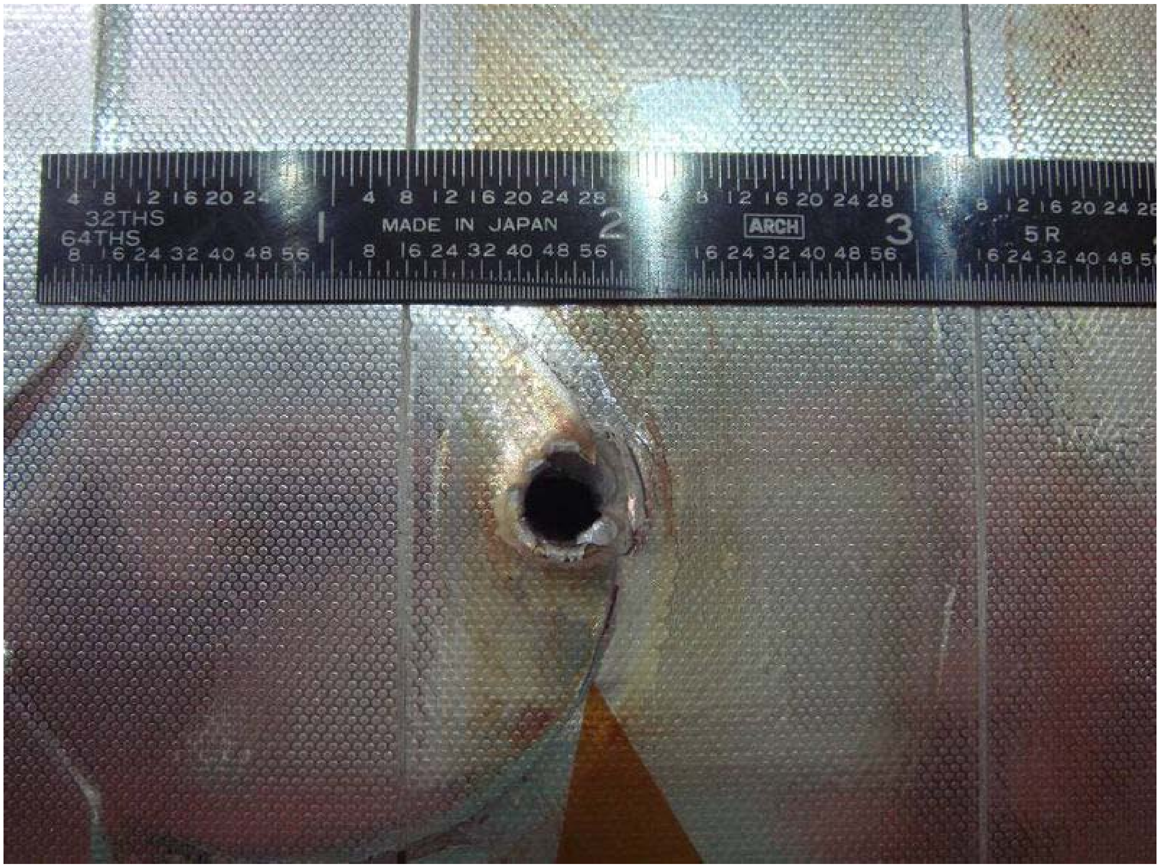
Cooling loop A failure

Early on 1 August 2010, a failure in cooling Loop A (starboard side), one of two external cooling loops, left the station with only half of its normal cooling capacity and zero redundancy in some systems. The problem appeared to be in the ammonia pump module that circulates the ammonia cooling fluid. Several subsystems, including two of the four CMGs, were shut down.

Planned operations on the ISS were interrupted through a series of EVAs to address the cooling system issue. A first EVA on 7 August 2010, to replace the failed pump module, was not fully completed due to an ammonia leak in one of four quick-disconnects. A second EVA on 11 August successfully removed the failed pump module. A third EVA was required to restore Loop A to normal functionality.

The station's cooling system is largely built by the American company Boeing, which is also the manufacturer of the failed pump.

Orbital debris



The entry hole in Space Shuttle *Endeavour*'s radiator panel caused by space debris during STS-118

At the low altitudes at which the ISS orbits there is a variety of space debris, consisting of everything from entire spent rocket stages and defunct satellites, to explosion fragments, paint flakes, slag from solid rocket motors, coolant released by RORSAT nuclear powered satellites, small needles, and many other objects. These objects, in addition to natural micrometeoroids, pose a threat to the station as they have the ability to puncture the pressurised modules and cause damage to other parts of the station. Micrometeoroids also pose a risk to spacewalking astronauts, as such objects could puncture their spacesuits, causing them to depressurise.

Space debris objects are tracked remotely from the ground, and the station crew can be notified of many objects with sufficient size to cause damage on impact. This allows for a Debris Avoidance Manoeuvre (DAM) to be conducted, which uses thrusters on the Russian Orbital Segment to alter the station's orbital altitude, avoiding the debris. DAMs are not uncommon, taking place if computational models show the debris will approach within a certain threat distance. Eight DAMs had been performed prior to March 2009, the first seven between October 1999 and May 2003. Usually the orbit is raised by one or two kilometres by means of an increase in orbital velocity of the order of 1 m/s.

Unusually there was a lowering of 1.7 km on 27 August 2008, the first such lowering for 8 years. There were two DAMs in 2009, on 22 March and 17 July. If a threat from orbital debris is identified too late for a DAM to be safely conducted, the station crew close all the hatches aboard the station and retreat into their Soyuz spacecraft, so that they would be able to evacuate in the event it was damaged by the debris. This partial station evacuation has occurred twice, on 6 April 2003 and 13 March 2009.

Radiation

Without the protection of the Earth's atmosphere, astronauts are exposed to higher levels of radiation from a steady flux of cosmic rays. The station's crews are exposed to about 1 millisievert of radiation each day, which is about the same as someone would get from natural sources on Earth in a year. This results in a higher risk of astronauts' developing cancer. High levels of radiation can cause damage to the chromosomes of lymphocytes. These cells are central to the immune system and so any damage to them could contribute to the lowered immunity experienced by astronauts. Over time lowered immunity results in the spread of infection between crew members, especially in such confined areas. Radiation has also been linked to a higher incidence of cataracts in astronauts. Protective shielding and protective drugs may lower the risks to an acceptable level, but data is scarce and longer-term exposure will result in greater risks.

Despite efforts to improve radiation shielding on the ISS compared to previous stations such as *Mir*, radiation levels within the station have not been vastly reduced, and it is thought that further technological advancement will be required to make long-duration human spaceflight further into the Solar System a possibility.

It should be noted, however, that the radiation levels experienced on ISS are not excessively greater than those experienced by airline passengers. The Earth's electromagnetic field provides almost the same level of protection against solar and other radiation in Low Earth Orbit as in the stratosphere. Airline passengers, however, only experience this level of radiation for no more than 15 hours for the longest transcontinental flights (London-Sydney or Chicago-Delhi) and often far less time. For instance, a 12 hour flight from Boston to Beijing, an airline passenger would experience 0.1 millisievert of radiation, or a rate of 0.2 millisieverts per day, only 1/5th the rate experienced by an astronaut in LEO.