Aviation, Aerodynamics and Spaceflight

(General Concepts and Applications)

Maci Valerio

First Edition, 2012

ISBN 978-81-323-3515-3

Published by:
University Publications
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

Table of Contents

Chapter 1 - Aircraft

Chapter 2 - Atmospheric Entry

Chapter 3 - Aviation

Chapter 4 - Satellite

Chapter 5 - Spacecraft

Chapter 6 - Wind Tunnel

Chapter- 1

Aircraft

An Airbus A380, the world's largest passenger airliner

A hot air balloon (aircraft) in flight.

Aircraft are vehicles which are able to fly by being supported by the air, or in general, the atmosphere of a planet. An aircraft counters the force of gravity by using either static lift or by using the dynamic lift of an airfoil, or in a few cases the downward thrust from jet engines.

Although rockets and missiles also travel through the atmosphere, most are not considered aircraft because they use rocket thrust instead of aerodynamics as the primary means of lift. However, rocket planes and cruise missiles are considered aircraft because they rely on lift from the air. Another type of aircraft is the spaceplane which is an aircraft designed to fly up to extreme altitudes into space and land as a conventional aircraft.

The human activity which surrounds aircraft is called *aviation*. Manned aircraft are flown by an onboard pilot. Unmanned aerial vehicles may be remotely controlled or self-controlled by onboard computers. Target drones are an example of UAVs. Aircraft may be classified by different criteria, such as lift type, propulsion, usage and others.

History

The history of aircraft development divides broadly into five eras:

- Pioneers of flight
- First World War
- Inter-war, sometimes called the Golden Age
- Second World War
- Postwar era, also called the jet age

Methods of lift

Lighter than air – aerostats

Aerostats use buoyancy to float in the air in much the same way that ships float on the water. They are characterized by one or more large gasbags or canopies, filled with a relatively low density gas such as helium, hydrogen or hot air, which is less dense than the surrounding air. When the weight of this is added to the weight of the aircraft structure, it adds up to the same weight as the air that the craft displaces.

Small hot air balloons called sky lanterns date back to the 3rd century BC, and were only the second type of aircraft to fly, the first being kites.

Originally, a balloon was any aerostat, while the term airship was used for large, powered aircraft designs – usually fixed-wing – though none had yet been built. The advent of powered balloons, called dirigible balloons, and later of rigid hulls allowing a great increase in size, began to change the way these words were used. Huge powered aerostats, characterized by a rigid outer framework and separate aerodynamic skin surrounding the gas bags, were produced, the Zeppelins being the largest and most famous. There were still no fixed-wing aircraft or non-rigid balloons large enough to be called airships, so "airship" came to be synonymous with these aircraft. Then several accidents, such as the Hindenburg disaster in 1937, led to the demise of these airships. Nowadays a "balloon" is an unpowered aerostat, whilst an "airship" is a powered one.

A powered, steerable aerostat is called a *dirigible*. Sometimes this term is applied only to non-rigid balloons, and sometimes *dirigible balloon* is regarded as the definition of an airship (which may then be rigid or non-rigid). Non-rigid dirigibles are characterized by a moderately aerodynamic gasbag with stabilizing fins at the back. These soon became known as *blimps*. During the Second World War, this shape was widely adopted for tethered balloons; in windy weather, this both reduces the strain on the tether and stabilizes the balloon. The nickname *blimp* was adopted along with the shape. In modern times any small dirigible or airship is called a blimp, though a blimp may be unpowered as well as powered.

Heavier than air – aerodynes

Heavier-than-air aircraft must find some way to push air or gas downwards, so that a reaction occurs (by Newton's laws of motion) to push the aircraft upwards. This dynamic movement through the air is the origin of the term *aerodyne*. There are two ways to produce dynamic upthrust: aerodynamic lift, and powered lift in the form of engine thrust.

Aerodynamic lift involving wings is the most common, with fixed-wing aircraft being kept in the air by the forward movement of wings, and rotorcraft by spinning wing-shaped rotors sometimes called rotary wings. A wing is a flat, horizontal surface, usually shaped in cross-section as an aerofoil. To fly, air must flow over the wing and generate lift. A *flexible wing* is a wing made of fabric or thin sheet material, often stretched over a rigid frame. A *kite* is tethered to the ground and relies on the speed of the wind over its wings, which may be flexible or rigid, fixed or rotary.

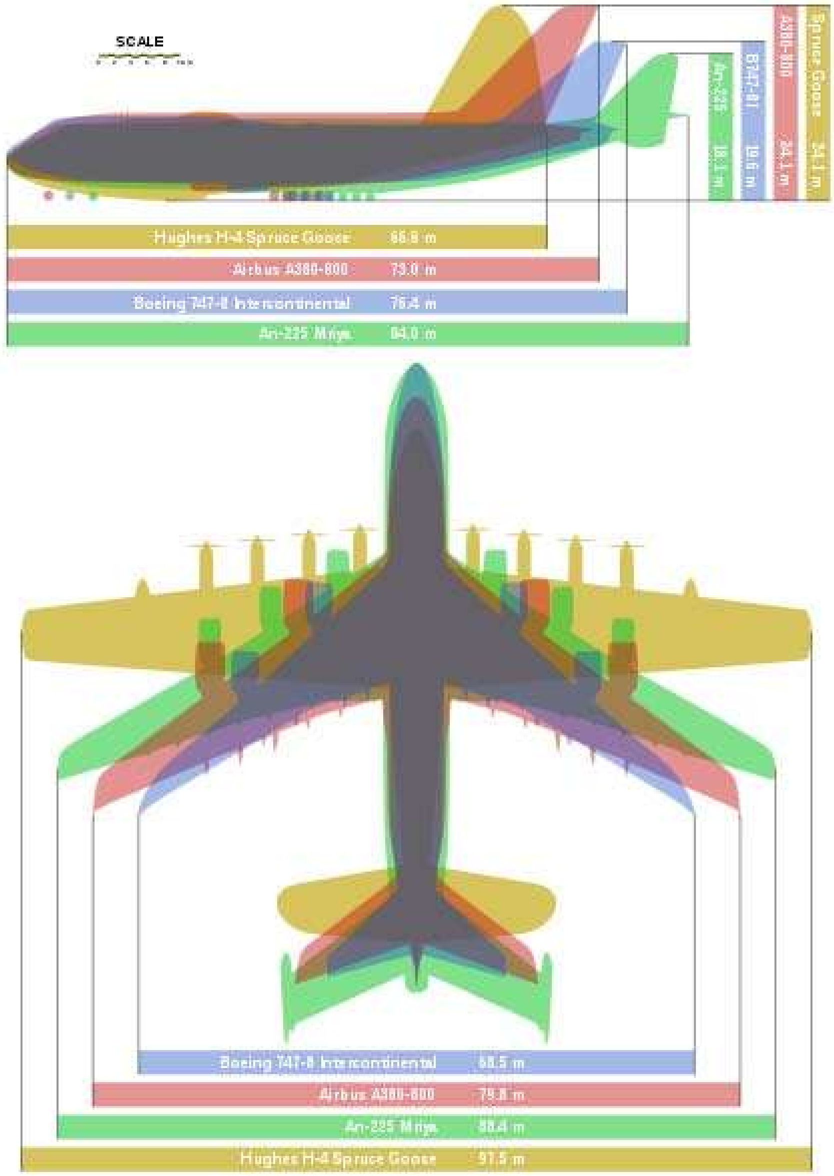
With powered lift, the aircraft directs its engine thrust vertically downwards.

The initialism *VTOL* (**v**ertical **t**ake **o**ff and **l**anding) is applied to aircraft that can take off and land vertically. Most are rotorcraft. Others, such as the Hawker Siddeley Harrier and F-35B, take off and land vertically using powered lift and transfer to aerodynamic lift in steady flight. Similarly, *STOL* stands for **s**hort **t**ake **o**ff and **l**anding. Some VTOL aircraft often operate in a **s**hort **t**ake **o**ff/**v**ertical **l**anding mode known as STOVL.

A pure rocket is not usually regarded as an aerodyne, because it does not depend on the air for its lift (and can even fly into space); however, many aerodynamic lift vehicles have been powered or assisted by rocket motors. Rocket-powered missiles which obtain aerodynamic lift at very high speed due to airflow over their bodies, are a marginal case.

Fixed-wing

NASA test aircraft



A size comparison of some of the largest fixed-wing aircraft. The Airbus A380-800 (largest airliner), the Boeing 747-8, the Antonov An-225 (aircraft with the greatest payload) and the Hughes H-4 "Spruce Goose" (aircraft with greatest wingspan).

Airplanes or *aeroplanes* are technically called *fixed-wing aircraft*.

The forerunner of the fixed-wing aircraft is the kite. Whereas a fixed-wing aircraft relies on its forward speed to create airflow over the wings, a kite is tethered to the ground and relies on the wind blowing over its wings to provide lift. Kites were the first kind of aircraft to fly, and were invented in China around 500 BC. Much aerodynamic research was done with kites before test aircraft, wind tunnels and computer modelling programs became available.

The first heavier-than-air craft capable of controlled free flight were gliders. A glider designed by Cayley carried out the first true manned, controlled flight in 1853.

Besides the method of propulsion, fixed-wing aircraft are generally characterized by their wing configuration. The most important wing characteristics are:

- Number of wings – Monoplane, biplane, etc.
- Wing support – Braced or cantilever, rigid or flexible.
- Wing planform – including aspect ratio, angle of sweep and any variations along the span (including the important class of delta wings).
- Location of the horizontal stabilizer, if any.
- Dihedral angle – positive, zero or negative (anhedral).

A variable geometry aircraft can change its wing configuration during flight.

A *flying wing* has no fuselage, though it may have small blisters or pods. The opposite of this is a *lifting body* which has no wings, though it may have small stabilising and control surfaces.

Most fixed-wing aircraft feature a tail unit or empennage incorporating vertical, and often horizontal, stabilising surfaces.

Seaplanes are aircraft that land on water, and they fit into two broad classes: Flying boats are supported on the water by their fuselage. A float plane's fuselage remains clear of the water at all times, the aircraft being supported by two or more floats attached to the fuselage and/or wings. Some examples of both flying boats and float planes are amphibious, being able to take off from and alight on both land and water.

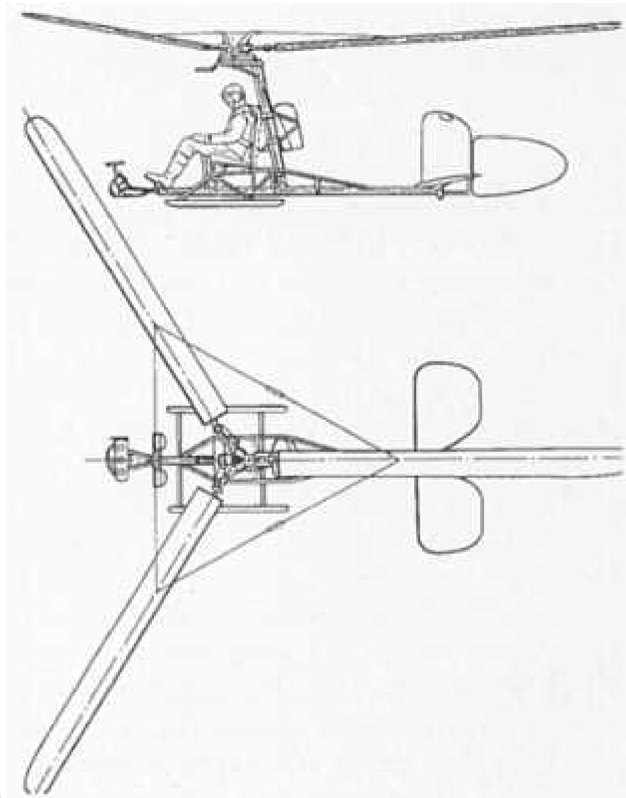
Some people consider wing-in-ground-effect vehicles to be fixed-wing aircraft, others do not. These craft "fly" close to the surface of the ground or water. An example is the Russian ekranoplan (nicknamed the "Caspian Sea Monster"). Man-powered aircraft also rely on ground effect to remain airborne, but this is only because they are so underpowered—the airframe is theoretically capable of flying much higher.

Rotorcraft

Mil Mi-26, the world's largest production helicopter.

Rotorcraft, or rotary-wing aircraft, use a spinning rotor with aerofoil section blades (a *rotary wing*) to provide lift. Types include helicopters, autogyros and various hybrids such as gyrodynes and compound rotorcraft.

Helicopters have powered rotors. The rotor is driven (directly or indirectly) by an engine and pushes air downwards to create lift. By tilting the rotor forwards, the downwards flow is tilted backwards, producing thrust for forward flight.



US-Recognition Manual (very likely copy of German drawing).

Autogyros or *gyroplanes* have unpowered rotors, with a separate power plant to provide thrust. The rotor is tilted backwards. As the autogyro moves forward, air blows upwards across the rotor, making it spin.(cf. Autorotation) This spinning dramatically increases the speed of airflow over the rotor, to provide lift. Juan de la Cierva (a Spanish civil engineer) used the product name *autogiro*, and Bensen used *gyrocopter*. *Rotor kites*, such as the Focke Achgelis Fa 330 are unpowered autogyros, which must be towed by a tether to give them forward ground speed or else be tether-anchored to a static anchor in a high-wind situation for kited flight.

Gyrodynes are a form of helicopter, where forward thrust is obtained from a separate propulsion device rather than from tilting the rotor. The definition of a 'gyrodyne' has changed over the years, sometimes including equivalent autogyro designs. The *Heliplane* is a similar idea.

Compound rotorcraft have wings which provide some or all of the lift in forward flight. Compound helicopters and compound autogyros have been built, and some forms of gyroplane may be referred to as compound gyroplanes. They are nowadays classified as *powered lift* types and not as rotorcraft. *Tiltrotor* aircraft (such as the V-22 Osprey) have their rotors horizontal for vertical flight, and pivot the rotors vertically like a propeller for forward flight. The *Coleopter* had a cylindrical wing forming a duct around the rotor. On the ground it sat on its tail, and took off and landed vertically like a helicopter. The whole aircraft would then have tilted forward to fly as a propeller-driven fixed-wing aircraft using the duct as a wing (though this transition was never achieved in practice.)

Some rotorcraft have reaction-powered rotors with gas jets at the tips, but most have one or more lift rotors powered from engine-driven shafts.

Other methods of lift

X24B lifting body, specialized glider

- A *lifting body* is the opposite of a flying wing. In this configuration the aircraft body is shaped to produce lift. If there are any wings, they are too small to provide significant lift and are used only for stability and control. Lifting bodies are not efficient: they suffer from high drag, and must also travel at high speed to generate enough lift to fly. Many of the research prototypes, such as the Martin-Marietta X-24, which led up to the Space Shuttle were lifting bodies (though the shuttle itself is not), and some supersonic missiles obtain lift from the airflow over a tubular body. The flat bodies of recent jet fighters also produce lift, as in the F-14 Tomcat's "pancake".
- *Powered lift* types rely on engine-derived lift for vertical takeoff and landing (VTOL). Most types transition to fixed-wing lift for horizontal flight. Classes of powered lift types include VTOL jet aircraft (such as the Harrier jump-jet) and tiltrotors (such as the V-22 Osprey), among others. A few examples rely entirely on engine thrust to provide lift throughout the whole flight. There are few practical applications. Experimental designs have been built for personal fan-lift

hover platforms and jetpacks or for VTOL research (for example the flying bedstead).

- The *Flettner airplane* has a spinning cylinder in place of a wing, relying on the Magnus effect to create lift.
- The *FanWing* is a recent innovation with some similarities to the Flettner rotor design. It uses a fixed wing with a cylindrical fan mounted spanwise just above. As the fan spins, it creates an airflow backwards over the upper surface of the wing, creating lift. The FanWing is (2010) in development in the United Kingdom.

Propulsion

Unpowered

Gliders

Heavier-than-air unpowered aircraft such as gliders (i.e. sailplanes), hang gliders and paragliders, and other gliders usually do not employ propulsion once airborne. Take-off may be by launching forwards and downwards from a high location, or by pulling into the air on a tow-line, by a ground-based winch or vehicle, or by a powered "tug" aircraft. For a glider to maintain its forward air speed and lift, it must descend in relation to the air (but not necessarily in relation to the ground). Some gliders can 'soar'- gain height from updrafts such as thermal currents. The first practical, controllable example was designed and built by the British scientist and pioneer George Cayley, who many recognise as the first aeronautical engineer.

Balloons

Balloons drift with the wind, though normally the pilot can control the altitude, either by heating the air or by releasing ballast, giving some directional control (since the wind direction changes with altitude). A wing-shaped hybrid balloon can glide directionally when rising or falling; but a spherically shaped balloon does not have such directional control.

Kites

Kites are aircraft that are tethered to the ground or other object (fixed or mobile) that maintains tension in the tether or kite line; they rely on virtual or real wind blowing over and under them to generate lift and drag. Kytoons are balloon kites that are shaped and tethered to obtain kiting deflections, and can be lighter-than-air, neutrally buoyant, or heavier-than air.

Powered

Propeller

A turboprop-engined DeHavilland Twin Otter adapted as a floatplane

A propeller or airscrew comprises a set of small, wing-like aerofoils set around a central hub which spins on an axis aligned in the direction of travel. Spinning the propeller creates aerodynamic lift, or *thrust*, in a forward direction.

A *tractor* design mounts the propeller in front of the power source, while a *pusher* design mounts it behind. Although the pusher design allows cleaner airflow over the wing, tractor configuration is more common because it allows cleaner airflow to the propeller and provides a better weight distribution.

A *contra-prop* arrangement has a second propeller close behind the first one on the same axis, which rotates in the opposite direction.

A variation on the propeller is to use many broad blades to create a fan. Such fans are traditionally surrounded by a ring-shaped fairing or duct, as *ducted fans*.

Many kinds of power plant have been used to drive propellers.

The earliest designs used man power to give dirigible balloons some degree of control, and go back to Jean-Pierre Blanchard in 1784. Attempts to achieve heavier-than-air man-powered flight did not succeed fully until Paul MacCready's Gossamer Condor in 1977.

Gossamer Albatross, a human-powered aircraft

The first powered flight was made in a steam-powered dirigible by Henri Giffard in 1852. Attempts to marry a practical lightweight steam engine to a practical fixed-wing airframe did not succeed until much later, by which time the internal combustion engine was already dominant.

From the first controlled powered fixed-wing aircraft flight by the Wright brothers until World War II, propellers turned by the internal combustion piston engine were virtually the only type of propulsion system in use. The piston engine is still used in the majority of smaller aircraft produced, since it is efficient at the lower altitudes and slower speeds suited to propellers.

Turbine engines need not be used as jets (see below), but may be geared to drive a propeller in the form of a turboprop. Modern helicopters also typically use turbine engines to power the rotor. Turbines provide more power for less weight than piston engines, and are better suited to small-to-medium size aircraft or larger, slow-flying types. Some turboprop designs (see below) mount the propeller directly on an engine turbine shaft, and are called propfans.

Since the 1940s, propellers and propfans with swept tips or curved "scimitar-shaped" blades have been studied for use in high-speed applications so as to delay the onset of shockwaves, in similar manner to wing sweepback, where the blade tips approach the speed of sound. The Airbus A400M turboprop transport aircraft is expected to provide the first production example: note that it is not a propfan because the propellers are not mounted direct on the engine shaft but are driven through reduction gearing.

Other less common power sources include:

- Electric motors, often linked to solar panels to create a solar-powered aircraft.
- Rubber bands, wound many times to store energy, are mostly used for flying models.

Jet

Airbreathing jet engines provide thrust by taking in air, burning it with fuel in a combustion chamber, and accelerating the exhaust rearwards so that it ejects at high speed. The reaction against this acceleration provides the engine thrust.

A jet-engined Boeing 777 taking off

Jet engines can provide much higher thrust than propellers, and are naturally efficient at higher altitudes, being able to operate above 40,000 ft (12,000 m). They are also much more fuel-efficient at normal flight speeds than rockets. Consequently, nearly all high-speed and high-altitude aircraft use jet engines.

The early turbojet and modern turbofan use a spinning turbine to create airflow for takeoff and to provide thrust. Many, mostly in military aviation, use afterburners which inject extra fuel into the exhaust.

Use of a turbine is not absolutely necessary: other designs include the crude pulse jet, high-speed ramjet and the still-experimental supersonic-combustion ramjet or scramjet. These designs require an existing airflow to work and cannot work when stationary, so they must be launched by a catapult or rocket booster, or dropped from a mother ship.

The bypass turbofan engines of the Lockheed SR-71 were a hybrid design – the aircraft took off and landed in jet turbine configuration, and for high-speed flight the afterburner was lit and the turbine bypassed, to create a ramjet.

The motorjet was a very early design which used a piston engine in place of the combustion chamber, similar to a turbocharged piston engine except that the thrust is derived from the turbine instead of the crankshaft. It was soon superseded by the turbojet and remained a curiosity.

Helicopters

HAL Dhruv, a multi-role utility helicopter.

The rotor of a helicopter, may, like a propeller, be powered by a variety of methods such as an internal-combustion engine or jet turbine. Tip jets, fed by gases passing along hollow rotor blades from a centrally mounted engine, have been experimented with. Attempts have even been made to mount engines directly on the rotor tips.

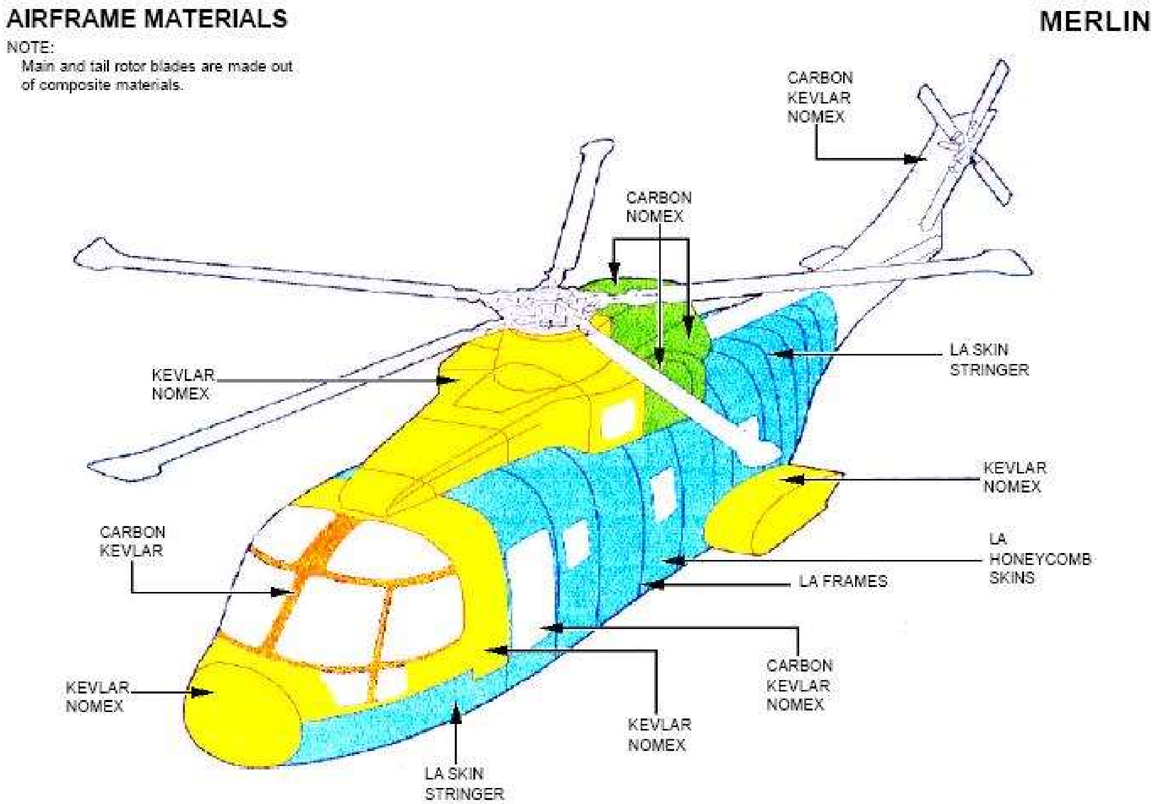
Helicopters obtain forward propulsion by angling the rotor disc so that a proportion of its lift is directed forwards to provide thrust.

Other methods of propulsion

- *Rocket-powered aircraft* have occasionally been experimented with, and the Messerschmitt *Komet* fighter even saw action in the Second World War. Since then they have been restricted to rather specialised niches, such as the Bell X-1 which broke the sound barrier or the North American X-15 which traveled up into space where no oxygen is available for combustion (rockets carry their own oxidant). Rockets have more often been used as a supplement to the main powerplant, typically to assist takeoff of heavily loaded aircraft, but also in a few experimental designs such as the Saunders-Roe SR.53 to provide a high-speed dash capability.
- The flapping-wing *ornithopter* is a category of its own. These designs may have potential, but no practical device has been created beyond research prototypes, simple toys, and a model hawk used to freeze prey into stillness so that it can be captured.

General construction

Airframe



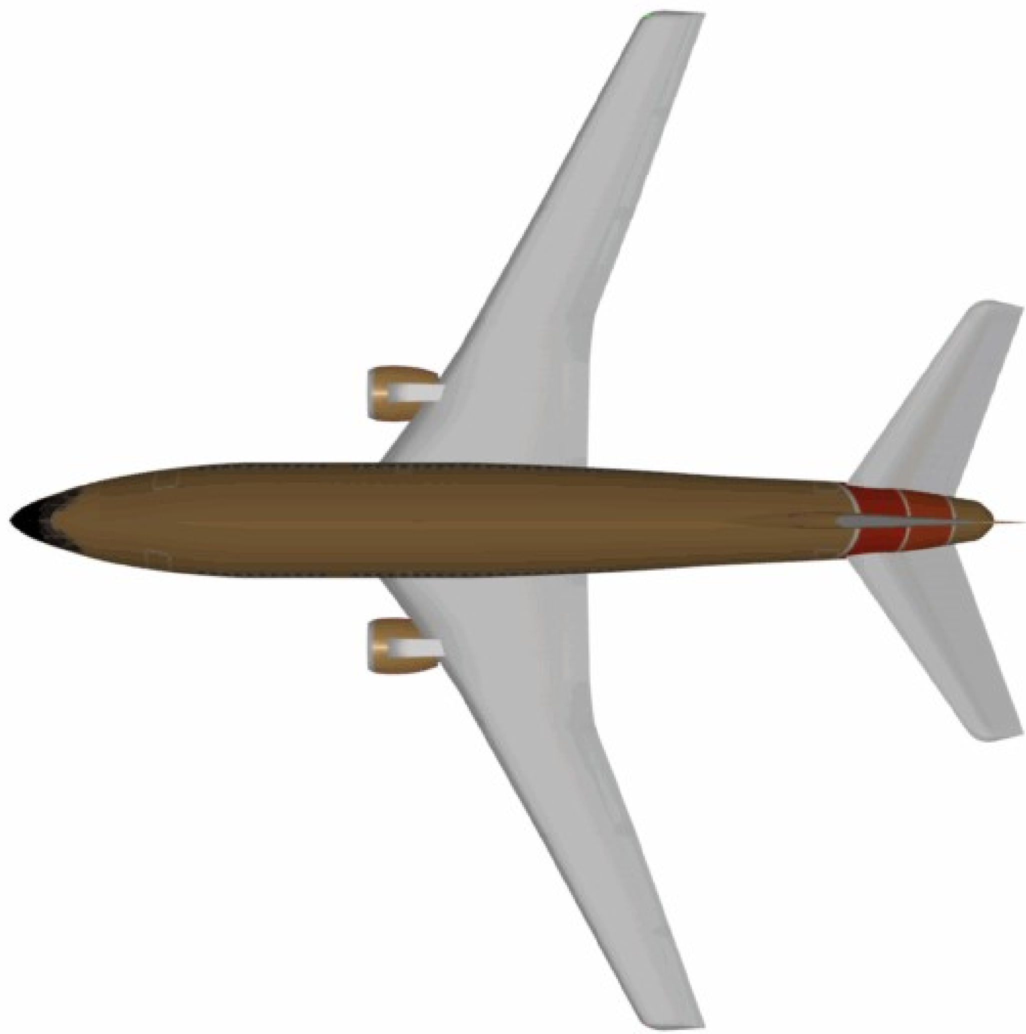
Airframe diagram for a AgustaWestland AW101 helicopter

The **airframe** of an **aircraft** is its mechanical structure, which is typically considered to exclude the propulsion system. Airframe design is a field of engineering that combines aerodynamics, materials technology and manufacturing methods to achieve balances of performance, reliability and cost.

Undercarriage

The **undercarriage** or **landing gear** in aviation, is the structure that supports an **aircraft** on the ground and allows it to taxi, takeoff and land. Typically wheels are used, but skids, floats or a combination of these and other elements can be deployed, depending on the surface.

Fuselage



Fuselage of a Boeing 737 shown in brown

The **fuselage** (from the French *fuselé* "spindle-shaped") is an **aircraft**'s main body section that holds crew and passengers or cargo. In single-engine aircraft it will usually contain an engine, although in some amphibious aircraft the single engine is mounted on a pylon attached to the fuselage which in turn is used as a floating hull. The fuselage also serves to position control and stabilization surfaces in specific relationships to lifting surfaces, required for aircraft stability and maneuverability.

Wing configuration

Many different styles and arrangements of wings have and are used on heavier-than-air aircraft, and some lighter than air aircraft also have wings. The common wing configuration types have included monoplanes which has one wing each side, biplane which have 4 wings.

Wings also vary greatly in **planform** which is their shape viewed from above. Wings can be swept backwards or be delta wings and can have many other shapes.

Aircraft engine

An **aircraft engine** is a power source for an **aircraft**. Aircraft engines are almost always either lightweight piston engines or gas turbines. Powered aircraft have one or more engines.

Propellant tanks

Propellant (a chemical carried on board that is used to power the aircraft's flight), is usually a fuel and is kept in tanks around the vehicle. Most aircraft store the fuel predominantly in the wings, but may have additional fuel tanks elsewhere.

Flight control surfaces

Aircraft **flight control surfaces** allow a pilot to adjust and control the aircraft's flight attitude.

Development of an effective set of flight controls was a critical advance in the development of aircraft. Early efforts at fixed-wing aircraft design succeeded in generating sufficient lift to get the aircraft off the ground, but once aloft, the aircraft proved uncontrollable, often with disastrous results. The development of effective flight controls is what allowed stable flight.

Empennage

Empennage

The empennage of a Boeing 747-200

Empennage is an aviation term used to describe the tail section of an **aircraft**. The empennage is also known as the **tail** or **tail assembly**; all three terms may be used interchangeably.

The empennage gives stability to the aircraft and controls the flight dynamics of pitch and yaw.

Flight deck

Airbus A380 cockpit. Most Airbus cockpits are computerised glass cockpits featuring fly-by-wire technology. The control column has been replaced with an electronic sidestick.

Swiss HB-IZX Saab 2000 cockpit

Robin DR400/500

1936 De Havilland Hornet Moth cockpit

A **cockpit** or **flight deck** is the area, usually near the front of an **aircraft**, from which a pilot controls the aircraft. Most modern cockpits are enclosed, except on some small aircraft, and cockpits on large airliners are also physically separated from the cabin. From the cockpit an aircraft is controlled on the ground and in the air.

Cockpit as a term for the pilot's compartment in an **aircraft** first appeared in 1914. From about 1935 cockpit also came to be used informally to refer to the driver's seat of a car, especially a high performance one, and this is official terminology in Formula One. The term is most likely related to the sailing term for the coxswain's station in a Royal Navy ship, and later the location of the ship's rudder controls.

The cockpit of an aircraft contains flight instruments on an instrument panel, and the controls which enable the pilot to fly the aircraft. In most airliners, a door separates the cockpit from the passenger compartment. After the September 11, 2001 terrorist attacks, all major airlines fortified the cockpit against access by hijackers.

On an airliner, the cockpit is usually referred to as the flight deck. This term derives from its use by the RAF for the separate, upper platform where the pilot and co-pilot sat in large flying boats.

Cabin

An **aircraft cabin** is the section of an **aircraft** in which any passengers travel, often just called the cabin. At cruising altitudes, if the surrounding atmosphere is too thin to breathe without an oxygen mask, cabin pressurization adapts the cabin to atmospheric pressures.

Performance of aircraft

Flight envelope

In aerodynamics, the **flight envelope** or **performance envelope** of an **aircraft** refers to the capabilities of a design in terms of airspeed and load factor or altitude. The term is somewhat loosely applied, and can also refer to other measurements such as maneuverability. When a plane is pushed, for instance by diving it at high speeds, it is said to be flown "outside the envelope", something considered rather dangerous.

Flight envelope is one of a number of related terms that are all used in a similar fashion. It is perhaps the most common term because it is the oldest, first being used in the early days of test flying. It is closely related to more modern terms known as **extra power** and a **doghouse plot** which are different ways of describing a flight envelope.

Aircraft range

The Boeing 777-200LR is the longest-range commercial airliner, capable of flights of more than halfway around the world.

The maximal total **range** is the distance an **aircraft** can fly between takeoff and landing, as limited by fuel capacity in powered aircraft, or cross-country speed and environmental conditions in unpowered aircraft.

Ferry range means the maximum range the aircraft can fly. This usually means maximum fuel load, optionally with extra fuel tanks and minimum equipment. It refers to transport of aircraft for use on remote location.

Combat range is the maximum range the aircraft can fly when carrying ordnance.

Combat radius is a related measure based on the maximum distance a warplane can travel from its base of operations, accomplish some objective, and return to its original airfield with minimal reserves.

The fuel time limit for powered aircraft is fixed by the fuel load and rate of consumption. When all fuel is consumed, the engines stop and the aircraft will lose its propulsion. For unpowered aircraft, the maximum flight time is variable, limited by available daylight hours, weather conditions, and pilot endurance.

The range can be seen as the cross-country ground speed multiplied by the maximum time in the air.

Aircraft flight dynamics

Flight dynamics is the science of **air** vehicle orientation and control in three dimensions. The three critical flight dynamics parameters are the angles of rotation in three dimensions about the vehicle's center of mass, known as *pitch*, *roll* and *yaw* (quite different from their use as Tait-Bryan angles).

Aerospace engineers develop control systems for a vehicle's orientation (attitude) about its center of mass. The control systems include actuators, which exert forces in various directions, and generate rotational forces or moments about the aerodynamic center of the aircraft, and thus rotate the aircraft in pitch, roll, or yaw. For example, a pitching moment is a vertical force applied at a distance forward or aft from the aerodynamic center of the **aircraft**, causing the aircraft to pitch up or down.

Roll, pitch and yaw refer to rotations about the respective axes starting from a defined equilibrium state. The equilibrium roll angle is known as wings level or zero bank angle, equivalent to a level heeling angle on a ship. Yaw is known as "heading". The equilibrium pitch angle in submarine and airship parlance is known as "trim", but in aircraft, this usually refers to angle of attack, rather than orientation. However, common usage ignores this distinction between equilibrium and dynamic cases.

The most common aeronautical convention defines the roll as acting about the longitudinal axis, positive with the starboard (right) wing down. The yaw is about the vertical body axis, positive with the nose to starboard. Pitch is about an axis perpendicular to the longitudinal plane of symmetry, positive nose up.

A fixed-wing aircraft increases or decreases the lift generated by the wings when it pitches nose up or down by increasing or decreasing the angle of attack (AOA). The roll angle is also known as bank angle on a fixed wing aircraft, which usually "banks" to change the horizontal direction of flight. An aircraft is usually streamlined from nose to tail to reduce drag making it typically advantageous to keep the sideslip angle near zero, though there are instances when an aircraft may be deliberately "sideslipped" for example a slip in a fixed wing aircraft.

Areas of use

The major distinction in aircraft types is between military aircraft, which includes not just combat types but many types of supporting aircraft, and civil aircraft, which include all non-military types.

Saab Gripen, a Swedish multi-role fighter aircraft.

Military

A **military aircraft** is any fixed-wing or rotary-wing aircraft that is operated by a legal or insurrectionary armed service of any type. Military aircraft can be either combat or non-combat:

- Combat aircraft are aircraft designed to destroy enemy equipment using its own armament.
- Non-Combat aircraft are aircraft not designed for combat as their primary function, but may carry weapons for self-defense. Mainly operating in support roles.

Combat aircraft divide broadly into fighters and bombers, with several in-between types such as fighter-bombers and ground-attack aircraft (including attack helicopters).

Other supporting roles are carried out by specialist patrol, search and rescue, reconnaissance, observation, transport, training and Tanker aircraft among others.

Many civil aircraft, both fixed-wing and rotary, have been produced in separate models for military use, such as the civil Douglas DC-3 airliner, which became the military C-47/C-53/R4D transport in the U.S. military and the "Dakota" in the UK and the

Commonwealth. Even the small fabric-covered two-seater Piper J3 Cub had a military version, the L-4 liaison, observation and trainer aircraft. Gliders and balloons have also been used as military aircraft; for example, balloons were used for observation during the American Civil War and World War I, and military gliders were used during World War II to land troops.

The *Premium Class* cabin of Jet Airways Boeing 777.

Eurocopter EC 145 of the Rega air rescue service.

Civil

Civil aircraft divide into *commercial* and *general* types, however there are some overlaps.

Commercial

Commercial aircraft include types designed for scheduled and charter airline flights, carrying both passengers and cargo. The larger passenger-carrying types are often referred to as airliners, the largest of which are wide-body aircraft. Some of the smaller types are also used in general aviation, and some of the larger types are used as VIP aircraft.

General aviation

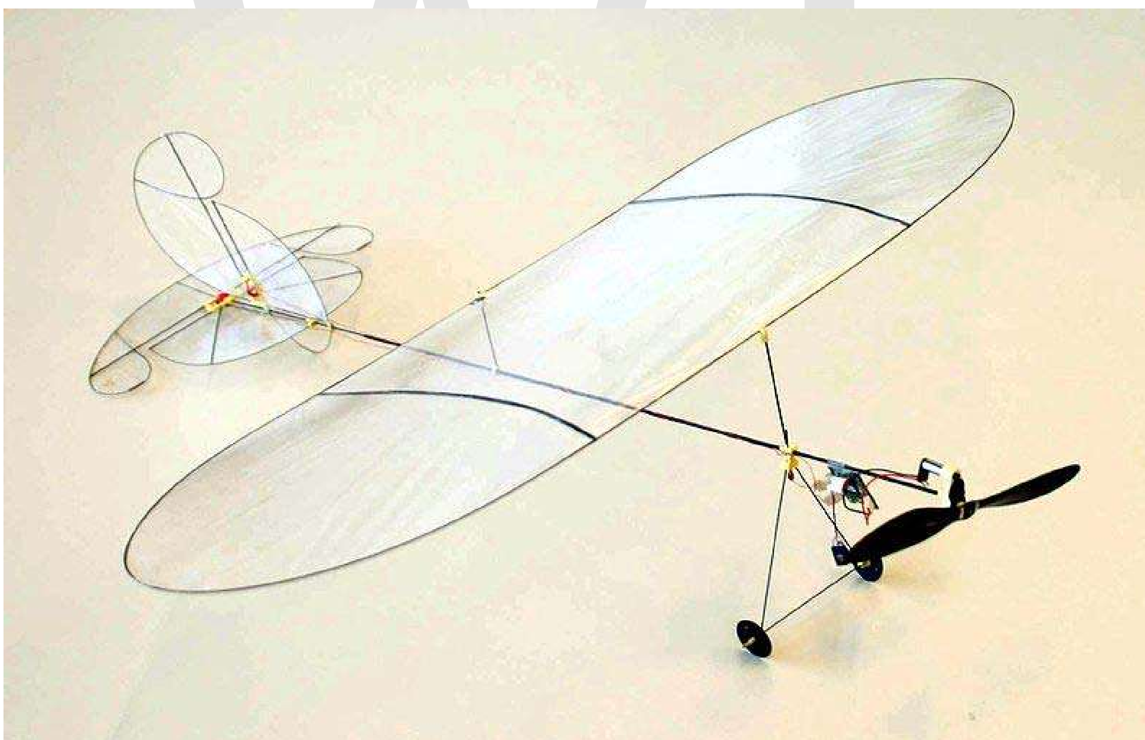
General aviation is a catch-all covering other kinds of private and commercial use, and involving a wide range of aircraft types such as business jets (bizjets), trainers, homebuilt, aerobatic types, racers, gliders, warbirds, firefighters, medical transports, and cargo transports, to name a few. The vast majority of aircraft today are general aviation types.

Within general aviation, there is a further distinction between private aviation (where the pilot is not paid for time or expenses) and commercial aviation (where the pilot is paid by a client or employer). The aircraft used in private aviation are usually light passenger, business, or recreational types, and are usually owned or rented by the pilot. The same types may also be used for a wide range of commercial tasks, such as flight training, pipeline surveying, passenger and freight transport, policing, crop dusting, and medical evacuations. However the larger, more complex aircraft are more likely to be found in the commercial sector.

For example, piston-powered propeller aircraft (single-engine or twin-engine) are common for both private and commercial general aviation, but for aircraft such as turboprops like the Beechcraft King Air and helicopters like the Bell JetRanger, there are fewer private owners than commercial owners. Conventional business jets are most often flown by paid pilots, whereas the new generation of smaller jets are being produced for private pilots.

Experimental

Experimental aircraft are one-off specials, built to explore some aspect of aircraft design and with no other useful purpose. The Bell X-1 rocket plane, which first broke the sound barrier in level flight, is a famous example.



A model aircraft, weighing six grams.

Boeing B-17E in flight. The Allies of World War II lost 160,000 airmen and 33,700 planes during the air war over Europe.

The formal designation of "experimental aircraft" also includes other types which are "not certified for commercial applications", including one-off modifications of existing aircraft such as the modified Boeing 747 which NASA uses to ferry the space shuttle from landing site to launch site, and aircraft homebuilt by amateurs for their own personal use.

Model

A model aircraft is a small unmanned type made to fly for fun, for static display, for aerodynamic research (cf Reynolds number) or for other purposes. A scale model is a replica of some larger design.

Aircraft manufacture

Manufacturers and types

Within any general category, aircraft are usually listed according to manufacturer and production type.

Aircraft design

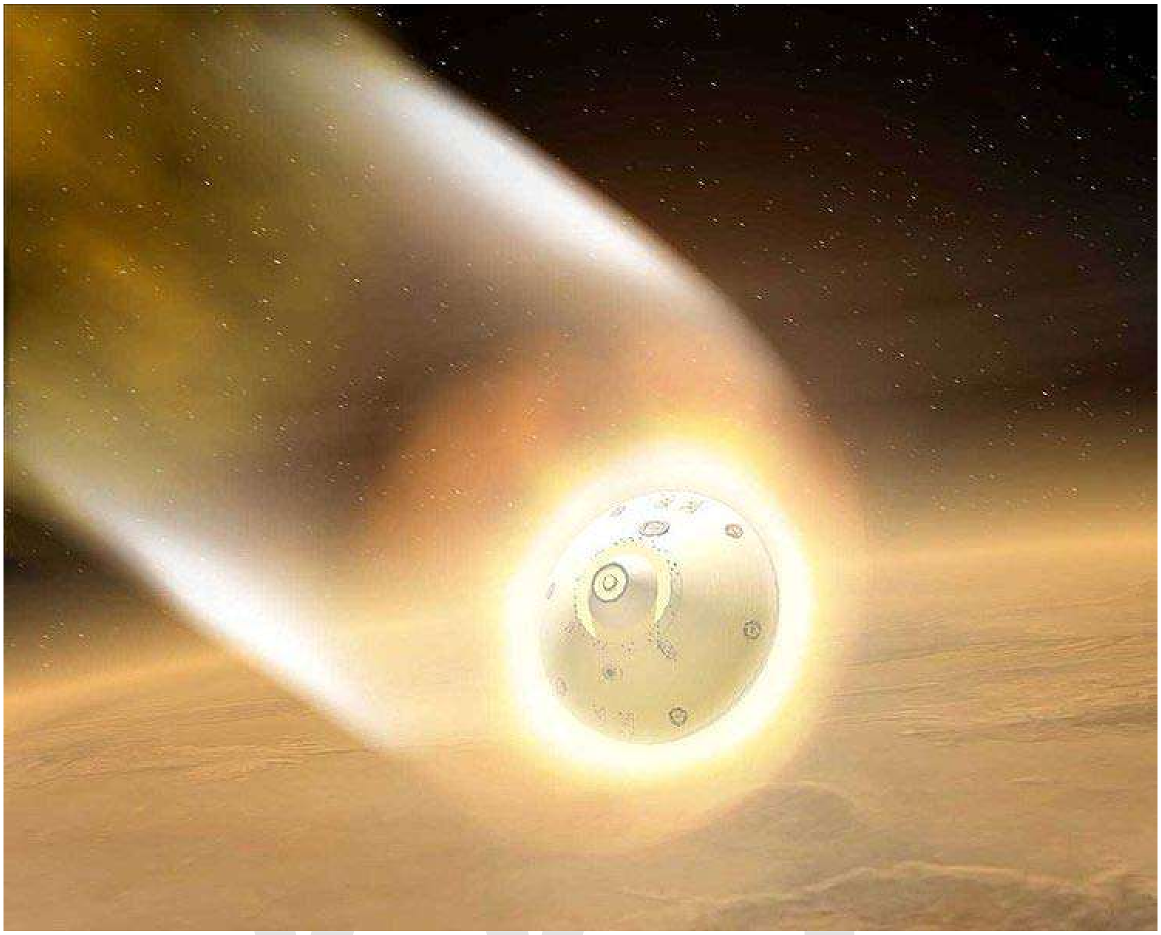
The **process** of **aircraft design** has evolved during the last century. The early pioneers mainly used experimental designs with trial and error being used to determine what would work. The modern process is now more rigorous and risk averse as the cost of modern aircraft is high and the manufacturing process and resulting airframes are expected to be free of error and weakness

Chapter- 2

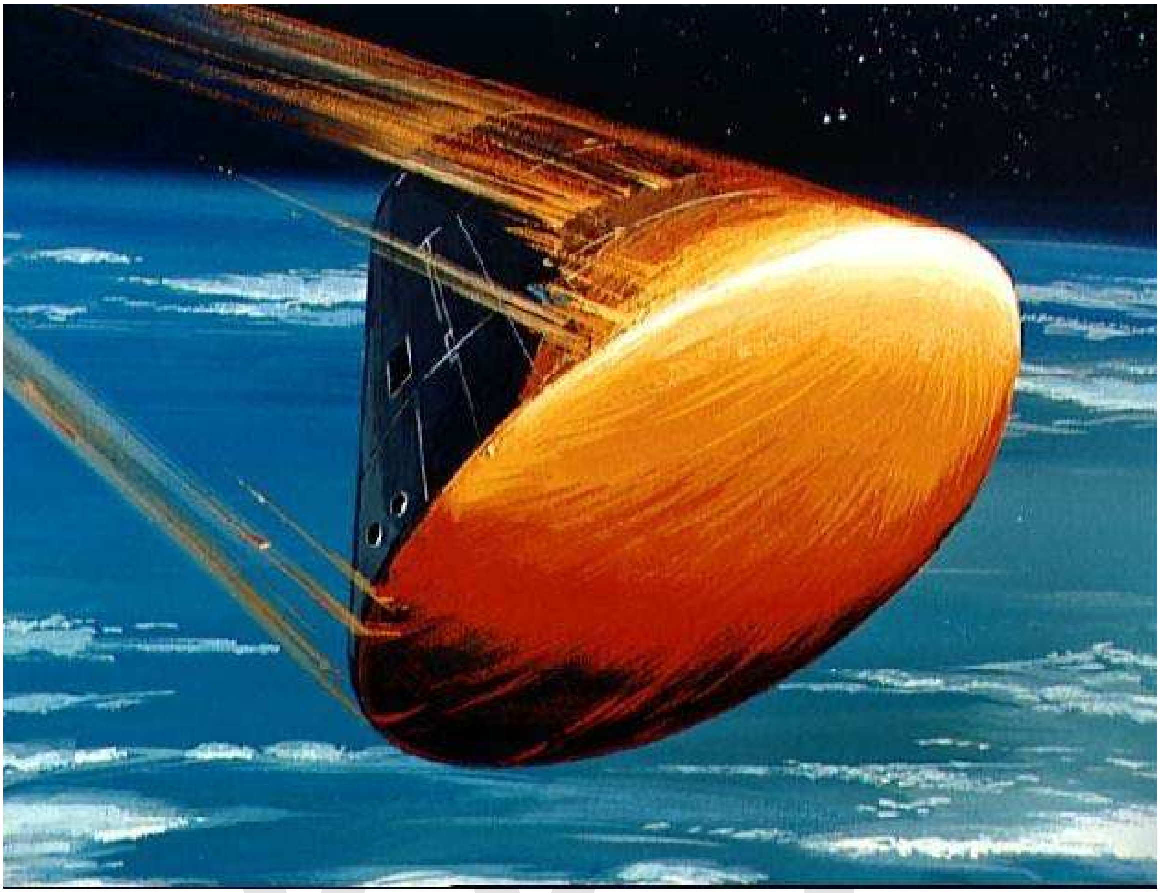
Atmospheric Entry

Atmospheric entry is the movement of human-made or natural objects as they enter the atmosphere of a celestial body from outer space—in the case of Earth from an altitude above the Kármán Line, (100 km).

Vehicles that undergo this process include ones returning from orbit (spacecraft) and ones on exo-orbital (suborbital) trajectories (ICBM reentry vehicles, some spacecraft). Typically this process requires special methods to protect against aerodynamic heating. Various advanced technologies have been developed to enable atmospheric reentry and flight at extreme velocities.



Mars Exploration Rover (MER) aeroshell, artistic rendition.



Apollo Command Module flying at a high angle of attack for lifting entry, artistic rendition.

Apollo 13 Objects believed to be Service Module and Lunar Module reentering and breaking up

History

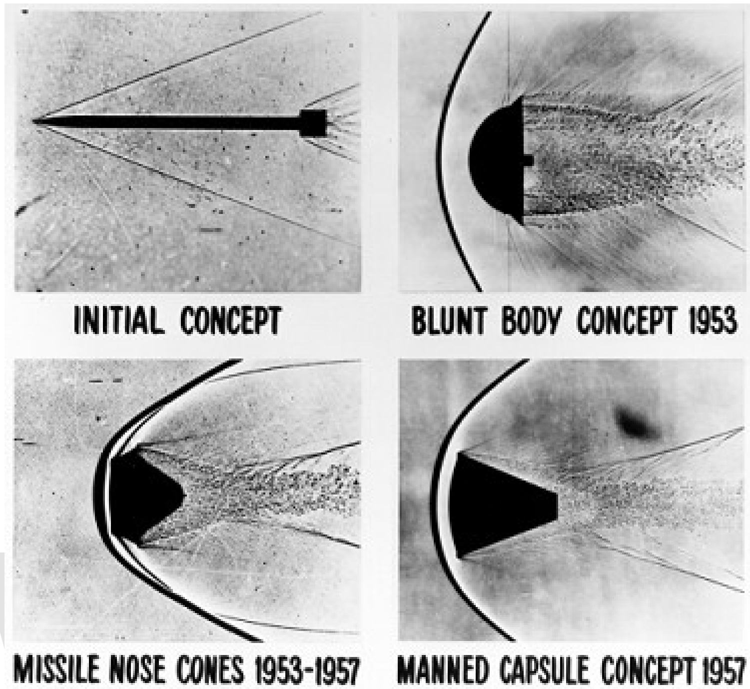
The concept of the ablative heat shield was described as early as 1920 by Robert Goddard: "In the case of meteors, which enter the atmosphere with speeds as high as 30 miles per second, the interior of the meteors remains cold, and the erosion is due, to a large extent, to chipping or cracking of the suddenly heated surface. For this reason, if the outer surface of the apparatus were to consist of layers of a very infusible hard substance with layers of a poor heat conductor between, the surface would not be eroded to any considerable extent, especially as the velocity of the apparatus would not be nearly so great as that of the average meteor."

Practical development of reentry systems began as the range and reentry velocity of ballistic missiles increased. For early short-range missiles, like the V-2, stabilization and aerodynamic stress were important issues (many V-2s broke apart during reentry), but heating was not a serious problem. Medium-range missiles like the Soviet R-5, with a 1200 km range, required ceramic composite heat shielding on separable reentry vehicles (it was no longer possible for the entire rocket structure to survive reentry). The first ICBMs, with ranges of 8000 to 12,000 km, were only possible with the development of modern ablative heat shields and blunt-shaped vehicles. In the USA, this technology was pioneered by H. Julian Allen at Ames Research. In the Soviet Union, Yuri A. Dunaev developed similar technology at the Leningrad Physical-Technical Institute.

Terminology, definitions and jargon

Over the decades since the 1950s, a rich technical jargon has grown around the engineering of vehicles designed to enter planetary atmospheres.

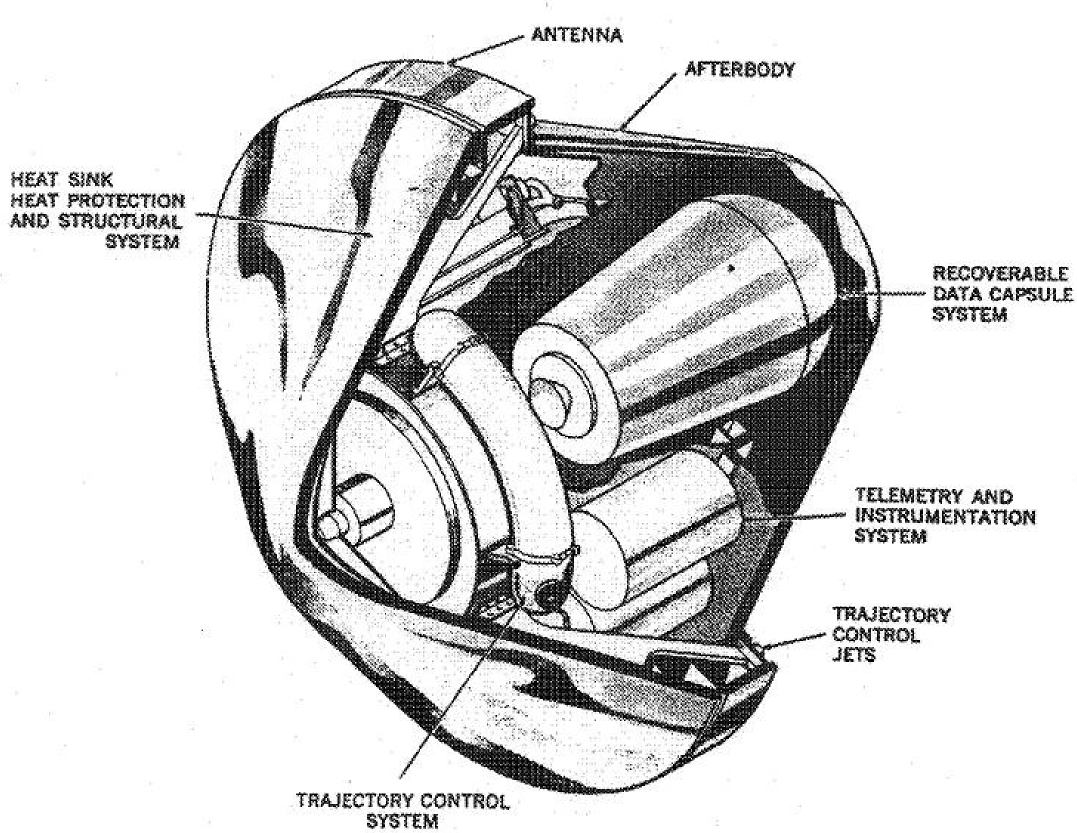
Blunt body entry vehicles



Various reentry shapes (NASA) using shadowgraphs to show high velocity flow

These four shadowgraph images represent early reentry-vehicle concepts. A shadowgraph is a process that makes visible the disturbances that occur in a fluid flow at high velocity, in which light passing through a flowing fluid is refracted by the density gradients in the fluid resulting in bright and dark areas on a screen placed behind the fluid.

In the United States, H. Julian Allen and A. J. Eggers, Jr. of the National Advisory Committee for Aeronautics (NACA) made the counterintuitive discovery in 1951 that a blunt shape (high drag) made the most effective heat shield. From simple engineering principles, Allen and Eggers showed that the heat load experienced by an entry vehicle was inversely proportional to the drag coefficient, i.e. the greater the drag, the less the heat load. Through making the reentry vehicle blunt, air can't "get out of the way" quickly enough, and acts as an air cushion to push the shock wave and heated shock layer forward (away from the vehicle). Since most of the hot gases are no longer in direct contact with the vehicle, the heat energy would stay in the shocked gas and simply move around the vehicle to later dissipate into the atmosphere.



Prototype of the Mk-2 Reentry Vehicle (RV), based on blunt body theory

The Allen and Eggers discovery, though initially treated as a military secret, was eventually published in 1958.

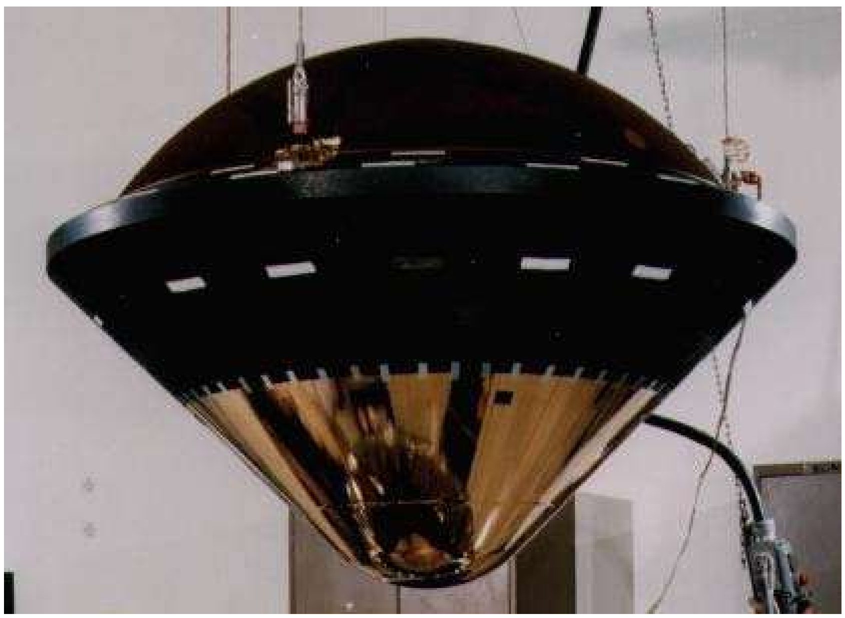
Entry vehicle shapes

There are several basic shapes used in designing entry vehicles:

Sphere or spherical section

The simplest axisymmetric shape is the sphere or spherical section. This can either be a complete sphere or a spherical section forebody with a converging conical afterbody. The aerodynamics of a sphere or spherical section are easy to model analytically using Newtonian impact theory. Likewise, the spherical section's heat flux can be accurately modeled with the Fay-Riddell equation. The static stability of a spherical section is assured if the vehicle's center of mass is upstream from the center of curvature (dynamic stability is more problematic). Pure spheres have no lift. However, by flying at an angle of attack, a spherical section has modest aerodynamic lift thus providing some cross-range capability and widening its entry corridor. In the late 1950s and early 1960s, high-speed computers were not yet available and computational fluid dynamics was still embryonic. Because the spherical section was amenable to closed-form analysis, that geometry became the default for conservative design. Consequently, manned capsules of that era were based upon the spherical section. Pure spherical entry vehicles were used in the early Soviet Vostok and in Soviet Mars and Venera descent vehicles. The Apollo Command/Service Module used a spherical section forebody heatshield with a converging conical afterbody. It flew a lifting entry with a hypersonic trim angle of attack of −27° (0° is blunt-end first) to yield an average L/D (lift-to-drag ratio) of 0.368. This angle of attack was achieved by precisely offsetting the vehicle's center of mass from its axis of symmetry. Other examples of the spherical section geometry in manned capsules are Soyuz/Zond, Gemini and Mercury. Even these small amounts of lift allow trajectories that have very significant effects on peak g-force (reducing g-force from 8-9g for a purely ballistic trajectory to 4-5g) as well as greatly reducing the total reentry heat.

Sphere-cone



Galileo Probe during final assembly

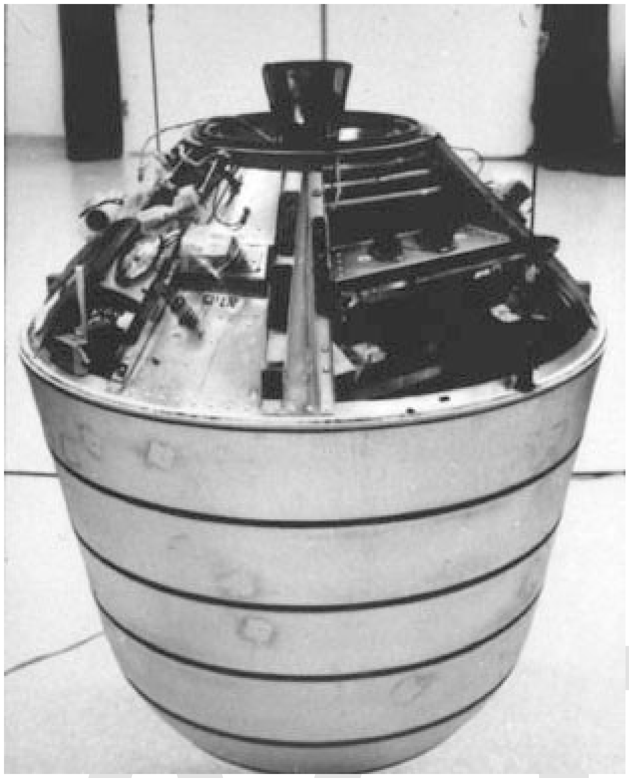
The sphere-cone is a spherical section with a frustum or blunted cone attached. The sphere-cone's dynamic stability is typically better than that of a spherical section. With a sufficiently small half-angle and properly placed center of mass, a sphere-cone can provide aerodynamic stability from Keplerian entry to surface impact. (The "half-angle" is the angle between the cone's axis of rotational symmetry and its outer surface, and thus half the angle made by the cone's surface edges.)

The original American sphere-cone aeroshell was the Mk-2 RV (reentry vehicle), which was developed in 1955 by the General Electric Corp. The Mk-2's design was derived from blunt-body theory and used a radiatively cooled thermal protection system (TPS) based upon a metallic heat shield. The Mk-2 had significant defects as a weapon delivery system, i.e., it loitered too long in the upper atmosphere due to its lower ballistic coefficient and also trailed a stream of vaporized metal making it very visible to radar. These defects made the Mk-2 overly susceptible to anti-ballistic missile (ABM) systems.

Consequently an alternative sphere-cone RV to the Mk-2 was developed by General Electric.

Mk-6 RV, Cold War weapon and ancestor to most of NASA's entry vehicles

This new RV was the Mk-6 which used a non-metallic ablative TPS (nylon phenolic). This new TPS was so effective as a reentry heat shield that significantly reduced bluntness was possible. However, the Mk-6 was a huge RV with an entry mass of 3360 kg, a length of 3.1 meters and a half-angle of 12.5°. Subsequent advances in nuclear weapon and ablative TPS design allowed RVs to become significantly smaller with a further reduced bluntness ratio compared to the Mk-6. Since the 1960s, the sphere-cone has become the preferred geometry for modern ICBM RVs with typical half-angles being between 10° to 11°.



"Discoverer" type reconnaissance satellite film Recovery Vehicle (RV)

Opportunity rover's heat shield lying inverted on the surface of Mars.

Reconnaissance satellite RVs (recovery vehicles) also used a sphere-cone shape and were the first American example of a non-munition entry vehicle (Discoverer-I, launched on 28 February 1959). The sphere-cone was later used for space exploration missions to other celestial bodies or for return from open space; e.g., Stardust probe. Unlike with military RVs, the advantage of the blunt body's lower TPS mass remained with space exploration entry vehicles like the Galileo Probe with a half angle of 45° or the Viking aeroshell with a half angle of 70°. Space exploration sphere-cone entry vehicles have landed on the surface or entered the atmospheres of Mars, Venus, Jupiter and Titan.

Biconic

The biconic is a sphere-cone with an additional frustum attached. The biconic offers a significantly improved L/D ratio. A biconic designed for Mars aerocapture typically has an L/D of approximately 1.0 compared to an L/D of 0.368 for the Apollo-CM. The higher

L/D makes a biconic shape better suited for transporting people to Mars due to the lower peak deceleration. Arguably, the most significant biconic ever flown was the *Advanced Maneuverable Reentry Vehicle* (AMaRV). Four AMaRVs were made by the McDonnell-Douglas Corp. and represented a significant leap in RV sophistication. Three of the AMaRVs were launched by Minuteman-1 ICBMs on 20 December 1979, 8 October 1980 and 4 October 1981. AMaRV had an entry mass of approximately 470 kg, a nose radius of 2.34 cm, a forward frustum half-angle of 10.4°, an inter-frustum radius of 14.6 cm, aft frustum half angle of 6°, and an axial length of 2.079 meters. No accurate diagram or picture of AMaRV has ever appeared in the open literature. However, a schematic sketch of an AMaRV-like vehicle along with trajectory plots showing hairpin turns has been published.

AMaRV's attitude was controlled through a split body flap (also called a "split-windward flap") along with two yaw flaps mounted on the vehicle's sides. Hydraulic actuation was used for controlling the flaps. AMaRV was guided by a fully autonomous navigation system designed for evading anti-ballistic missile (ABM) interception. The McDonnell Douglas DC-X (also a biconic) was essentially a scaled up version of AMaRV. AMaRV and the DC-X also served as the basis for an unsuccessful proposal for what eventually became the Lockheed Martin X-33. Amongst aerospace engineers, AMaRV has achieved legendary status alongside such marvels as the SR-71 Blackbird and the Saturn V Rocket.

Non-axisymmetric shapes

Non-axisymmetric shapes have been used for manned entry vehicles. One example is the winged orbit vehicle that uses a delta wing for maneuvering during descent much like a conventional glider. This approach has been used by the American Space Shuttle and the Soviet Buran. The lifting body is another entry vehicle geometry and was used with the X-23 PRIME (Precision Recovery Including Maneuvering Entry) vehicle.

The FIRST (Fabrication of Inflatable Re-entry Structures for Test) system was an Aerojet proposal for an inflated-spar Rogallo wing made up from Inconel wire cloth impregnated with silicone rubber and silicon carbide dust. FIRST was proposed in both one-man and six man versions, used for emergency escape and reentry of stranded space station crews, and was based on an earlier unmanned test program that resulted in a partially successful reentry flight from space (the launcher nose cone fairing hung up on the material, dragging it too low and fast for the TPS, but otherwise it appears the concept would have worked; even with the fairing dragging it, the test article flew stably on reentry until burn-through).

The proposed MOOSE system would have used a one-man inflatable ballistic capsule as an emergency astronaut entry vehicle. This concept was carried further by the Douglas Paracone project. While these concepts were unusual, the inflated shape on reentry was in fact axisymmetric.

Shock layer gas physics

An approximate rule-of-thumb used by heat shield designers for estimating peak shock layer temperature is to assume the air temperature in kelvins to be equal to the entry speed in meters per second — a mathematical coincidence. For example, a spacecraft entering the atmosphere at 7.8 km/s would experience a peak shock layer temperature of 7800 K. This is unexpected, since the kinetic energy increases with the square of the velocity, and can only occur because the specific heat of the gas increases greatly with temperature (unlike the nearly constant specific heat assumed for solids under ordinary conditions).

At typical reentry temperatures, the air in the shock layer is both ionized and dissociated. This chemical dissociation necessitates various physical models to describe the shock layer's thermal and chemical properties. There are four basic physical models of a gas that are important to aeronautical engineers who design heat shields:

Perfect gas model

Almost all aeronautical engineers are taught the perfect (ideal) gas model during their undergraduate education. Most of the important perfect gas equations along with their corresponding tables and graphs are shown in NACA Report 1135. Excerpts from NACA Report 1135 often appear in the appendices of thermodynamics textbooks and are familiar to most aeronautical engineers who design supersonic aircraft.

The perfect gas theory is elegant and extremely useful for designing aircraft, but assumes the gas is chemically inert. From the standpoint of aircraft design, air can be assumed to be inert for temperatures less than 550 K at one atmosphere pressure. The perfect gas theory begins to break down at 550 K and is not usable at temperatures greater than 2000 K. For temperatures greater than 2000 K, a heat shield designer must use a *real gas model*.

Real (equilibrium) gas model

The real gas equilibrium model is normally taught to aeronautical engineers studying towards a master's degree. Not surprisingly, it is a common error for a bachelor's-level engineer to incorrectly use perfect-gas theory on a hypersonic design. An entry vehicle's pitching moment can be significantly influenced by real-gas effects. Both the Apollo-CM and the Space Shuttle were designed using incorrect pitching moments determined through inaccurate real-gas modeling. The Apollo-CM's trim-angle angle of attack was higher than originally estimated, resulting in a narrower lunar return entry corridor. The actual aerodynamic center of the *Columbia* was upstream from the calculated value due to real-gas effects. On *Columbia*'s maiden flight (STS-1), astronauts John W. Young and Robert Crippen had some anxious moments during reentry when there was concern about losing control of the vehicle.

An equilibrium real-gas model assumes that a gas is chemically reactive, but also assumes all chemical reactions have had time to complete and all components of the gas have the same temperature (this is called *thermodynamic equilibrium*). When air is processed by a shock wave, it is superheated by compression and chemically dissociates through many different reactions (Direct friction upon the reentry object is not the main cause of shock-layer heating. It is caused mainly from isentropic heating of the air molecules within the compression wave. Friction based entropy increases of the molecules within the wave also account for some heating.). The distance from the shock wave to the stagnation point on the entry vehicle's leading edge is called *shock wave stand off*. An approximate rule of thumb for shock wave standoff distance is 0.14 times the nose radius. One can estimate the time of travel for a gas molecule from the shock wave to the stagnation point by assuming a free stream velocity of 7.8 km/s and a nose radius of 1 meter, i.e., time of travel is about 18 microseconds. This is roughly the time required for shock-wave-initiated chemical dissociation to approach chemical equilibrium in a shock layer for a 7.8 km/s entry into air during peak heat flux. Consequently, as air approaches the entry vehicle's stagnation point, the air effectively reaches chemical equilibrium thus enabling an equilibrium model to be usable. For this case, most of the shock layer between the shock wave and leading edge of an entry vehicle is chemically reacting and *not* in a state of equilibrium. The Fay-Riddell equation, which is of extreme importance towards modeling heat flux, owes its validity to the stagnation point being in chemical equilibrium. The time required for the shock layer gas to reach equilibrium is strongly dependent upon the shock layer's pressure. For example, in the case of the Galileo Probe's entry into Jupiter's atmosphere, the shock layer was mostly in equilibrium during peak heat flux due to the very high pressures experienced (this is counterintuitive given the free stream velocity was 39 km/s during peak heat flux).

Determining the thermodynamic state of the stagnation point is more difficult under an equilibrium gas model than a perfect gas model. Under a perfect gas model, the *ratio of specific heats* (also called "isentropic exponent", adiabatic index, "gamma" or "kappa") is assumed to be constant along with the gas constant. For a real gas, the ratio of specific heats can wildly oscillate as a function of temperature. Under a perfect gas model there is an elegant set of equations for determining thermodynamic state along a constant entropy stream line called the *isentropic chain*. For a real gas, the isentropic chain is unusable and a *Mollier diagram* would be used instead for manual calculation. However, graphical solution with a Mollier diagram is now considered obsolete with modern heat shield designers using computer programs based upon a digital lookup table (another form of Mollier diagram) or a chemistry based thermodynamics program. The chemical composition of a gas in equilibrium with fixed pressure and temperature can be determined through the *Gibbs free energy method*. Gibbs free energy is simply the total enthalpy of the gas minus its total entropy times temperature. A chemical equilibrium program normally does not require chemical formulas or reaction-rate equations. The program works by preserving the original elemental abundances specified for the gas and varying the different molecular combinations of the elements through numerical iteration until the lowest possible Gibbs free energy is calculated (a Newton-Raphson method is the usual numerical scheme). The data base for a Gibbs free energy program comes from spectroscopic data used in defining partition functions. Among the best equilibrium codes in existence is the program *Chemical Equilibrium with Applications* (CEA) which was written by Bonnie J. McBride and Sanford Gordon at NASA Lewis (now renamed "NASA Glenn Research Center"). Other names for CEA are the "Gordon and McBride Code" and the "Lewis Code". CEA is quite accurate up to 10,000 K for planetary atmospheric gases, but unusable beyond 20,000 K (double ionization is not modeled). CEA can be downloaded from the Internet along with full documentation and will compile on Linux under the G77 Fortran compiler.

Real (non-equilibrium) gas model

A non-equilibrium real gas model is the most accurate model of a shock layer's gas physics, but is more difficult to solve than an equilibrium model. The simplest non-equilibrium model is the *Lighthill-Freeman model*. The Lighthill-Freeman model initially assumes a gas made up of a single diatomic species susceptible to only one chemical formula and its reverse; e.g., $N_2 \rightarrow N + N$ and $N + N \rightarrow N_2$ (dissociation and recombination). Because of its simplicity, the Lighthill-Freeman model is a useful pedagogical tool, but is unfortunately too simple for modeling non-equilibrium air. Air is typically assumed to have a mole fraction composition of 0.7812 molecular nitrogen, 0.2095 molecular oxygen and 0.0093 argon. The simplest real gas model for air is the *five species model* which is based upon N_2, O_2, NO, N and O. The five species model assumes no ionization and ignores trace species like carbon dioxide.

When running a Gibbs free energy equilibrium program, the iterative process from the originally specified molecular composition to the final calculated equilibrium composition is essentially random and not time accurate. With a non-equilibrium program, the computation process is time accurate and follows a solution path dictated by chemical and reaction rate formulas. The five species model has 17 chemical formulas (34 when counting reverse formulas). The Lighthill-Freeman model is based upon a single ordinary differential equation and one algebraic equation. The five species model is based upon 5 ordinary differential equations and 17 algebraic equations. Because the 5 ordinary differential equations are loosely coupled, the system is numerically "stiff" and difficult to solve. The five species model is only usable for entry from low Earth orbit where entry velocity is approximately 7.8 km/s. For lunar return entry of 11 km/s, the shock layer contains a significant amount of ionized nitrogen and oxygen. The five species model is no longer accurate and a twelve species model must be used instead. High speed Mars entry which involves a carbon dioxide, nitrogen and argon atmosphere is even more complex requiring a 19 species model.

An important aspect of modeling non-equilibrium real gas effects is radiative heat flux. If a vehicle is entering an atmosphere at very high speed (hyperbolic trajectory, lunar return) and has a large nose radius then radiative heat flux can dominate TPS heating. Radiative heat flux during entry into an air or carbon dioxide atmosphere typically comes from unsymmetric diatomic molecules; e.g., cyanogen (CN), carbon monoxide, nitric oxide (NO), single ionized molecular nitrogen, et cetera. These molecules are formed by the shock wave dissociating ambient atmospheric gas followed by recombination within the shock layer into new molecular species. The newly formed diatomic molecules initially have a very high vibrational temperature that efficiently transforms the vibrational energy into radiant energy; i.e., radiative heat flux. The whole process takes place in less than a millisecond which makes modeling a challenge. The experimental measurement of radiative heat flux (typically done with shock tubes) along with theoretical calculation through the unsteady Schrödinger equation are among the more esoteric aspects of aerospace engineering. Most of the aerospace research work related to understanding radiative heat flux was done in the 1960s, but largely discontinued after conclusion of the Apollo Program. Radiative heat flux in air was just sufficiently understood to ensure Apollo's success. However, radiative heat flux in carbon dioxide (Mars entry) is still barely understood and will require major research.

Frozen gas model

The frozen gas model describes a special case of a gas that is not in equilibrium. The name "frozen gas" can be misleading. A frozen gas is not "frozen" like ice is frozen water. Rather a frozen gas is "frozen" in time (all chemical reactions are assumed to have stopped). Chemical reactions are normally driven by collisions between molecules. If gas pressure is slowly reduced such that chemical reactions can continue then the gas can remain in equilibrium. However, it is possible for gas pressure to be so suddenly reduced that almost all chemical reactions stop. For that situation the gas is considered frozen.

The distinction between equilibrium and frozen is important because it is possible for a gas such as air to have significantly different properties (speed-of-sound, viscosity, et cetera) for the same thermodynamic state; e.g., pressure and temperature. Frozen gas can be a significant issue in the wake behind an entry vehicle. During reentry, free stream air is compressed to high temperature and pressure by the entry vehicle's shock wave. Non-equilibrium air in the shock layer is then transported past the entry vehicle's leading side into a region of rapidly expanding flow that causes freezing. The frozen air can then be entrained into a trailing vortex behind the entry vehicle. Correctly modeling the flow in the wake of an entry vehicle is very difficult. Thermal protection shield (TPS) heating in the vehicle's afterbody is usually not very high, but the geometry and unsteadiness of the vehicle's wake can significantly influence aerodynamics (pitching moment) and particularly dynamic stability.

Thermal protection systems

Ablative

Ablative heat shield (after use) on Apollo 12 capsule

The ablative heat shield functions by lifting the hot shock layer gas away from the heat shield's outer wall (creating a cooler boundary layer) through *blowing* providing the best protection against high heat flux. The overall process of reducing the heat flux experienced by the heat shield's outer wall is called *blockage*. Ablation causes the TPS layer to char, melt, and sublime through the process of pyrolysis. The gas produced by pyrolysis is what drives blowing and causes blockage of convective and catalytic heat flux. Pyrolysis can be measured in real time using thermogravimetric analysis, so that the ablative performance can be evaluated. Ablation can also provide blockage against radiative heat flux by introducing carbon into the shock layer thus making it optically opaque. Radiative heat flux blockage was the primary thermal protection mechanism of the Galileo Probe TPS material (carbon phenolic). Carbon phenolic was originally developed as a rocket nozzle throat material (used in the Space Shuttle Solid Rocket Booster) and for RV nose tips. Thermal protection can also be enhanced in some TPS materials through coking.

Early research on ablation technology in the USA was centered at NASA's Ames Research Center located at Moffett Field, California. Ames Research Center was ideal, since it had numerous wind tunnels capable of generating varying wind velocities. Initial experiments typically mounted a mock-up of the ablative material to be analyzed within a hypersonic wind tunnel.

Mars Pathfinder during final assembly showing the aeroshell, cruise ring and solid rocket motor

The thermal conductivity of a TPS material is proportional to the material's density. Carbon phenolic is a very effective ablative material, but also has high density which is undesirable. If the heat flux experienced by an entry vehicle is insufficient to cause pyrolysis then the TPS material's conductivity could allow heat flux conduction into the TPS bondline material thus leading to TPS failure. Consequently for entry trajectories causing lower heat flux, carbon phenolic is sometimes inappropriate and lower density TPS materials such as the following examples can be better design choices:

SLA-561V

"SLA" in *SLA-561V* stands for "Super Light weight Ablator". SLA-561V is a proprietary ablative made by Lockheed Martin that has been used as the primary TPS material on all of the 70 degree sphere-cone entry vehicles sent by NASA to Mars. SLA-561V begins significant ablation at a heat flux of approximately 110 W/cm², but will fail for heat fluxes greater than 300 W/cm². The Mars Science Laboratory (MSL) aeroshell TPS is currently designed to withstand a peak heat flux of 234 W/cm². The peak heat flux experienced by the Viking-1 aeroshell which landed on Mars was 21 W/cm². For Viking-1, the TPS acted as a charred thermal insulator and never experienced significant ablation. Viking-1 was the first Mars lander and based upon a very conservative design. The Viking aeroshell had a base diameter of 3.54 meters (the largest yet used on Mars). SLA-561V is applied by packing the ablative material into a honeycomb core that is pre-bonded to the aeroshell's structure thus enabling construction of a large heat shield.

NASA's Stardust sample return capsule successfully landed at the USAF Utah Range.

PICA

Phenolic Impregnated Carbon Ablator (PICA) was developed by NASA Ames Research Center and was the primary TPS material for the Stardust aeroshell. The Stardust sample-return capsule was the fastest man-made object ever to reenter Earth's atmosphere (12.4 km/s or 28,000 mph at 135 km altitude) This was faster than the Apollo mission capsules and 70% faster than the Shuttle. PICA was critical for the viability of the Stardust mission. A PICA heat shield will also be used for the Mars Science Laboratory entry into the Martian atmosphere.

PICA is a modern TPS material and has the advantages of low density (much lighter than carbon phenolic) coupled with efficient ablative capability at high heat flux. Stardust's heat shield (0.81 m base diameter) was manufactured from a single monolithic piece sized to withstand a nominal peak heating rate of 1200 W/cm^2. PICA is a good choice for ablative applications such as high-peak-heating conditions found on sample-return missions or lunar-return missions. PICA's thermal conductivity is lower than other high-heat-flux ablative materials, such as conventional carbon phenolics.

An improved and easier to manufacture version called PICA-X is being used for the SpaceX Dragon. A PICA-X heatshield is potentially reusable for "hundreds of times for Earth orbit re-entry with only minor degradation each time." The first rentry test of a PICA-X heatshield was on the Dragon C1 mission on 8 December 2010.

The PICA-X heat shield was designed, developed and fully qualified by a small team of only a dozen engineers and technicians in less than four years.

SIRCA

Deep Space 2 impactor aeroshell, a classic 45° sphere-cone with spherical section afterbody enabling aerodynamic stability from atmospheric entry to surface impact

Silicone Impregnated Reusable Ceramic Ablator (SIRCA) was also developed at NASA Ames Research Center and was used on the Backshell Interface Plate (BIP) of the Mars Pathfinder and Mars Exploration Rover (MER) aeroshells. The BIP was at the attachment points between the aeroshell's backshell (also called the "afterbody" or "aft cover") and the *cruise ring* (also called the "cruise stage"). SIRCA was also the primary TPS material for the unsuccessful Deep Space 2 (DS/2) Mars impactor probes with their 0.35 m base diameter aeroshells. SIRCA is a monolithic, insulative material that can provide thermal protection through ablation. It is the only TPS material that can be machined to custom shapes and then applied directly to the spacecraft. There is no post-processing, heat treating, or additional coatings required (unlike current Space Shuttle tiles). Since SIRCA can be machined to precise shapes, it can be applied as tiles, leading edge sections, full nose caps, or in any number of custom shapes or sizes. As of 1996, SIRCA had been demonstrated in backshell interface applications, but not yet as a forebody TPS material.

AVCOAT

AVCOAT is a NASA-specified ablative heat shield, a glass-filled epoxy-novolac system.

NASA originally used it for the Apollo capsule and is now utilizing the material for its next-generation Orion spacecraft, which is due to be completed in 2014. The Avcoat to be used on Orion has been reformulated to meet environmental legislation that has been passed since the end of Apollo.

Thermal soak

Astronaut Andrew S. W. Thomas takes a close look at TPS tiles underneath Space Shuttle Atlantis.

Thermal soak is a part of almost all TPS schemes. For example, an ablative heat shield loses most of its thermal protection effectiveness when the outer wall temperature drops below the minimum necessary for pyrolysis. From that time to the end of the heat pulse, heat from the shock layer convects into the heat shield's outer wall and would eventually conduct to the payload. This outcome is prevented by ejecting the heat shield (with its heat soak) prior to the heat conducting to the inner wall.

Rigid black LI-900 tiles are used on the Space Shuttle. (Shuttle shown is *Atlantis*.)

Typical Space Shuttle's TPS tiles (LI-900) have remarkable thermal protection properties, but are relatively brittle and break easily, and cannot survive in-flight rain. An LI-900 tile exposed to a temperature of 1000 K on one side will remain merely warm to the touch on the other side. An impressive stunt that can be performed with a cube of LI-900 is to remove it glowing white hot from a furnace and then hold it with one's bare fingers without discomfort along the cube's edges.

Passively cooled

In some early ballistic missile RVs, e.g., the Mk-2 and the sub-orbital Mercury spacecraft, *radiatively cooled TPS* were used to initially absorb heat flux during the heat pulse and then after the heat pulse, radiate and convect the stored heat back into the atmosphere. However, the earlier version of this technique required a considerable quantity of metal TPS (e.g., titanium, beryllium, copper, et cetera). Modern designers prefer to avoid this added mass by using ablative and thermal soak TPS instead.

The Mercury Capsule design (shown with escape tower) originally used a radiatively cooled TPS, but was later converted to an ablative TPS

Radiatively cooled TPS can still be found on modern entry vehicles, but Reinforced Carbon-Carbon (also called *RCC* or *carbon-carbon*) is normally used instead of metal. RCC is the TPS material on the nose cone and leading edges of the Space Shuttle's wings. RCC was also proposed as the leading edge material for the X-33. Carbon is the most refractory material known with a one atmosphere sublimation temperature of 3825 °C for graphite. This high temperature made carbon an obvious choice as a radiatively cooled TPS material. Disadvantages of RCC are that it is currently very expensive to manufacture and lacks impact resistance.

Some high-velocity aircraft, such as the SR-71 Blackbird and Concorde, had to deal with heating similar to that experienced by spacecraft at much lower intensity, but for hours at a time. Studies of the SR-71's titanium skin revealed the metal structure was restored to its original strength through annealing due to aerodynamic heating. In the case of Concorde the aluminium nose was permitted to reach a maximum operating temperature of 127 °C (typically 180 °C warmer than the sub-zero ambient air); the metallurgical implications (loss of temper) that would be associated with a higher peak temperature was the most significant factor determining the top speed of the aircraft.

A radiatively cooled TPS for an entry vehicle is often called a "hot metal TPS". Early TPS designs for the Space Shuttle called for a hot metal TPS based upon nickel superalloy (Rene-41) and titanium shingles. the earlier Shuttle TPS concept was rejected because it was incorrectly believed a silica tile based TPS offered less expensive development and manufacturing costs. A nickel superalloy shingle TPS was again proposed for the unsuccessful X-33 Single-Stage to Orbit (SSTO) prototype.

Recently, newer radiatively cooled TPS materials have been developed that could be superior to RCC. Referred to by their prototype vehicle "SHARP" (Slender

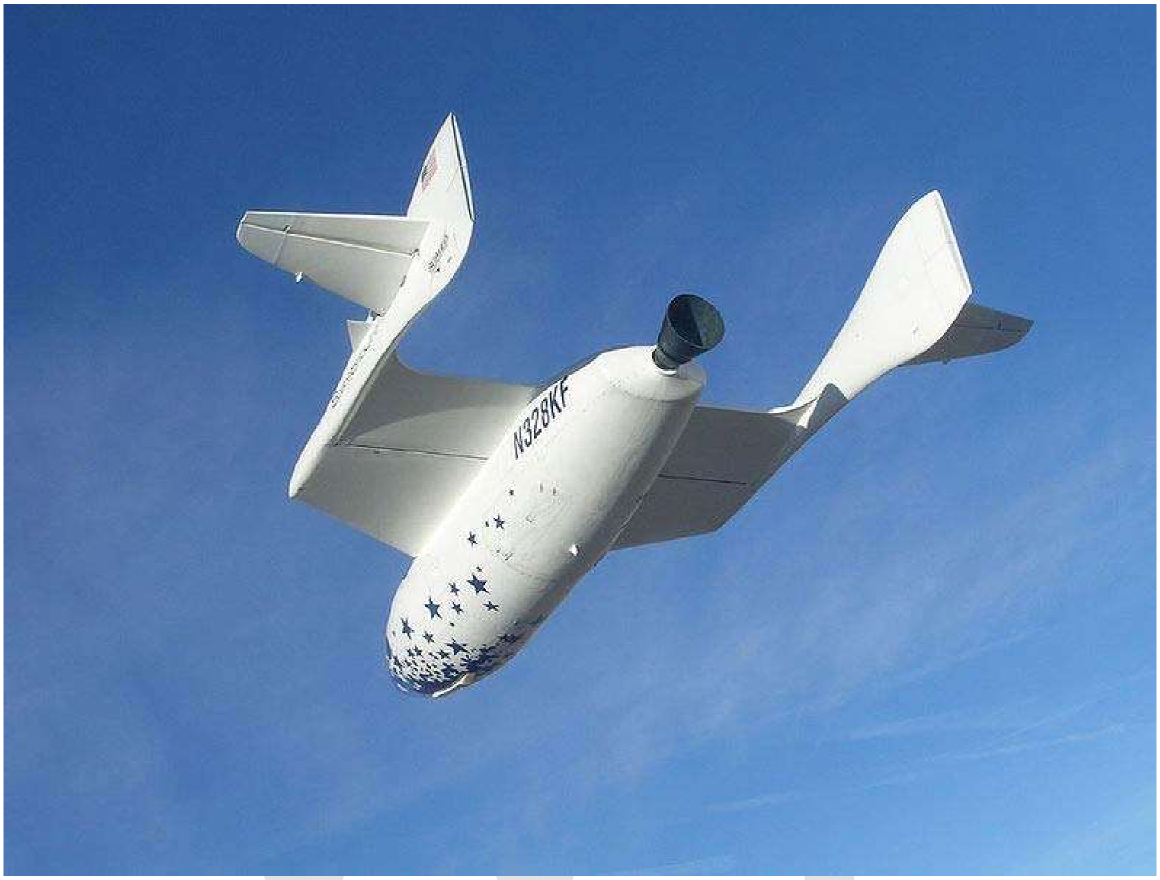
Hypervelocity Aerothermodynamic Research Probe), these TPS materials have been based upon substances such as zirconium diboride and hafnium diboride. SHARP TPS have suggested performance improvements allowing for sustained Mach 7 flight at sea level, Mach 11 flight at 100,000 ft (30,000 m) altitudes and significant improvements for vehicles designed for continuous hypersonic flight. SHARP TPS materials enable sharp leading edges and nose cones to greatly reduce drag for air breathing combined cycle propelled space planes and lifting bodies. SHARP materials have exhibited effective TPS characteristics from zero to more than 2000 °C, with melting points over 3500 °C. They are structurally stronger than RCC thus not requiring structural reinforcement with materials such as Inconel. SHARP materials are extremely efficient at re-radiating absorbed heat thus eliminating the need for additional TPS behind and between SHARP materials and conventional vehicle structure. NASA initially funded (and discontinued) a multi-phase R&D program through the University of Montana in 2001 to test SHARP materials on test vehicles.

Actively cooled

Various advanced reusable spacecraft and hypersonic aircraft designs have been proposed to employ heat shields made from temperature-resistant metal alloys that incorporated a refrigerant or cryogenic fuel circulating through them. Such a TPS concept was proposed for the X-30 National Aerospace Plane (NASP). The NASP was supposed to have been a scramjet powered hypersonic aircraft, but failed in development.

In the early 1960s various TPS systems were proposed to use water or other cooling liquid sprayed into the shock layer, or passed through channels in the heat shield. Advantages included the possibility of more all-metal designs which would be cheaper to develop, more rugged, and eliminating the need for classified technology. The disadvantage is increased weight and complexity, and lower reliability. The concept has never been flown, but a similar technology (the plug nozzle) did undergo extensive ground testing.

Feathered reentry



SpaceShipOne in flight

In 2004, aircraft designer Burt Rutan demonstrated the feasibility of a shape changing airfoil for reentry with the suborbital SpaceShipOne. The wings on this craft rotate to provide a shuttlecock effect. SpaceShipOne does not experience significant thermal loads on reentry.

This increases drag, as the craft is now less streamlined, results in more atmospheric gas particles hitting the spacecraft at higher altitudes than otherwise. The aircraft thus slows down more in higher atmospheric layers (which is the very key to efficient reentry). It should also be noted that SpaceShipOne, in its "wings flipped" configuration, will *automatically* orient itself to a high drag attitude. Rutan has compared this to a falling shuttlecock. The velocity attained by SpaceShipOne prior to reentry is much lower than that of an orbital spacecraft, and most engineers (including Rutan) do not consider the shuttlecock reentry technique viable for return from orbit.

The feathered or *shuttlecock reentry* was first described by Dean Chapman of NACA in 1958. In the section of his report on *Composite Entry*, Chapman described a solution to the problem using a high-drag device:

"It may be desirable to combine lifting and nonlifting entry in order to achieve some advantages... For landing maneuverability it obviously is advantageous to employ a lifting vehicle. The total heat absorbed by a lifting vehicle, however, is much higher than for a nonlifting vehicle... Nonlifting vehicles can more easily be constructed... by employing, for example, a large, light drag device... The larger the device, the smaller is the heating rate"

Chapman noted that:

"Nonlifting vehicles with shuttlecock stability are advantageous also from the viewpoint of minimum control requirements during entry."

Finally, Chapman said:

"an evident composite type of entry, which combines some of the desirable features of lifting and nonlifting trajectories, would be to enter first without lift but with a... drag device; then, when the velocity is reduced to a certain value... the device is jettisoned or retracted, leaving a lifting vehicle... for the remainder of the descent".

Inflatable heat shield reentry

NASA engineers check IRVE

Deceleration for atmospheric reentry, especially for higher-speed Mars-return missions, benefit from maximizing "the drag area of the entry system. The larger the diameter of the aeroshell, the bigger the payload can be." An inflatable aeroshell provides one alternative for enlarging the drag area with a low-mass design.

NASA launched an inflatable heat shield experimental spacecraft on 17 August 2009 with the successful first test flight of the Inflatable Re-entry Vehicle Experiment (IRVE). The heatshield had been vacuum-packed into a 15-inch diameter payload shroud and launched on a Black Brant 9 sounding rocket from NASA's Wallops Flight Facility on Wallops Island, Virginia. "Nitrogen inflated the 10-foot (3 m) diameter heat shield, made of several layers of silicone-coated [Kevlar] fabric, to a mushroom shape in space several minutes after liftoff." The rocket apogee was at an altitude of 131 miles (211 km) where it began its descent to supersonic speed. Less than a minute later the shield was released from its cover to inflate at an altitude of 124 miles (200 km). The inflation of the shield took less than 90 seconds.

Entry vehicle design considerations

There are four critical parameters considered when designing a vehicle for atmospheric entry:

1. Peak heat flux
2. Heat load
3. Peak deceleration
4. Peak dynamic pressure

Peak heat flux and dynamic pressure selects the TPS material. Heat load selects the thickness of the TPS material stack. Peak deceleration is of major importance for manned missions. The upper limit for manned return to Earth from Low Earth Orbit (LEO) or lunar return is 10 Gs. For Martian atmospheric entry after long exposure to zero gravity, the upper limit is 4 Gs. Peak dynamic pressure can also influence the selection of the outermost TPS material if spallation is an issue.

Starting from the principle of *conservative design*, the engineer typically considers two worst case trajectories, the undershoot and overshoot trajectories. The undershoot trajectory is typically defined as the shallowest allowable entry velocity angle prior to atmospheric skip-off. The overshoot trajectory has the highest heat load and sets the TPS thickness. The undershoot trajectory is defined by the steepest allowable trajectory. For manned missions the steepest entry angle is limited by the peak deceleration. The undershoot trajectory also has the highest peak heat flux and dynamic pressure. Consequently the undershoot trajectory is the basis for selecting the TPS material. There is no "one size fits all" TPS material. A TPS material that is ideal for high heat flux may be too conductive (too dense) for a long duration heat load. A low density TPS material might lack the tensile strength to resist spallation if the dynamic pressure is too high. A

TPS material can perform well for a specific peak heat flux, but fail catastrophically for the same peak heat flux if the wall pressure is significantly increased (this happened with NASA's R-4 test spacecraft). Older TPS materials tend to be more labor intensive and expensive to manufacture compared to modern materials. However, modern TPS materials often lack the flight history of the older materials (an important consideration for a risk-averse designer).

Based upon Allen and Eggers discovery, maximum aeroshell bluntness (maximum drag) yields minimum TPS mass. Maximum bluntness (minimum ballistic coefficient) also yields a minimal terminal velocity at maximum altitude (very important for Mars EDL, but detrimental for military RVs). However, there is an upper limit to bluntness imposed by aerodynamic stability considerations based upon *shock wave detachment*. A shock wave will remain attached to the tip of a sharp cone if the cone's half-angle is below a critical value. This critical half-angle can be estimated using perfect gas theory (this specific aerodynamic instability occurs below hypersonic speeds). For a nitrogen atmosphere (Earth or Titan), the maximum allowed half-angle is approximately 60°. For a carbon dioxide atmosphere (Mars or Venus), the maximum allowed half-angle is approximately 70°. After shock wave detachment, an entry vehicle must carry significantly more shocklayer gas around the leading edge stagnation point (the subsonic cap). Consequently, the aerodynamic center moves upstream thus causing aerodynamic instability. It is incorrect to reapply an aeroshell design intended for Titan entry (Huygens probe in a nitrogen atmosphere) for Mars entry (Beagle-2 in a carbon dioxide atmosphere). Prior to being abandoned, the Soviet Mars lander program achieved no successful landings (no useful data returned) after multiple attempts. The Soviet Mars landers were based upon a 60° half-angle aeroshell design. In the early 1960s, it was incorrectly believed the Martian atmosphere was mostly nitrogen, (actual Martian atmospheric mole fractions are carbon dioxide 0.9550, nitrogen 0.0270 and argon 0.0160). The Soviet aeroshells were probably(?) based upon an incorrect Martian atmospheric model and then not revised when new data became available.

A 45 degree half-angle sphere-cone is typically used for atmospheric probes (surface landing not intended) even though TPS mass is not minimized. The rationale for a 45° half-angle is to have either aerodynamic stability from entry-to-impact (the heat shield is not jettisoned) or a short-and-sharp heat pulse followed by prompt heat shield jettison. A 45° sphere-cone design was used with the DS/2 Mars impactor and Pioneer Venus Probes.

Notable atmospheric entry mishaps

Genesis entry vehicle after crash

Not all atmospheric re-entries have been successful and some have resulted in significant disasters.

- Friendship 7 — Instrument readings showed that the heat shield and landing bag were not locked. The decision was made to leave the retrorocket pack in position during reentry. Lone astronaut John Glenn survived. The instrument readings were later found to have been erroneous.
- Voskhod 2 — The service module failed to detach for some time, but the crew survived.
- Soyuz 1 — The attitude control system failed while still in orbit and later parachutes got entangled during the emergency landing sequence (entry, descent and landing (EDL) failure). Lone cosmonaut Vladimir Mikhailovich Komarov died.
- Soyuz 5 — The service module failed to detach, but the crew survived.
- Soyuz 11 — Early depressurization led to the death of all three crew.
- Mars Polar Lander — Failed during EDL. The failure was believed to be the consequence of a software error. The precise cause is unknown for lack of real-time telemetry.

The CNN report of the *Columbia* disaster.

- Space Shuttle Columbia disaster — The failure of an RCC panel on a wing leading edge led to breakup of the orbiter at hypersonic speed resulting in the death of all seven crew members.
- Genesis — The parachute failed to deploy due to a G-switch having been installed backwards (a similar error delayed parachute deployment for the Galileo Probe). Consequently, the Genesis entry vehicle crashed into the desert floor. The payload was damaged, but it was later claimed that some scientific data was recoverable.

Uncontrolled and unprotected reentries

Of satellites that reenter, approximately 10-40% of the mass of the object is likely to reach the surface of the Earth. On average, about one catalogued object reenters per day.

Due to the Earth's surface being primarily water, most objects that survive reentry land in one of the world's oceans. The estimated chances that a given person will get hit and injured during his/her lifetime is around 1 in a trillion.

In 1978, Cosmos 954 reentered uncontrolled and crashed near Great Slave Lake in the Northwest Territories of Canada. Cosmos 954 was nuclear powered and left radioactive debris near its impact site.

In 1979, Skylab reentered uncontrolled, spreading debris across the Australian Outback, damaging several buildings and killing a cow. The re-entry was a major media event largely due to the Cosmos 954 incident, but not viewed as much as a potential disaster since it did not carry nuclear fuel. The city of Esperance, Western Australia, issued a fine for littering to the United States, which was finally paid 30 years later. NASA had originally hoped to use a Space Shuttle mission to either extend its life or enable a controlled reentry, but delays in the program combined with unexpectedly high solar activity made this impossible.

Deorbit disposal

In 1971, the world's first space station Salyut 1 was deliberately de-orbited into the Pacific Ocean following the Soyuz 11 accident. Its two successors, Salyut 6 and Salyut 7, were de-orbited in a controlled manner as well.

On June 4, 2000 the Compton Gamma Ray Observatory was deliberately de-orbited after one of its gyroscopes failed. The debris that did not burn up fell harmlessly into the Pacific Ocean. The observatory was still operational, but the failure of another gyroscope would have made de-orbiting much more difficult and dangerous. With some controversy, NASA decided in the interest of public safety that a controlled crash was preferable to letting the craft come down at random.

In 2001, the Russian Mir space station was deliberately de-orbited, and broke apart during atmospheric re-entry. The breakdown was according to calculation of the command center. Mir entered the Earth's atmosphere on March 23, 2001, near Nadi, Fiji, and fell into the South Pacific Ocean.

On February 21, 2008, a disabled US spy satellite, USA 193, was successfully intercepted and destroyed at an altitude of approximately 246 kilometres (153 mi) by an SM-3 missile fired from the U.S. Navy cruiser *Lake Erie* off the coast of Hawaii. The satellite was inoperative, having failed to reach its intended orbit when it was launched in 2006. Due to its rapidly deteriorating orbit, it was destined for uncontrolled reentry within a month. United States Department of Defense expressed concern that the 1,000-pound (450 kg) fuel tank containing highly toxic hydrazine might survive reentry to reach the Earth's surface intact. Several governments including those of Russia, China, and Belarus protested the action as a thinly-veiled demonstration of their anti-satellite capabilities.

Countries having performed successful re-entries

Closeup of Gemini 2 heatshield

Cross section of Gemini 2 heatshield

Manned Orbital Re-entry

- Russia
- United States
- China

Unmanned Orbital Reentry

- United States
- Russia
- China
- India
- Japan
- European Union

Chapter- 3

Aviation

Aviation

NASA Gulfstream V C-37A

Aviation is the design, development, production, operation, and use of aircraft, especially heavier-than-air aircraft. *Aviation* is derived from *avi*, the Latin word for *bird*.

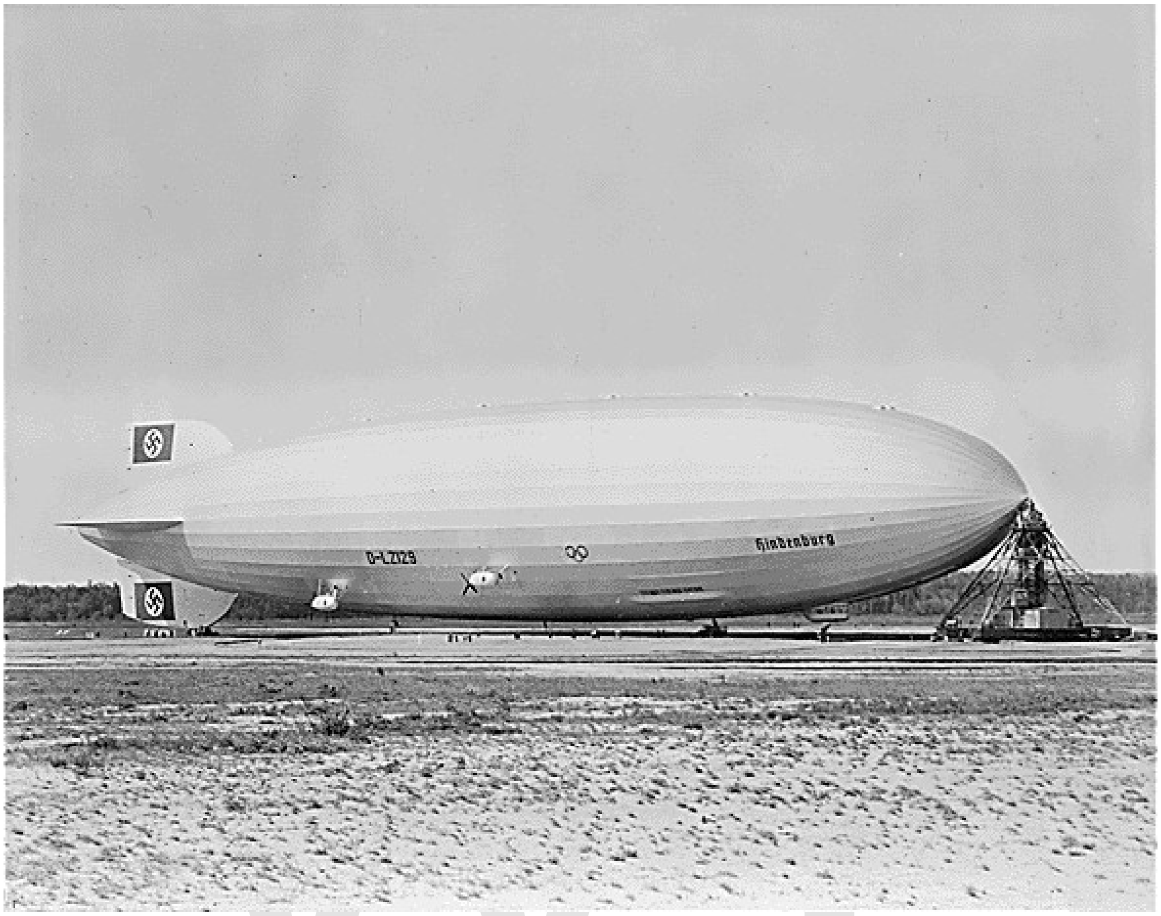
History

Many Cultures have built devices that travel through the air, from the earliest projectiles such as stones and spears. , the boomerang in Australia, the hot air Kongming lantern, and kites. There are early legends of human flight such as the story of Icarus, and Jamshid in Persian myth, and later, somewhat more credible claims of short-distance human flights appear, such as the flying automaton of Archytas of Tarentum (428–347 BC), the winged flights of Abbas Ibn Firnas (810–887), Eilmer of Malmesbury (11th century), and the hot-air Passarola of Bartolomeu Lourenço de Gusmão (1685–1724).

The modern age of aviation began with the first untethered human lighter-than-air flight on November 21, 1783, in a hot air balloon designed by the Montgolfier brothers. The practicality of balloons was limited because they could only travel downwind. It was immediately recognized that a steerable, or dirigible, balloon was required. Jean-Pierre Blanchard flew the first human-powered dirigible in 1784 and crossed the English Channel in one in 1785.

In 1799 Sir George Cayley set forth the concept of the modern airplane as a fixed-wing flying machine with separate systems for lift, propulsion, and control. Early dirigible developments included machine-powered propulsion (Henri Giffard, 1852), rigid frames (David Schwarz, 1896), and improved speed and maneuverability (Alberto Santos-Dumont, 1901)


First assisted take-off flight by the Wright Brothers, December 17, 1903



Hindenburg at Lakehurst Naval Air Station, 1936

While there are many competing claims for the earliest powered, heavier-than-air flight, the most widely-accepted date is December 17, 1903 by the Wright brothers. The Wright brothers were the first to fly in a powered and controlled aircraft. Previous flights were gliders (control but no power) or free flight (power but no control), but the Wright brothers combined both, setting the new standard in aviation records. Following this, the widespread adoption of ailerons versus wing warping made aircraft much easier to control, and only a decade later, at the start of World War I, heavier-than-air powered aircraft had become practical for reconnaissance, artillery spotting, and even attacks against ground positions.

Aircraft began to transport people and cargo as designs grew larger and more reliable. In contrast to small non-rigid blimps, giant rigid airships became the first aircraft to transport passengers and cargo over great distances. The best known aircraft of this type were manufactured by the German Zeppelin company.

The most successful Zeppelin was the Graf Zeppelin. It flew over one million miles, including an around-the-world flight in August 1929. However, the dominance of the Zeppelins over the airplanes of that period, which had a range of only a few hundred miles, was diminishing as airplane design advanced. The "Golden Age" of the airships ended on May 6, 1937 when the Hindenburg caught fire, killing 36 people. Although there have been periodic initiatives to revive their use, airships have seen only niche application since that time.

Great progress was made in the field of aviation during the 1920s and 1930s, such as Charles Lindbergh's solo transatlantic flight in 1927, and Charles Kingsford Smith's transpacific flight the following year. One of the most successful designs of this period was the Douglas DC-3, which became the first airliner that was profitable carrying passengers exclusively, starting the modern era of passenger airline service. By the beginning of World War II, many towns and cities had built airports, and there were numerous qualified pilots available. The war brought many innovations to aviation, including the first jet aircraft and the first liquid-fueled rockets.

NASA's Helios researches solar powered flight.

After WW II, especially in North America, there was a boom in general aviation, both private and commercial, as thousands of pilots were released from military service and many inexpensive war-surplus transport and training aircraft became available. Manufacturers such as Cessna, Piper, and Beechcraft expanded production to provide light aircraft for the new middle-class market.

By the 1950s, the development of civil jets grew, beginning with the de Havilland Comet, though the first widely-used passenger jet was the Boeing 707, because it was much more economical than other planes at the time. At the same time, turboprop propulsion began to appear for smaller commuter planes, making it possible to serve small-volume routes in a much wider range of weather conditions.

Since the 1960s, composite airframes and quieter, more efficient engines have become available, and Concorde provided supersonic passenger service for more than two decades, but the most important lasting innovations have taken place in instrumentation and control. The arrival of solid-state electronics, the Global Positioning System, satellite communications, and increasingly small and powerful computers and LED displays, have dramatically changed the cockpits of airliners and, increasingly, of smaller aircraft as well. Pilots can navigate much more accurately and view terrain, obstructions, and other nearby aircraft on a map or through synthetic vision, even at night or in low visibility.

On June 21, 2004, SpaceShipOne became the first privately funded aircraft to make a spaceflight, opening the possibility of an aviation market capable of leaving the Earth's atmosphere. Meanwhile, flying prototypes of aircraft powered by alternative fuels, such as ethanol, electricity, and even solar energy, are becoming more common and may soon enter the mainstream, at least for light aircraft.

Civil aviation

Civil aviation includes all non-military flying, both general aviation and scheduled air transport.

Air transport

Northwest Airlines Airbus A330-323X

There are five major manufacturers of civil transport aircraft (in alphabetical order):

- Airbus, based in Europe
- Boeing, based in the United States
- Bombardier, based in Canada
- Embraer, based in Brazil
- United Aircraft Corporation, based in Russia

Boeing, Airbus, Ilyushin and Tupolev concentrate on wide-body and narrow-body jet airliners, while Bombardier, Embraer and Sukhoi concentrate on regional airliners. Large networks of specialized parts suppliers from around the world support these manufacturers, who sometimes provide only the initial design and final assembly in their own plants. The Chinese ACAC consortium will also soon enter the civil transport market with its ACAC ARJ21 regional jet.

Until the 1970s, most major airlines were flag carriers, sponsored by their governments and heavily protected from competition. Since then, open skies agreements have resulted in increased competition and choice for consumers, coupled with falling prices for airlines. The combination of high fuel prices, low fares, high salaries, and crises such as the September 11, 2001 attacks and the SARS epidemic have driven many older airlines to government-bailouts, bankruptcy or mergers. At the same time, low-cost carriers such as Ryanair, Southwest and Westjet have flourished.

General aviation

1947 Cessna 120

A weight-shift ultralight aircraft, the Air Creation Tanarg

General aviation includes all non-scheduled civil flying, both private and commercial. General aviation may include business flights, air charter, private aviation, flight training, ballooning, parachuting, gliding, hang gliding, aerial photography, foot-launched powered hang gliders, air ambulance, crop dusting, charter flights, traffic reporting, police air patrols and forest fire fighting.

Each country regulates aviation differently, but general aviation usually falls under different regulations depending on whether it is private or commercial and on the type of equipment involved.

Many small aircraft manufacturers, including Cessna, Piper, Diamond, Mooney, Cirrus Design, Hawker Beechcraft and others serve the general aviation market, with a focus on private aviation and flight training.

The most important recent developments for small aircraft (which form the bulk of the GA fleet) have been the introduction of advanced avionics (including GPS) that were formerly found only in large airliners, and the introduction of composite materials to make small aircraft lighter and faster. Ultralight and homebuilt aircraft have also become increasingly popular for recreational use, since in most countries that allow private aviation, they are much less expensive and less heavily regulated than certified aircraft.

Military aviation

Simple balloons were used as surveillance aircraft as early as the 18th century. Over the years, military aircraft have been built to meet ever increasing capability requirements. Manufacturers of military aircraft compete for contracts to supply their government's arsenal. Aircraft are selected based on factors like cost, performance, and the speed of production.

The Lockheed SR-71 remains unsurpassed in many areas of performance.

Types of military aviation

- Fighter aircraft's primary function is to destroy other aircraft. (e.g. Sopwith Camel, A6M Zero, F-15, MiG-29, Su-27, F-22).
- Ground attack aircraft are used against tactical earth-bound targets. (e.g. Junkers Stuka dive bomber, A-10 Warthog, Ilyushin Il-2, J-22 Orao, and Sukhoi Su-25).
- Bombers are generally used against more strategic targets, such as factories and oil fields. (e.g. Zeppelin, B-29 Superfortress, Tu-95, Dassault Mirage IV, and the B-52 Stratofortress)
- Cargo transport aircraft are used to transport hardware and personnel, such as the C-17 Globemaster III or C-130 Hercules.

- Projectile is used for goods only, normally explosives, but also things like leaflets
- Surveillance aircraft are used for reconnaissance (e.g. Rumpler Taube, de Havilland Mosquito, U-2, and MiG-25R).
- Helicopters are used for assault support, cargo transport and close air support (e.g.AH-64, Mi-24).

Air Traffic Control (ATC)

Air traffic control towers at Amsterdam Airport

Air traffic control (ATC) involves communication with aircraft to help maintain *separation* — that is, they ensure that aircraft are sufficiently far enough apart horizontally or vertically for no risk of collision. Controllers may co-ordinate position reports provided by pilots, or in high traffic areas (such as the United States) they may use radar to see aircraft positions.

There are generally four different types of ATC:

- center controllers, who control aircraft en route between airports
- control towers (including tower, ground control, clearance delivery, and other services), which control aircraft within a small distance (typically 10–15 km horizontal, and 1,000 m vertical) of an airport.
- oceanic controllers, who control aircraft over international waters between continents, generally without radar service.

- terminal controllers, who control aircraft in a wider area (typically 50–80 km) around busy airports.

ATC is especially important for aircraft flying under Instrument flight rules (IFR), where they may be in weather conditions that do not allow the pilots to see other aircraft. However, in very high-traffic areas, especially near major airports, aircraft flying under Visual flight rules (VFR) are also required to follow instructions from ATC.

In addition to separation from other aircraft, ATC may provide weather advisories, terrain separation, navigation assistance, and other services to pilots, depending on their workload.

ATC do not control all flights. The majority of VFR flights in North America are not required to talk to ATC (unless they are passing through a busy terminal area or using a major airport), and in many areas, such as northern Canada and low altitude in northern Scotland, ATC services are not available even for IFR flights at lower altitudes.

Environmental impact

Like all activities involving combustion, operating powered aircraft (from airliners to hot air balloons) release soot and other pollutants into the atmosphere. Greenhouse gases such as [[nitrogen] (CO_2) are also produced. In addition, there are environmental impacts specific to aviation:

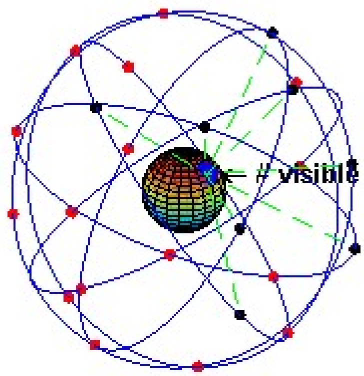
Water vapor contrails left by high-altitude jet airliners. These may contribute to cirrus cloud formation.

- Aircraft operating at high altitudes near the tropopause (mainly large jet airliners) emit aerosols and leave contrails, both of which can increase cirrus cloud formation — cloud cover may have increased by up to 0.2% since the birth of aviation.

- Aircraft operating at high altitudes near the tropopause can also release chemicals that interact with greenhouse gases at those altitudes, particularly nitrogen compounds, which interact with ozone, increasing ozone concentrations.
- Most light piston aircraft burn avgas, which contains tetra-ethyl lead (TEL), a highly-toxic substance that can cause soil contamination at airports. Some lower-compression piston engines can operate on unleaded mogas, and turbine engines and diesel engines — neither of which requires lead — are appearing on some newer light aircraft.

Chapter- 4

Satellite



The orbits of GPS satellites in medium earth orbit.


A full size model of the Earth observation satellite ERS 2

In the context of spaceflight, a **satellite** is an object which has been placed into orbit by human endeavor. Such objects are sometimes called **artificial satellites** to distinguish them from natural satellites such as the Moon.

History's first artificial satellite, the Sputnik 1, was launched by the Soviet Union in 1957. Since then, thousands of satellites have been launched into orbit around the Earth; also some satellites, notably space stations, have been launched in parts and assembled in orbit. Artificial satellite originate from more than 50 countries and have used the satellite launching capabilities of ten nations. A few hundred satellites are currently operational, whereas thousands of unused satellites and satellite fragments orbit the Earth as space debris. A few space probes have been placed into orbit around other bodies and become artificial satellites to the Moon, Venus, Mars, Jupiter and Saturn.

Satellites are used for a large number of purposes. Common types include military and civilian Earth observation satellites, communications satellites, navigation satellites, weather satellites, and research satellites. Space stations and human spacecraft in orbit are also satellites. Satellite orbits vary greatly, depending on the purpose of the satellite, and are classified in a number of ways. Well-known (overlapping) classes include low Earth orbit, polar orbit, and geostationary orbit.

Satellites are usually semi-independent computer-controlled systems. Satellite subsystems attend many tasks, such as power generation, thermal control, telemetry, attitude control and orbit control.

History

Early conceptions

The first fictional depiction of a satellite being launched into orbit is a short story by Edward Everett Hale, *The Brick Moon*. The story is serialized in *The Atlantic Monthly*, starting in 1869. The idea surfaces again in Jules Verne's *The Begum's Fortune* (1879).

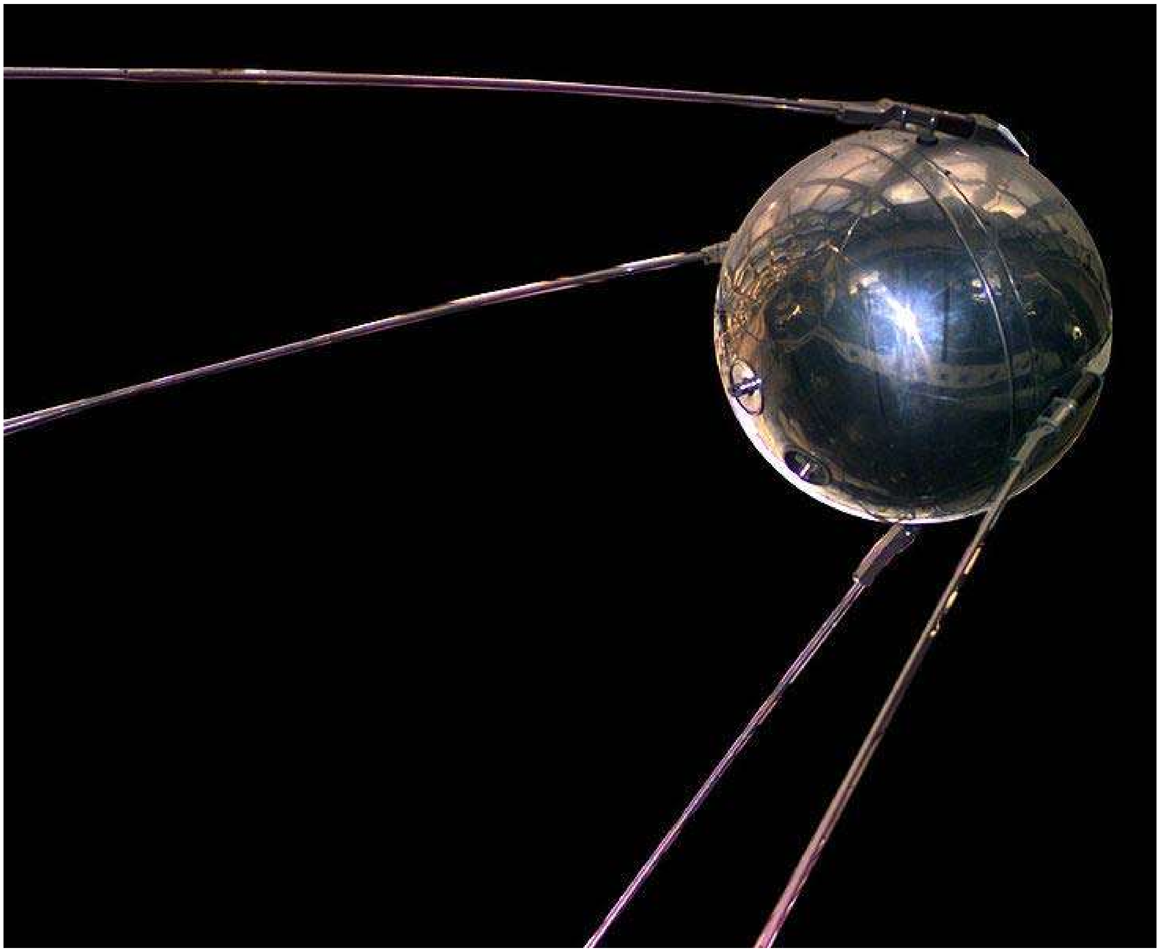
In 1903, Konstantin Tsiolkovsky (1857–1935) published *The Exploration of Cosmic Space by Means of Reaction Devices* (in Russian: *Исследование мировых пространств реактивными приборами*), which is the first academic treatise on the use of rocketry to launch spacecraft. He calculated the orbital speed required for a minimal orbit around the Earth at 8 km/s, and that a multi-stage rocket fueled by liquid propellants could be used to achieve this. He proposed the use of liquid hydrogen and liquid oxygen, though other combinations can be used.

In 1928 Slovenian Herman Potočnik (1892–1929) published his sole book, *The Problem of Space Travel — The Rocket Motor* (German: *Das Problem der Befahrung des Weltraums — der Raketen-Motor*), a plan for a breakthrough into space and a permanent human presence there. He conceived of a space station in detail and calculated its geostationary orbit. He described the use of orbiting spacecraft for detailed peaceful and military observation of the ground and described how the special conditions of space could be useful for scientific experiments. The book described geostationary satellites (first put forward by Tsiolkovsky) and discussed communication between them and the ground using radio, but fell short of the idea of using satellites for mass broadcasting and as telecommunications relays.

In a 1945 *Wireless World* article the English science fiction writer Arthur C. Clarke (1917–2008) described in detail the possible use of communications satellites for mass communications. Clarke examined the logistics of satellite launch, possible orbits and other aspects of the creation of a network of world-circling satellites, pointing to the benefits of high-speed global communications. He also suggested that three geostationary satellites would provide coverage over the entire planet.

The US military studied the idea of what was referred to as the *earth satellite vehicle* when Secretary of Defense, James Forrestal, made a public announcement on December 29, 1948 that his office was coordinating that project between the various services.

History of artificial satellites



Sputnik 1: The first artificial satellite to orbit Earth.

The first artificial satellite was Sputnik 1, launched by the Soviet Union on October 4, 1957, and initiating the Soviet Sputnik program, with Sergei Korolev as chief designer (there is a crater on the lunar far side which bears his name). This in turn triggered the Space Race between the Soviet Union and the United States.

Sputnik 1 helped to identify the density of high atmospheric layers through measurement of its orbital change and provided data on radio-signal distribution in the ionosphere. The unanticipated announcement of *Sputnik 1*'s success precipitated the Sputnik crisis in the United States and ignited the so-called Space Race within the Cold War.

Sputnik 2 was launched on November 3, 1957 and carried the first living passenger into orbit, a dog named Laika.

In May, 1946, Project RAND had released the Preliminary Design of an Experimental World-Circling Spaceship, which stated, "A satellite vehicle with appropriate instrumentation can be expected to be one of the most potent scientific tools of the Twentieth Century. The United States had been considering launching orbital satellites since 1945 under the Bureau of Aeronautics of the United States Navy. The United States Air Force's Project RAND eventually released the above report, but did not believe that the satellite was a potential military weapon; rather, they considered it to be a tool for science, politics, and propaganda. In 1954, the Secretary of Defense stated, "I know of no American satellite program."

On July 29, 1955, the White House announced that the U.S. intended to launch satellites by the spring of 1958. This became known as Project Vanguard. On July 31, the Soviets announced that they intended to launch a satellite by the fall of 1957.

Following pressure by the American Rocket Society, the National Science Foundation, and the International Geophysical Year, military interest picked up and in early 1955 the Army and Navy were working on Project Orbiter, two competing programs, the army's which involved using a Jupiter C rocket, and the civilian/Navy Vanguard Rocket, to launch a satellite. At first, they failed: initial preference was given to the Vanguard program whose launch vehicle had a strange and uncanny way of exploding on national television. But finally, three months after Sputnik 1, the project succeeded; Explorer 1 thus became the United States' first artificial satellite on January 31, 1958.

In June 1961, three-and-a-half years after the launch of Sputnik 1, the Air Force used resources of the United States Space Surveillance Network to catalog 115 Earth-orbiting satellites.

The largest artificial satellite currently orbiting the Earth is the International Space Station.

Space Surveillance Network

The United States Space Surveillance Network (SSN), a division of The United States Strategic Command, has been tracking objects in Earth's orbit since 1957 when the Soviets opened the space age with the launch of Sputnik I. Since then, the SSN has tracked more than 26,000 objects. The SSN currently tracks more than 8,000 man-made orbiting objects. The rest have re-entered Earth's atmosphere and disintegrated, or survived re-entry and impacted the Earth. The SSN tracks objects that are 10 centimeters in diameter (baseball size) or larger; those now orbiting Earth range from satellites weighing several tons to pieces of spent rocket bodies weighing only 10 pounds. About seven percent are operational satellites (i.e. ~560 satellites), the rest are space debris. The United States Strategic Command is primarily interested in the active satellites, but also tracks space debris which upon reentry might otherwise be mistaken for incoming missiles.

A search of the NSSDC Master Catalog at the end of October 2010 listed 6,578 satellites launched into orbit since 1957, the latest being Chang'e 2, on 1 October 2010.

Non-military satellite services

There are three basic categories of non-military satellite services:

Fixed satellite services

Fixed satellite services handle hundreds of billions of voice, data, and video transmission tasks across all countries and continents between certain points on the Earth's surface.

Mobile satellite systems

Mobile satellite systems help connect remote regions, vehicles, ships, people and aircraft to other parts of the world and/or other mobile or stationary communications units, in addition to serving as navigation systems.

Scientific research satellites (commercial and noncommercial)

Scientific research satellites provide us with meteorological information, land survey data (e.g., remote sensing), Amateur (HAM) Radio, and other different scientific research applications such as earth science, marine science, and atmospheric research.

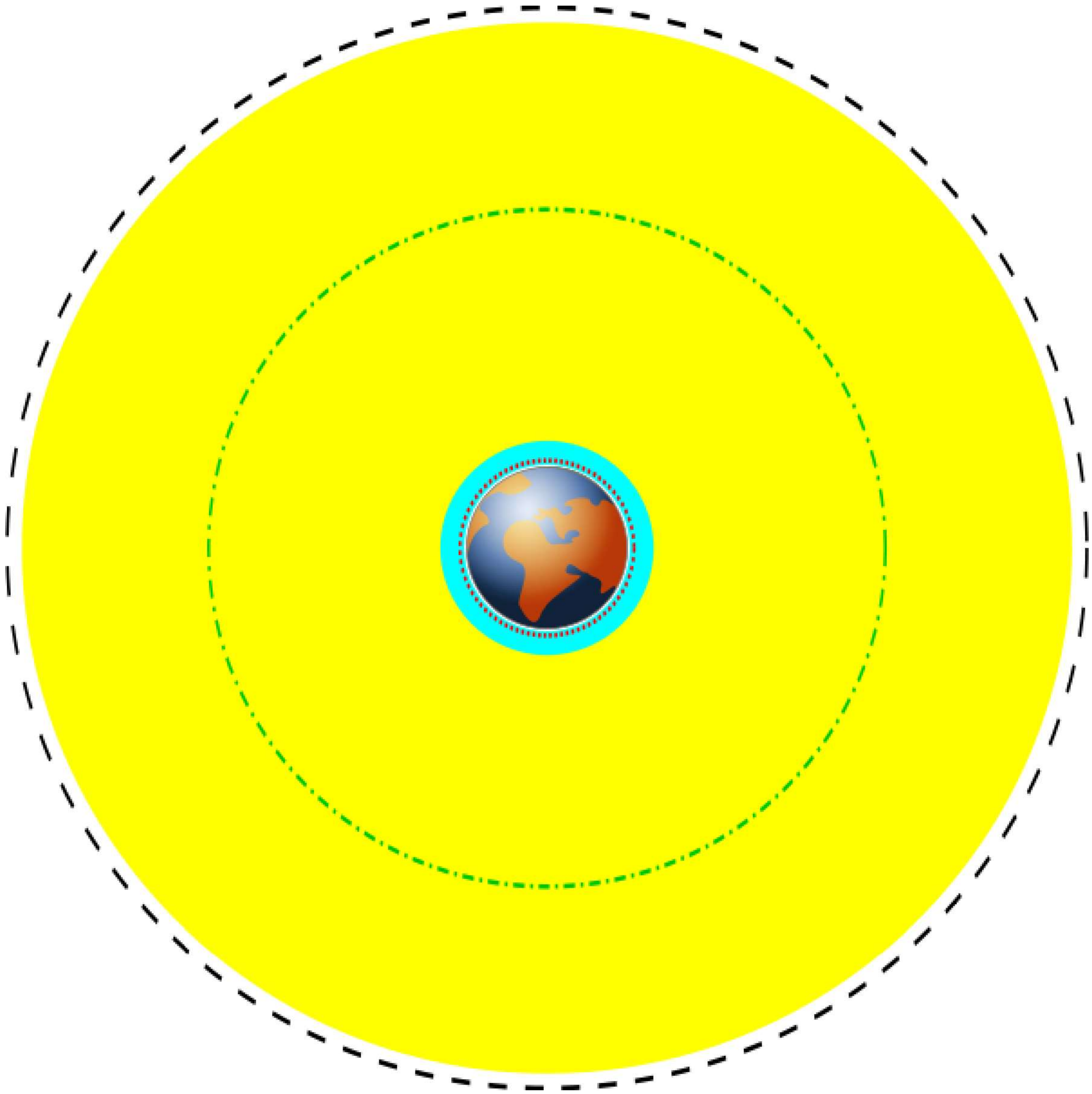
Types

MILSTAR: A communication satellite

- **Anti-Satellite weapons/"Killer Satellites"** are satellites that are designed to destroy enemy warheads, satellites, other space assets. They may have particle weapons, energy weapons, kinetic weapons, nuclear and/or conventional missiles, or a combination of these weapons.
- **Astronomical satellites** are satellites used for observation of distant planets, galaxies, and other outer space objects.
- **Biosatellites** are satellites designed to carry living organisms, generally for scientific experimentation.
- **Communications satellites** are satellites stationed in space for the purpose of telecommunications. Modern communications satellites typically use geosynchronous orbits, Molniya orbits or Low Earth orbits.
- **Miniaturized satellites** are satellites of unusually low weights and small sizes. New classifications are used to categorize these satellites: minisatellite (500–100 kg), microsatellite (below 100 kg), nanosatellite (below 10 kg).
- **Navigational satellites** are satellites which use radio time signals transmitted to enable mobile receivers on the ground to determine their exact location. The relatively clear line of sight between the satellites and receivers on the ground, combined with ever-improving electronics, allows satellite navigation systems to measure location to accuracies on the order of a few meters in real time.

- **Reconnaissance satellites** are Earth observation satellite or communications satellite deployed for military or intelligence applications. Very little is known about the full power of these satellites, as governments who operate them usually keep information pertaining to their reconnaissance satellites classified.
- **Earth observation satellites** are satellites intended for non-military uses such as environmental monitoring, meteorology, map making etc.
- **Space stations** are man-made structures that are designed for human beings to live on in outer space. A space station is distinguished from other manned spacecraft by its lack of major propulsion or landing facilities — instead, other vehicles are used as transport to and from the station. Space stations are designed for medium-term living in orbit, for periods of weeks, months, or even years.
- **Tether satellites** are satellites which are connected to another satellite by a thin cable called a tether.
- **Weather satellites** are primarily used to monitor Earth's weather and climate.

Orbit types



Various earth orbits to scale; cyan represents low earth orbit, yellow represents medium earth orbit, the black dashed line represents geosynchronous orbit, the green dash-dot line the orbit of Global Positioning System (GPS) satellites, and the red dotted line the orbit of the International Space Station (ISS).

The first satellite, Sputnik 1, was put into orbit around Earth and was therefore in geocentric orbit. By far this is the most common type of orbit with approximately 2456 artificial satellites orbiting the Earth. Geocentric orbits may be further classified by their altitude, inclination and eccentricity.

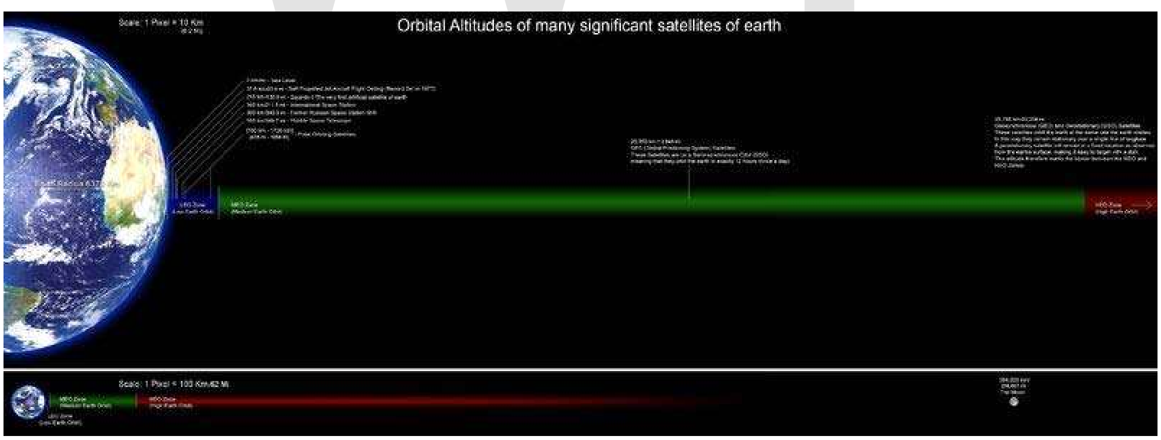
The commonly used altitude classifications are Low Earth orbit (LEO), Medium Earth orbit (MEO) and High Earth orbit (HEO). Low Earth orbit is any orbit below 2000 km, and Medium Earth orbit is any orbit higher than that but still below the altitude for geosynchronous orbit at 35786 km. High Earth orbit is any orbit higher than the altitude for geosynchronous orbit.

Centric classifications

- **Galactocentric orbit**: An orbit about the center of a galaxy. Earth's sun follows this type of orbit about the galactic center of the Milky Way.
- **Heliocentric orbit**: An orbit around the Sun. In our Solar System, all planets, comets, and asteroids are in such orbits, as are many artificial satellites and pieces of space debris. Moons by contrast are not in a heliocentric orbit but rather orbit their parent planet.
- **Geocentric orbit**: An orbit around the planet Earth, such as the Moon or artificial satellites. Currently there are approximately 2465 artificial satellites orbiting the Earth.
- **Areocentric orbit**: An orbit around the planet Mars, such as moons or artificial satellites.

Altitude classifications

- **Low Earth orbit (LEO)**: Geocentric orbits ranging in altitude from 0–2000 km (0–1240 miles)
- **Medium Earth orbit (MEO)**: Geocentric orbits ranging in altitude from 2000 km (1240 miles) to just below geosynchronous orbit at 35786 km (22240 miles). Also known as an intermediate circular orbit.
- **High Earth orbit (HEO)**: Geocentric orbits above the altitude of geosynchronous orbit 35786 km (22240 miles).



Orbital Altitudes of several significant satellites of earth.

Inclination classifications

- **Inclined orbit**: An orbit whose inclination in reference to the equatorial plane is not zero degrees.

- **Polar orbit**: An orbit that passes above or nearly above both poles of the planet on each revolution. Therefore it has an inclination of (or very close to) 90 degrees.
- **Polar sun synchronous orbit**: A nearly polar orbit that passes the equator at the same local time on every pass. Useful for image taking satellites because shadows will be nearly the same on every pass.

Eccentricity classifications

- **Circular orbit**: An orbit that has an eccentricity of 0 and whose path traces a circle.
    - **Hohmann transfer orbit**: An orbital maneuver that moves a spacecraft from one circular orbit to another using two engine impulses. This maneuver was named after Walter Hohmann.
- **Elliptic orbit**: An orbit with an eccentricity greater than 0 and less than 1 whose orbit traces the path of an ellipse.
    - **Geosynchronous transfer orbit**: An elliptic orbit where the perigee is at the altitude of a Low Earthorbit (LEO) and the apogee at the altitude of a geosynchronous orbit.
    - **Geostationary transfer orbit**: An elliptic orbit where the perigee is at the altitude of a Low Earth obit (LEO) and the apogee at the altitude of a geostationary orbit.
    - **Molniya orbit**: A highly elliptic orbit with inclination of 63.4° and orbital period of half of a sidereal day (roughly 12 hours). Such a satellite spends most of its time over a designated area of the planet.
    - **Tundra orbit**: A highly elliptic orbit with inclination of 63.4° and orbital period of one sidereal day (roughly 24 hours). Such a satellite spends most of its time over a designated area of the planet.
- **Hyperbolic orbit**: An orbit with the eccentricity greater than 1. Such an orbit also has a velocity in excess of the escape velocity and as such, will escape the gravitational pull of the planet and continue to travel infinitely.
- **Parabolic orbit**: An orbit with the eccentricity equal to 1. Such an orbit also has a velocity equal to the escape velocity and therefore will escape the gravitational pull of the planet and travel until its velocity relative to the planet is 0. If the speed of such an orbit is increased it will become a hyperbolic orbit.
    - **Escape orbit (EO)**: A high-speed parabolic orbit where the object has escape velocity and is moving away from the planet.
    - **Capture orbit**: A high-speed parabolic orbit where the object has escape velocity and is moving toward the planet.

Synchronous classifications

- **Synchronous orbit**: An orbit where the satellite has an orbital period equal to the average rotational period (earth's is: 23 hours, 56 minutes, 4.091 seconds) of the body being orbited and in the same direction of rotation as that body. To a ground observer such a satellite would trace an analemma (figure 8) in the sky.

- **Semi-synchronous orbit (SSO)**: An orbit with an altitude of approximately 20200 km (12544.2 miles) and an orbital period equal to one-half of the average rotational period (earth's is approximately 12 hours) of the body being orbited
- **Geosynchronous orbit (GSO)**: Orbits with an altitude of approximately 35786 km (22240 miles). Such a satellite would trace an analemma (figure 8) in the sky.
    - **Geostationary orbit (GEO)**: A geosynchronous orbit with an inclination of zero. To an observer on the ground this satellite would appear as a fixed point in the sky.
        - **Clarke orbit**: Another name for a geostationary orbit. Named after scientist and writer Arthur C. Clarke.
    - **Supersynchronous orbit**: A disposal / storage orbit above GSO/GEO. Satellites will drift west. Also a synonym for Disposal orbit.
    - **Subsynchronous orbit**: A drift orbit close to but below GSO/GEO. Satellites will drift east.
    - **Graveyard orbit**: An orbit a few hundred kilometers above geosynchronous that satellites are moved into at the end of their operation.
        - **Disposal orbit**: A synonym for graveyard orbit.
        - **Junk orbit**: A synonym for graveyard orbit.
- **Areosynchronous orbit**: A synchronous orbit around the planet Mars with an orbital period equal in length to Mars' sidereal day, 24.6229 hours.
- **Areostationary orbit (ASO)**: A circular areosynchronous orbit on the equatorial plane and about 17000 km(10557 miles) above the surface. To an observer on the ground this satellite would appear as a fixed point in the sky.
- **Heliosynchronous orbit**: A heliocentric orbit about the Sun where the satellite's orbital period matches the Sun's period of rotation. These orbits occur at a radius of 24,360 Gm (0.1628 AU) around the Sun, a little less than half of the orbital radius of Mercury.

Special classifications

- **Sun-synchronous orbit**: An orbit which combines altitude and inclination in such a way that the satellite passes over any given point of the planets's surface at the same local solar time. Such an orbit can place a satellite in constant sunlight and is useful for imaging, spy, and weather satellites.
- **Moon orbit**: The orbital characteristics of Earth's Moon. Average altitude of 384403 kilometres (238857 mi), elliptical–inclined orbit.

Pseudo-orbit classifications

- **Horseshoe orbit**: An orbit that appears to a ground observer to be orbiting a certain planet but is actually in co-orbit with the planet.
- **Exo-orbit**: A maneuver where a spacecraft approaches the height of orbit but lacks the velocity to sustain it.
    - **Suborbital spaceflight**: A synonym for exo-orbit.
- **Lunar transfer orbit (LTO)**

- **Prograde orbit**: An orbit with an inclination of less than 90°. Or rather, an orbit that is in the same direction as the rotation of the primary.
- **Retrograde orbit**: An orbit with an inclination of more than 90°. Or rather, an orbit counter to the direction of rotation of the planet. Apart from those in sun-synchronous orbit, few satellites are launched into retrograde orbit because the quantity of fuel required to launch them is much greater than for a prograde orbit. This is because when the rocket starts out on the ground, it already has an eastward component of velocity equal to the rotational velocity of the planet at its launch latitude.
- **Halo orbit** and **Lissajous orbit**: Orbits "around" Lagrangian points.

Satellite modules

The satellite's functional versatility is imbedded within its technical components and its operations characteristics. Looking at the "anatomy" of a typical satellite, one discovers two modules. Note that some novel architectural concepts such as Fractionated Spacecraft somewhat upset this taxonomy.

Spacecraft bus or service module

This bus module consist of the following subsystems:

- **The Structural Subsystems**

The structural subsystem provides the mechanical base structure, shields the satellite from extreme temperature changes and micro-meteorite damage, and controls the satellite's spin functions.

- **The Telemetry Subsystems** (aka Command and Data Handling, C&DH)

The telemetry subsystem monitors the on-board equipment operations, transmits equipment operation data to the earth control station, and receives the earth control station's commands to perform equipment operation adjustments.

- **The Power Subsystems**

The power subsystem consists of solar panels and backup batteries that generate power when the satellite passes into the Earth's shadow. Nuclear power sources (Radioisotope thermoelectric generators) have been used in several successful satellite programs including the Nimbus program (1964–1978).

- **The Thermal Control Subsystems**

The thermal control subsystem helps protect electronic equipment from extreme temperatures due to intense sunlight or the lack of sun exposure on different sides of the satellite's body (e.g. Optical Solar Reflector)

- **The Attitude and Orbit Controlled Control Subsystems**

The attitude and orbit controlled subsystem consists of small rocket thrusters that keep the satellite in the correct orbital position and keep antennas positioning in the right directions.

Communication payload

The second major module is the communication payload, which is made up of transponders. A transponder is capable of :

- Receiving uplinked radio signals from earth satellite transmission stations (antennas).
- Amplifying received radio signals
- Sorting the input signals and directing the output signals through input/output signal multiplexers to the proper downlink antennas for retransmission to earth satellite receiving stations (antennas).

End of life

When satellites reach the end of their mission, satellite operators have the option of de-orbiting the satellite, leaving the satellite in its current orbit or moving the satellite to a graveyard orbit. Historically, due to budgetary constraints at the beginning of satellite missions, satellites were rarely designed to be de-orbited. One example of this practice is the satellite Vanguard 1. Launched in 1958, Vanguard 1, the 4th manmade satellite put in Geocentric orbit, was still in orbit as of August 2009.

Instead of being de-orbited, most satellites are either left in their current orbit or moved to a graveyard orbit. As of 2002, the FCC now requires all geostationary satellites to commit to moving to a graveyard orbit at the end of their operational life prior to launch.

Launch-capable countries

Launch of the first British Skynet military satellite.

This list includes countries with an independent capability to place satellites in orbit, including production of the necessary launch vehicle. Note: many more countries have the capability to design and build satellites but are unable to launch them, instead relying on foreign launch services. This list does not consider those numerous countries, but only lists those capable of launching satellites indigenously, and the date this capability was first demonstrated. Does not include consortium satellites or multi-national satellites.

'First launch by country				
Order	**Country**	**Year of first launch**	**Rocket**	**Satellite**
1	Soviet Union	1957	Sputnik-PS	*Sputnik 1*
2	United States	1958	Juno I	*Explorer 1*
3	France	1965	Diamant	*Astérix*
4	Japan	1970	Lambda-4S	*Ōsumi*
5	China	1970	Long March 1	*Dong Fang Hong I*
6	United Kingdom	1971	Black Arrow	*Prospero X-3"*
7	India	1980	SLV	*Rohini*
8	Israel	1988	Shavit	*Ofeq 1*
_	Russia	1992	Soyuz-U	*Kosmos 2175*
_	Ukraine	1992	Tsyklon-3	*Strela*
9	Iran	2009	Safir-2	*Omid*

Notes

1. Russia and Ukraine were parts of the Soviet Union and thus inherited their launch capability without the need to develop it indigenously. Through Soviet Union they also are on the number one position in this list of accomplishments.
2. France, United Kingdom launched their first satellites by own launchers from foreign spaceports.
3. North Korea (1998) and Iraq (1989) have claimed orbital launches (satellite and warhead accordingly), but these claims are unconfirmed.
4. In addition to the above, countries such as South Africa, Spain, Italy, Germany, Canada, Australia, Argentina, Egypt and private companies such as OTRAG, have developed their own launchers, but have not had a successful launch.
5. As of 2009, only eight countries from the list above (Russia and Ukraine instead of USSR, also USA, Japan, China, India, Israel and Iran) and one regional organization (the European Space Agency, ESA) have independently launched satellites on their own indigenously developed launch vehicles. (The launch capabilities of the United Kingdom and France now fall under the ESA.)
6. Several other countries, including South Korea, Brazil, Pakistan, Romania, Taiwan, Indonesia, Kazakhstan, Australia, Malaysia and Turkey, are at various stages of development of their own small-scale launcher capabilities.
7. South Korea launched a KSLV rocket (created with assistance of Russia) in 25 August 2009, but it failed to put satellite STSAT-2 into precise orbit and the satellite did not start to function.
8. North Korea claimed a launch in April 2009, but U.S. and South Korea] defense officials and weapons experts later reported that the rocket failed to send a satellite into orbit, if that was the goal. The United States, Japan and South Korea believe this was actually a ballistic missile test, which is a claim also made after North Korea's 1998 satellite launch, and later rejected.

Launch capable private entities

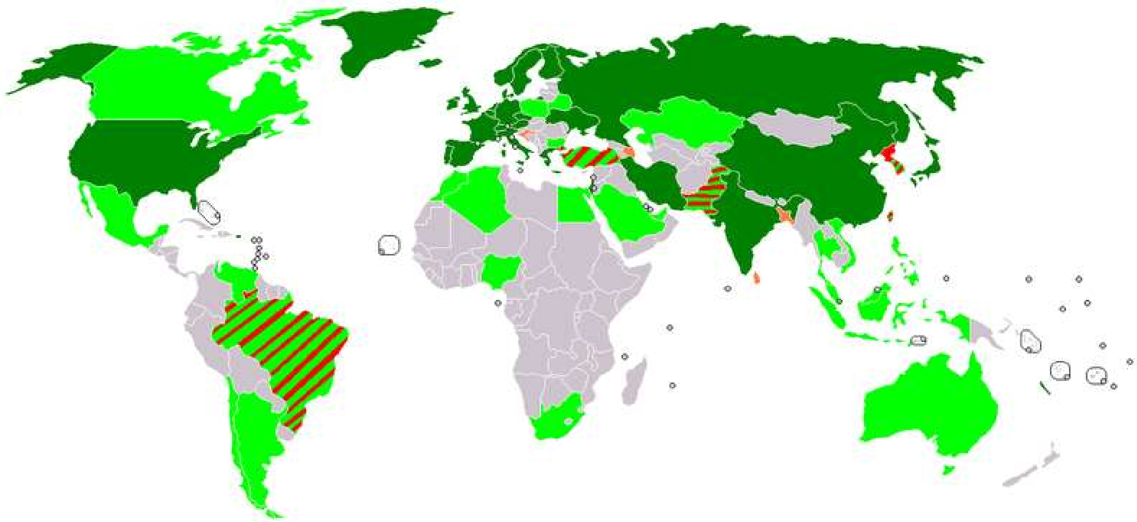
- Orbital Sciences Corporation is conducting launches using its Taurus I rocket.
- On September 28, 2008, the private aerospace firm SpaceX successfully launched its Falcon 1 rocket in to orbit. This marked the first time that a privately built liquid-fueled booster was able to reach orbit. The rocket carried a prism shaped 1.5 m (5 ft) long payload mass simulator that was set into orbit. The dummy satellite, known as Ratsat, will remain in orbit for between five and ten years before burning up in the atmosphere.

A few other private companies are capable of sub-orbital launches.

First satellites of countries

First satellites of countries including launched indigenously or by help of other			
Country	**Year of first launch**	**First satellite**	**Payloads in orbit in 2010**
Soviet Union (Russia)	1957 (1992)	*Sputnik 1* *(Cosmos-2175)*	1435
United States	1958	*Explorer 1*	1093
United Kingdom	1962	*Ariel 1*	29
Canada	1962	*Alouette 1*	31
Italy	1964	*San Marco 1*	17
France	1965	*Astérix*	49
Australia	1967	*WRESAT*	11
Germany	1969	*Azur*	42
Japan	1970	*Ōsumi*	124
China	1970	*Dong Fang Hong I*	102
Poland	1973	*Intercosmos Kopernikus 500*	?
Netherlands	1974	*ANS*	5
Spain	1974	*Intasat*	9
India	1975	*Aryabhata*	34
Indonesia	1976	*Palapa A1*	10
Czechoslovakia	1978	*Magion 1*	5
Bulgaria	1981	*Intercosmos Bulgaria 1300*	1
Brazil	1985	*Brasilsat A1*	11
Mexico	1985	*Morelos 1*	7
Sweden	1986	*Viking*	11

Israel	1988	*Ofeq 1*	7
Luxembourg	1988	*Astra 1A*	15
Argentina	1990	*Lusat*	10
Pakistan	1990	*Badr-1*	5
South Korea	1992	*Kitsat A*	10
Portugal	1993	*PoSAT-1*	1
Thailand	1993	*Thaicom 1*	6
Turkey	1994	*Turksat 1B*	5
Ukraine	1995	*Sich-1*	6
Chile	1995	*FASat-Alfa*	1
Malaysia	1996	*MEASAT*	4
Norway	1997	*Thor 2*	3
Philippines	1997	*Mabuhay 1*	2
Egypt	1998	*Nilesat 101*	3
Singapore	1998	*ST-1*	1
Taiwan	1999	*ROCSAT-1*	9
Denmark	1999	*Ørsted*	4
South Africa	1999	*SUNSAT*	2
Saudi Arabia	2000	*Saudisat 1A*	12
United Arab Emirates	2000	*Thuraya 1*	3
Morocco	2001	*Maroc-Tubsat*	1
Algeria	2002	*Alsat 1*	1
Greece	2003	*Hellas Sat 2*	2
Nigeria	2003	*Nigeriasat 1*	2
Iran	2005	*Sina-1*	4
Kazakhstan	2006	*KazSat 1*	1
Belarus	2006	*BelKA*	1
Colombia	2007	*Libertad 1*	1
Mauritius	2007	*Rascom-QAF 1*	2
Vietnam	2008	*VINASAT-1*	1
Venezuela	2008	*Venesat-1*	1
Switzerland	2009	*SwissCube-1*	1



orbital launch and satellite operation
satellite operation, launched by foreign supplier
satellite in development
orbital launch project at advanced stage or indigenous ballistic missiles deployed

While Canada was the third country to build a satellite which was launched into space, it was launched aboard a U.S. rocket from a U.S. spaceport. The same goes for Australia, who launched on-board a donated Redstone rocket. The first Italian-launched was San Marco 1, launched on 15 December 1964 on a U.S. Scout rocket from Wallops Island (VA,USA) with an Italian Launch Team trained by NASA. Australia's launch project (WRESAT) involved a donated U.S. missile and U. S. support staff as well as a joint launch facility with the United Kingdom.

Planned first satellites

- Azerbaijan is developing its space satellite Azerspace. According to the approved plan, Azerspace satellite will be launched into orbit in 2011.
- Bangladesh announced in 2009 that it intends to launch its first satellite into space by 2011.
- Croatia has a goal to construct a satellite by 2013–2014. Launch into Earth orbit would be done by a foreign provider.
- Finland Aalto-1 is a student satellite project of Aalto University, Finland. When launched, it would be the first Finnish satellite.
- Latvia The project of nano-satellite Venta-1 which will be built in Latvia, in cooperation with the German engineers. The satellite is intended for automatic system of identification of the ships of a sailing charter developed by *OHB-System AG.* The launch of the satellite was planned for the end of 2009 using the Indian carrier rocket. Due to the financial crisis the launch has been postponed until 2010.
- Peru is developing its space satellite with the National Engineering University, called Chasqui 1. The nano-satellite will be launched into orbit by

2011, and will have an expected 60-day lifespan. As payload are installed two small VGA cameras. One of both will have a NIR filter.

-  Romania announced that it has finished construction of its first satellite, called Goliat. The satellite will be launched into orbit in 2011.
-  Sri Lanka has a goal to construct two satellites. Sri Lankan Telecommunications Regulatory Commission has signed an agreement with Surrey Satellite Technology Ltd to get relevant help and resources. Launch into Earth orbit would be done by a foreign provider.
-  Tunisia is developing its first satellite, ERPSat01. Consisting of a CubeSat of 1 kg weight, it will be developed by the Sfax School of Engineering. ERPSat satellite is planned to be launched into orbit in 2013.

Attacks on satellites

In recent times satellites have been hacked by militant organizations to broadcast propaganda and to pilfer classified information from military communication networks.

As test, satellites in low earth orbit have been destroyed by ballistic missiles launched from earth. Russia, the United States and China have demonstrated the ability to eliminate satellites. In 2007 the Chinese military shot down an aging weather satellite, followed by the US Navy shooting down a defunct spy satellite in February 2008.

Jamming

Due to the low received signal strength of satellite transmissions, they are prone to jamming by land-based transmitters. Such jamming is limited to the geographical area within the transmitter's range. GPS satellites are potential targets for jamming, but satellite phone and television signals have also been subjected to jamming.

Also, it is trivial to transmit a carrier radio signal to a geostationary satellite and thus interfere with the legitimate uses of the satellite's transponder. It is common for Earth stations to transmit at the wrong time or on the wrong frequency in commercial satellite space, and dual-illuminate the transponder, rendering the frequency unusable. Satellite operators now have sophisticated monitoring that enables them to pinpoint the source of any carrier and manage the transponder space effectively.

Chapter- 5

Spacecraft

Soyuz 19 spacecraft for the Apollo Soyuz Test Project

A **spacecraft** or **spaceship** is a craft or machine designed for spaceflight. Spacecraft are used for a variety of purposes, including communications, earth observation, meteorology, navigation, planetary exploration and transportation of humans and cargo.

On a sub-orbital spaceflight, a spacecraft enters space and then returns to the surface, without having gone into an orbit. For orbital spaceflights, spacecraft enter closed orbits around the Earth or around other celestial bodies. Spacecraft used for human spaceflight carry people on board as crew or passengers, while those used for robotic space missions operate either autonomously or telerobotically. Robotic spacecraft used to support scientific research are space probes. Robotic spacecraft that remain in orbit around a planetary body are artificial satellites. Only a handful of interstellar probes, such as Pioneer 10 and 11, Voyager 1 and 2, and New Horizons, are currently on trajectories that leave our Solar System.

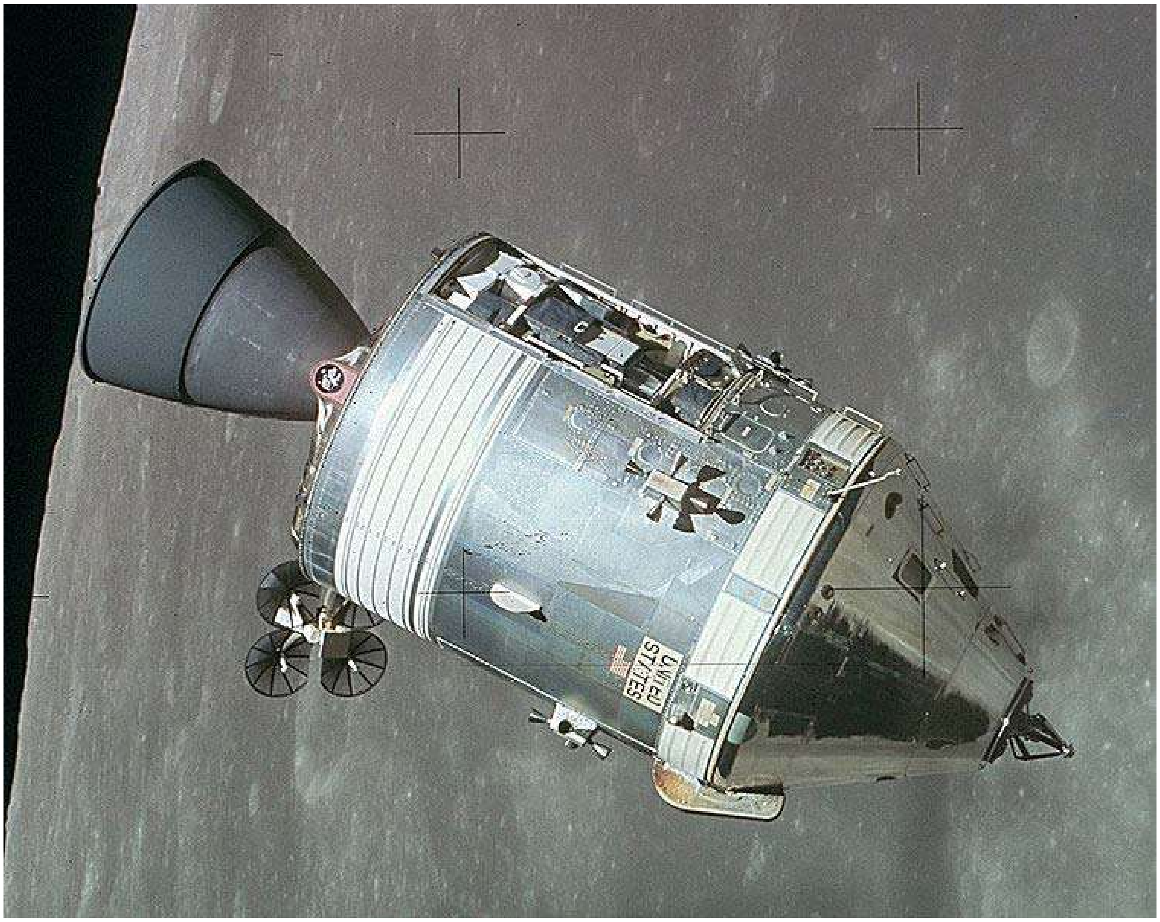
Spacecraft and space travel are common themes in works of science fiction.

History

The first Earth orbiting satellite was Sputnik 1, which was launched 4 October 1957, and remained in orbit for several months. While Sputnik 1 was the first spacecraft to orbit the Earth, other man-made objects had previously reached an altitude of 100 km, which is the height required by the international organization Fédération Aéronautique Internationale to count as a spaceflight. This altitude is called the Kármán line. In particular, in the 1940's there were several test launches of the V-2 rocket, some of which reached altitudes well over 100 km.

Past and present spacecraft

Manned spacecraft



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

A Russian Soyuz bringing a crew to the ISS.

The first manned spacecraft was Vostok 1, which carried Soviet cosmonaut Yuri Gagarin into space in 1961, and complete a full Earth orbit. There were five other manned missions which used a Vostok spacecraft. The second manned spacecraft was named *Freedom 7*, and it performed a sub-orbital spaceflight carrying American astronaut Alan Shepherd to an altitude of just over 187 kilometres (116 mi). There were five other manned missions using at Mercury spacecraft, like *Freedom 7*.

Other Soviet manned spacecraft include the Voskhod spacecraft, Soyuz spacecraft, and the Salyut space stations as well as the space station *Mir*. Other American manned spacecraft include the Gemini Spacecraft, Apollo Spacecraft, the Skylab space station, and the Space Shuttle. China was also developed the Shenzhou spacecraft, which as of January 2011 has been used for three manned missions, the first being Shenzhou 5 in 2003.

The International Space Station, which has been manned since November 2000, in a joint venture between Russian, the United States, as well as several other countries.

Strictly speaking, the Manned Maneuvering Unit, the propulsion system used by spacewalking astronauts, could be counted as a manned spacecraft.

Spaceplanes

There have been some reusable vehicles designed only for manned spaceflight, and these are often called spaceplanes. The first example of such was the North American X-15 spaceplane, which conducted two manned flights which reached a height over 100 km, both of which were in the 1960's.

Space Shuttle Columbia's first launch.

Columbia orbiter landing

The first reusable spacecraft, the X-15, was air-launched on a suborbital trajectory on July 19, 1963. The first partially reusable orbital spacecraft, the Space Shuttle, was launched by the USA on the 20th anniversary of Yuri Gagarin's flight, on April 12, 1981. During the Shuttle era, six orbiters were built, all of which have flown in the atmosphere and five of which have flown in space. The *Enterprise* was used only for approach and landing tests, launching from the back of a Boeing 747 and gliding to deadstick landings at Edwards AFB, California. The first Space Shuttle to fly into space was the *Columbia*, followed by the *Challenger*, *Discovery*, *Atlantis*, and *Endeavour*. The *Endeavour* was built to replace the *Challenger* when it was lost in January 1986. The *Columbia* broke up during reentry in February 2003.

The first automatic partially reusable spacecraft was the Buran (Snowstorm), launched by the USSR on November 15, 1988, although it made only one flight. This spaceplane was designed for a crew and strongly resembled the U.S. Space Shuttle, although its drop-off boosters used liquid propellants and its main engines were located at the base of what would be the external tank in the American Shuttle. Lack of funding, complicated by the dissolution of the USSR, prevented any further flights of Buran. The Space Shuttle has since been modified to allow for autonomous re-entry via the addition of a control cable running from the control cabin to the mid-deck which would allow for the automated deployment of the landing gear in the event a un-crewed re-entry was required following abandonment due to damage at the ISS.

Per the Vision for Space Exploration, the Space Shuttle is due to be retired in 2011 due mainly to its old age and high cost of program reaching over a billion dollars per flight. The Shuttle's human transport role is to be replaced by the partially reusable Crew

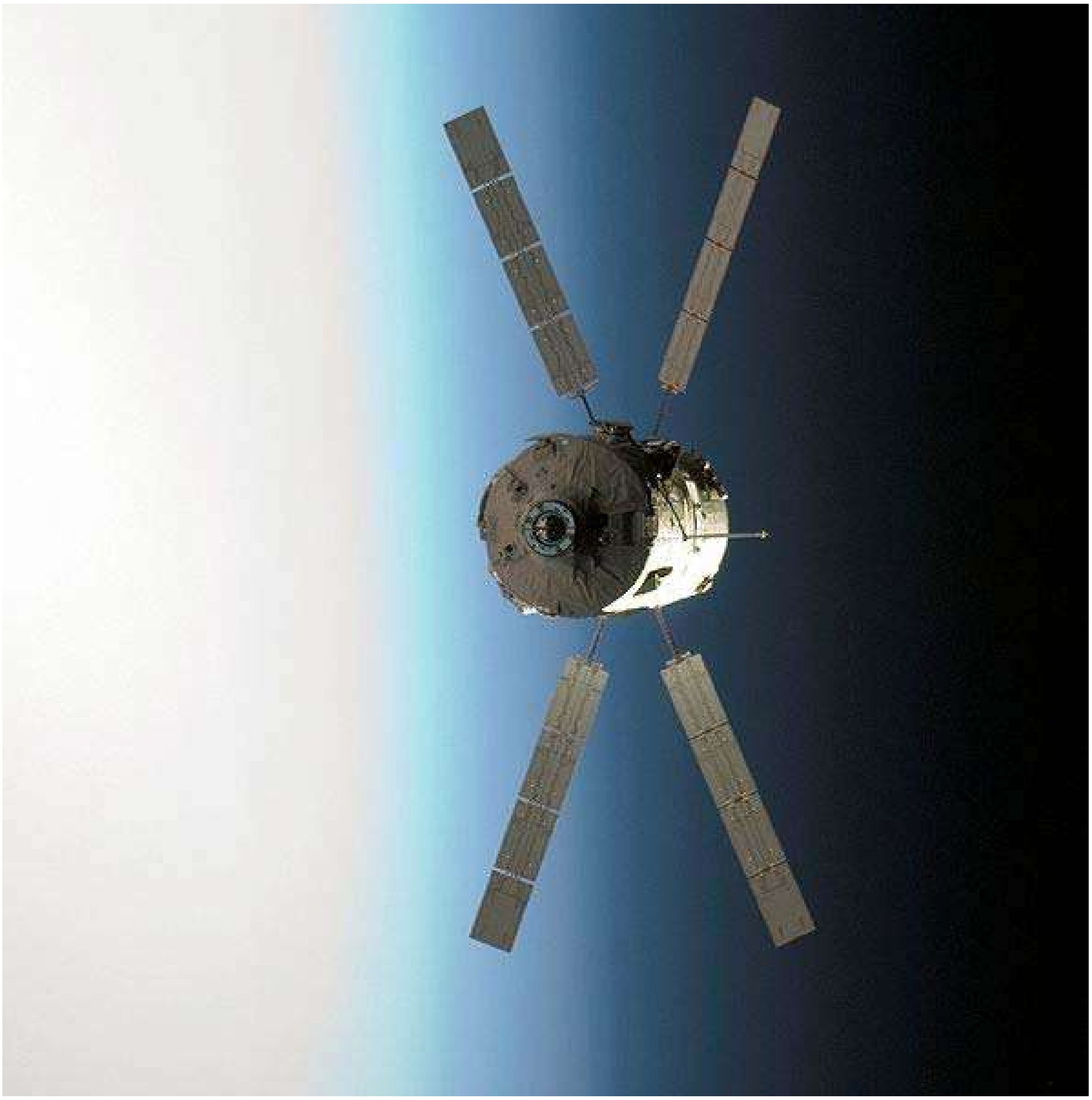
Exploration Vehicle (CEV) no later than 2014. The Shuttle's heavy cargo transport role is to be replaced by expendable rockets such as the Evolved Expendable Launch Vehicle (EELV) or a Shuttle Derived Launch Vehicle.

Scaled Composites' SpaceShipOne was a reusable suborbital spaceplane that carried pilots Mike Melvill and Brian Binnie on consecutive flights in 2004 to win the Ansari X Prize. The Spaceship Company will build its successor SpaceShipTwo. A fleet of SpaceShipTwos operated by Virgin Galactic should begin reusable private spaceflight carrying paying passengers in 2011.

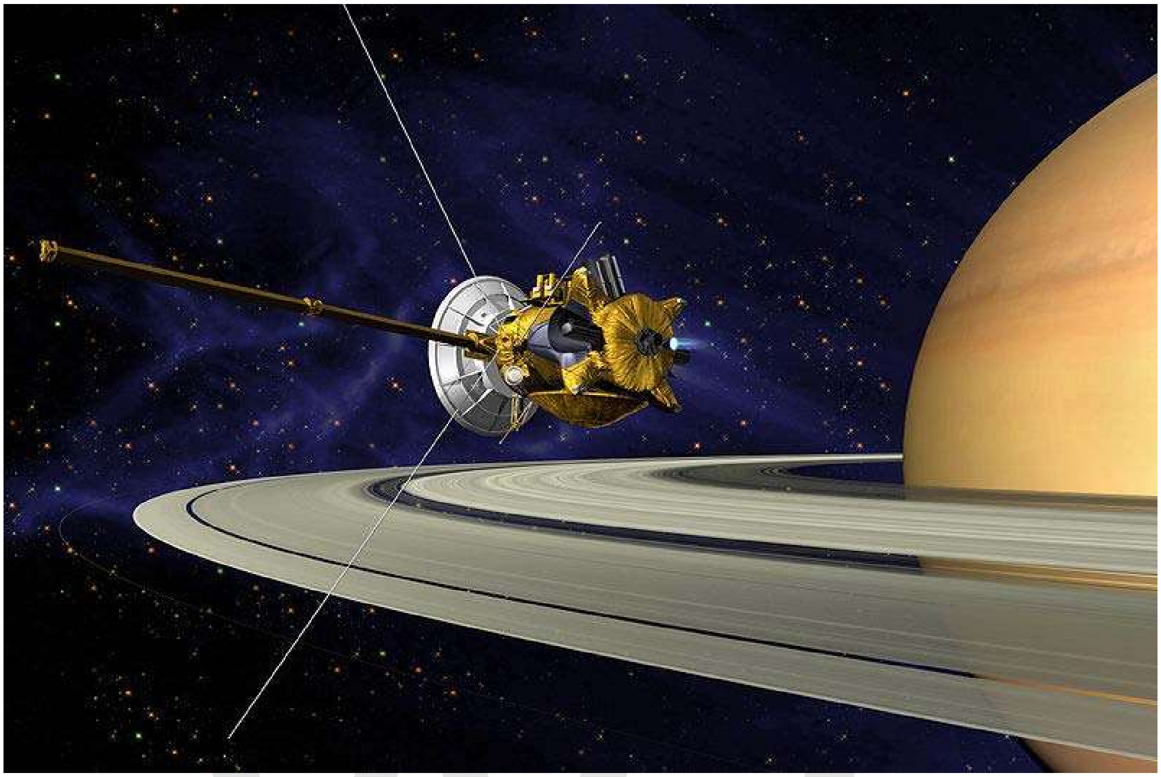
XCOR Aerospace also plans to initiate a suborbital commercial spaceflight service with the Lynx rocketplane in 2012 through a partnership with RocketShip Tours. First test flights are planned for 2011.

Unmanned spacecraft

The Hubble Space Telescope



The Jules Verne Automated Transfer Vehicle (ATV) approaches the International Space Station on Monday, March 31, 2008.


Artist's conception of Cassini-Huygens as it enters Saturn's orbit

Semi-manned or manned-spec unmanned spacecraft

- Automated Transfer Vehicle (ATV) – unmanned European cargo spacecraft
- Buran manned-spec Soviet shuttle (one mission only)
- H-II Transfer Vehicle (HTV) – unmanned Japanese cargo spacecraft
- Progress – unmanned USSR/Russia cargo spacecraft
- TKS – manned-spec unmanned USSR cargo spacecraft

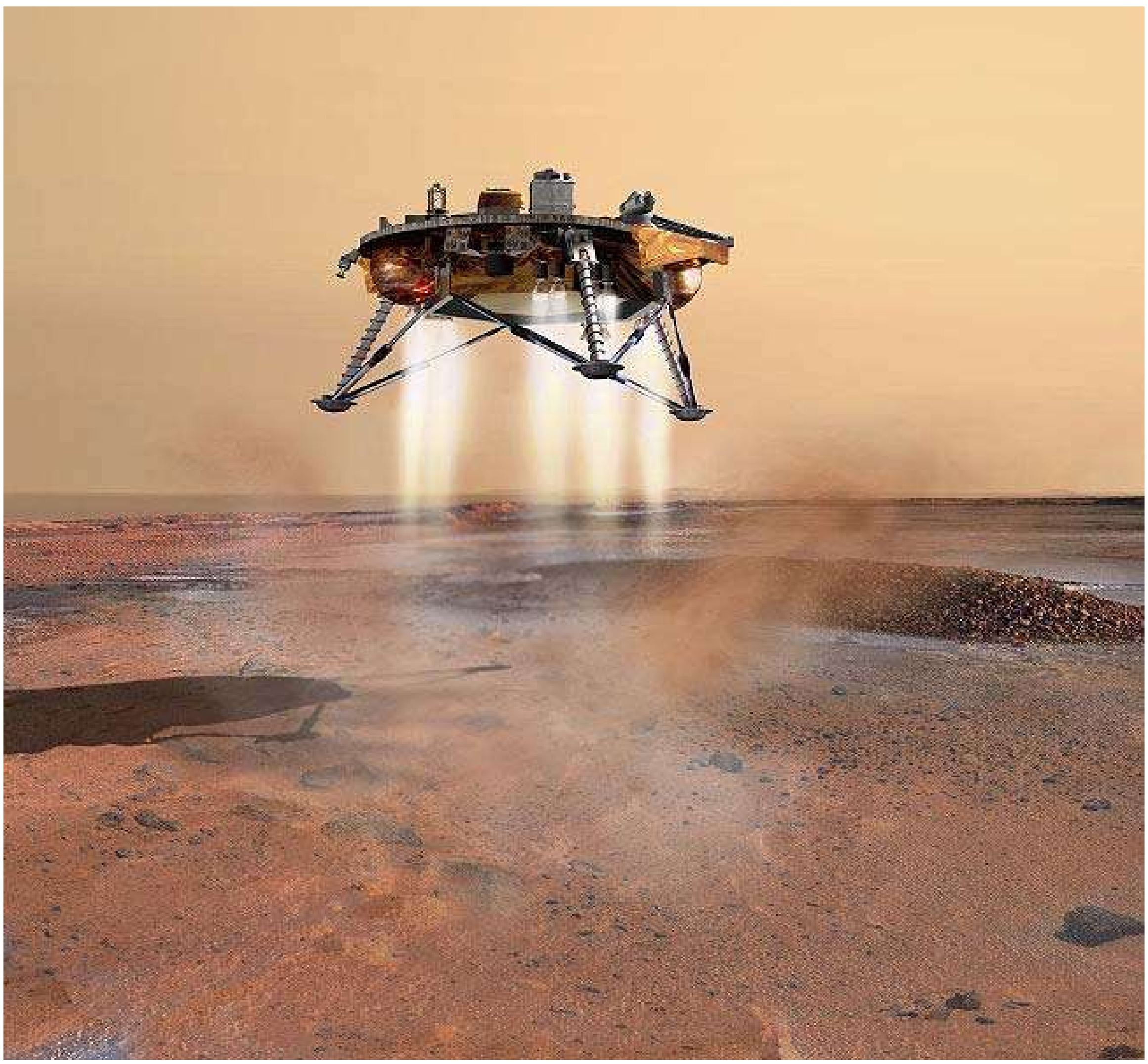
Earth Orbit

- Explorer 1 – first US satellite
- Project SCORE – first communications satellite
- SOHO
- Sputnik 1 – world's first artificial satellite
- Sputnik 2 – first animal in orbit (Laika)
- Sputnik 5 – first capsule recovered from orbit (Vostok precursor) – animals survived
- STEREO – Earth environment observation
- Syncom – first geosynchronous communications satellite
- X-37 – spaceplane
- There are more than 2,000 spacecrafts in orbit.

Lunar

- Clementine – US Navy mission, orbited Moon, detected hydrogen at the poles

- Kaguya JPN – Lunar orbiter
- Luna 1 – first lunar flyby
- Luna 2 – first lunar impact
- Luna 3 – first images of lunar far side
- Luna 9 – first soft landing on the Moon
- Luna 10 – first lunar orbiter
- Luna 16 – first unmanned lunar sample retrieval
- Lunar Orbiter – very successful series of lunar mapping spacecraft
- Lunar Prospector – confirmed detection of hydrogen at the lunar poles
- Lunar Reconnaissance Orbiter – Identifies safe landing sites & Locates moon resources
- SMART-1 ESA – Lunar Impact
- Surveyor – first USA soft lander
- Chandrayaan 1 – first Indian Lunar mission



Artist's conception of the Phoenix spacecraft as it lands on Mars

Planetary

- Akatsuki JPN – a Venus orbiter
- Cassini-Huygens – first Saturn orbiter + Titan lander
- Galileo – first Jupiter orbiter+descent probe
- IKAROS JPN – first solar-sail spacecraft
- Mariner 4 – first Mars flyby, first close and high resulution images of Mars
- Mariner 9 – first Mars orbiter
- Mariner 10 – first Mercury flyby, first close up images
- Mars Exploration Rover – a Mars rover
- Mars Express – a Mars orbiter
- Mars Global Surveyor – a Mars orbiter
- Mars Reconnaissance Orbiter – an advanced climate, imaging, sub-surface radar, and telecommunications Mars orbiter
- MESSENGER – first Mercury orbiter (arrival 2011)
- Mars Pathfinder – a Mars lander + rover
- New Horizons – first Pluto flyby (arrival 2015)
- Pioneer 10 – first Jupiter flyby, first close up images
- Pioneer 11 – second Jupiter flyby + first Saturn flyby (first close up images of Saturn)
- Pioneer Venus – first Venus orbiter+landers
- Vega 1 **-** Balloon release into Venus atmosphere and lander (joint mission with Vega 2), mothership continued on to rendesvous with Halley's Comet
- Venera 4 – first soft landing on another planet (Venus)
- Viking 1 – first soft landing on Mars
- Voyager 2 – Jupiter flyby + Saturn flyby + first flybys/images of Neptune and Uranus

Other – deep space

- Cluster
- Deep Space 1
- Deep Impact
- Genesis
- Hayabusa
- Near Earth Asteroid Rendezvous
- Stardust
- WMAP

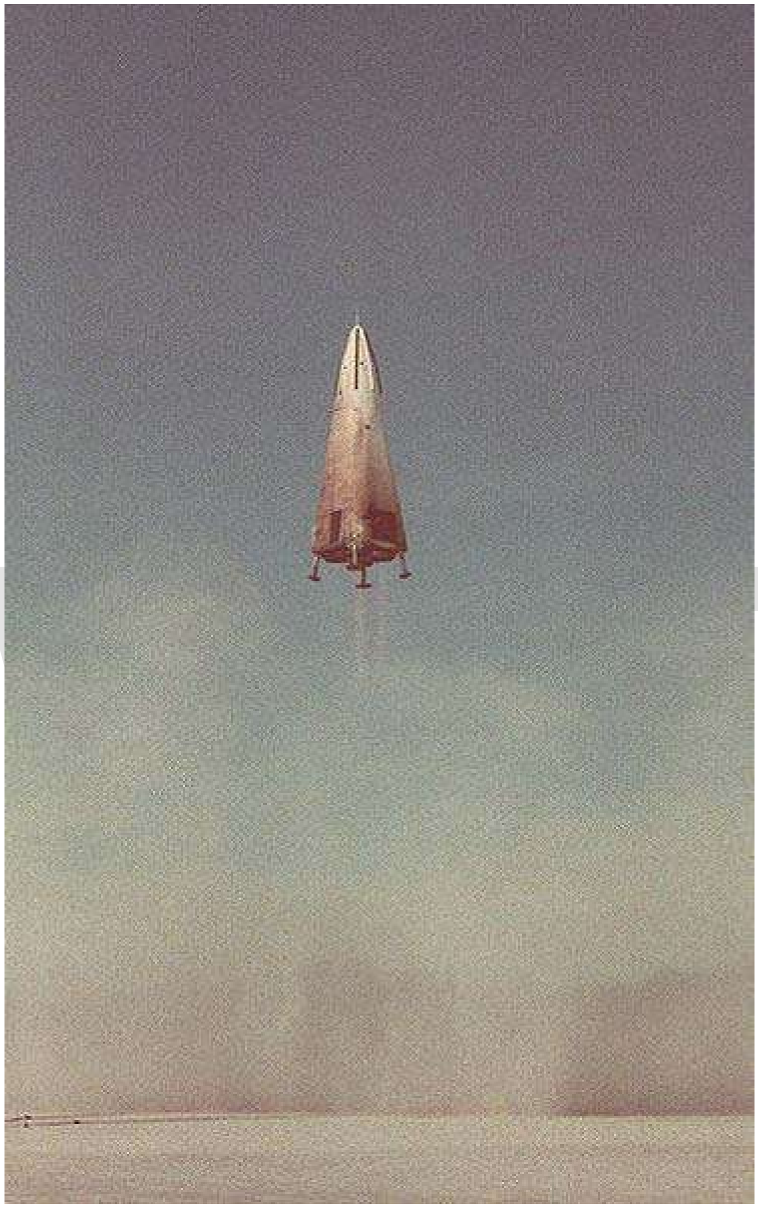
Fastest spacecraft

- Helios I & II *Solar Probes* (252,792 km/h/157,078 mph)

Furthest spacecraft from the Sun

- Voyager 1 at 106.3 AU as of July 2008, traveling outward at about 3.6 AU/year
- Pioneer 10 at 89.7 AU as of 2005, traveling outward at about 2.6 AU/year
- Voyager 2 at 85.49 AU as of July 2008, traveling outward at about 3.3 AU/year

Unfunded / canceled programs



The First Test Flight of the Delta Clipper-Experimental Advanced (DC-XA)
Multi-stage

- Chinese Project 921-3 Shuttle
- Kliper—Russian "Clipper"
- ESA Hermes Shuttle
- Soviet Buran Shuttle
- Soyuz Kontakt
- Teledesic
- Manned Orbiting Laboratory
- X-20
- Altair - lunar lander

SSTO

- RR/British Aerospace HOTOL
- ESA Hopper Orbiter
- McDonnell Douglas DC-X (Delta Clipper)
- Roton Rotored-Hybrid
- Lockheed-Martin VentureStar

Spacecraft under development

The Orion spacecraft

Manned

- Orion - capsule
- SpaceX Dragon - capsule
- Lynx rocketplane - suborbital
- ISRO Orbital Vehicle - capsule
- PTK NP spacecraft- capsule
- Dream Chaser - spaceplane
- Prometheus - spaceplane
- SpaceShipTwo - spaceplane
- Boeing CST-100 - capsule
- proposed ESA Advanced Reentry Vehicle - capsule
- Skylon - single-stage-to-orbit spaceplane

Unmanned

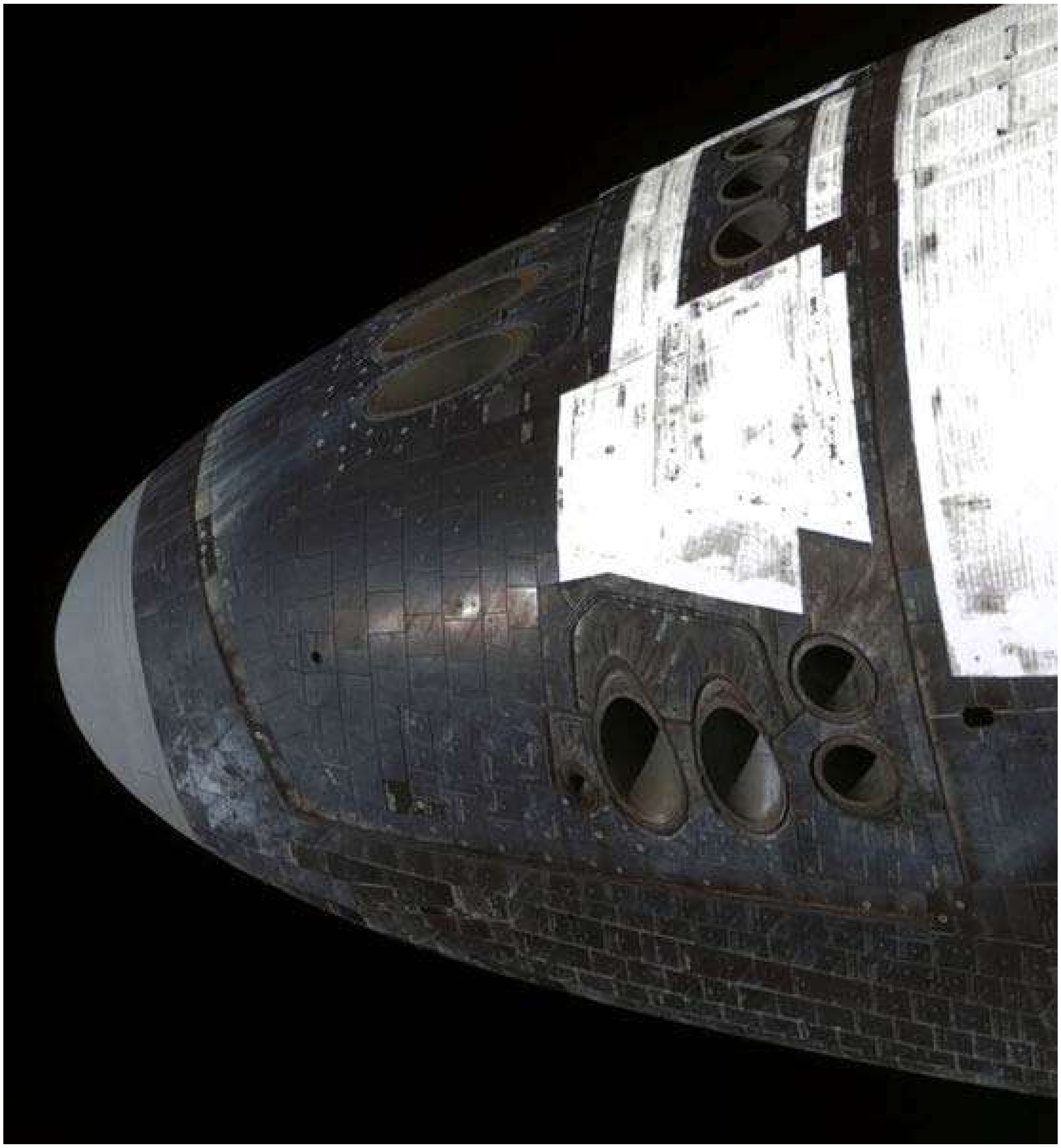
- SpaceX Dragon - cargo delivery to the ISS
- Orbital Sciences Cygnus - cargo delivery to the ISS
- CNES Mars Netlander
- James Webb Space Telescope (delayed)
- ESA Darwin probe
- Mars Science Laboratory rover
- Shenzhou spacecraft Cargo
- Terrestrial Planet Finder probe
- System F6—a DARPA Fractionated Spacecraft demonstrator

Subsystems

A spacecraft system comprises various subsystems, dependent upon mission profile. Spacecraft subsystems comprise the spacecraft "*bus*" and may include: attitude determination and control (variously called ADAC, ADC or ACS), guidance, navigation and control (GNC or GN&C), communications (Comms), command and data handling (CDH or C&DH), power (EPS), thermal control (TCS), propulsion, and structures. Attached to the bus are typically *payloads*.

Life support

Spacecraft intended for human spaceflight must also include a life support system for the crew.



Reaction control system thrusters on the nose of the U.S. Space Shuttle

Attitude control

A Spacecraft needs an attitude control subsystem to be correctly oriented in space and respond to external torques and forces properly. The attitude control subsystem consists of sensors and actuators, together with controlling algorithms. The attitude control subsystem permits proper pointing for the science objective, sun pointing for power to the solar arrays and earth-pointing for communications.

GNC

Guidance refers to the calculation of the commands (usually done by the CDH subsystem) needed to steer the spacecraft where it is desired to be. Navigation means determining a spacecraft's orbital elements or position. Control means adjusting the path of the spacecraft to meet mission requirements. On some missions, GNC and Attitude Control are combined into one subsystem of the spacecraft.

Command and data handling

The CDH subsystem receives commands from the communications subsystem, performs validation and decoding of the commands, and distributes the commands to the appropriate spacecraft subsystems and components. The CDH also receives housekeeping data and science data from the other spacecraft subsystems and components, and packages the data for storage on a data recorder or transmission to the ground via the communications subsystem. Other functions of the CDH include maintaining the spacecraft clock and state-of-health monitoring.

Power

Spacecraft need an electrical power generation and distribution subsystem for powering the various spacecraft subsystems. For spacecraft near the Sun, solar panels are frequently used to generate electrical power. Spacecraft designed to operate in more distant locations, for example Jupiter, might employ a Radioisotope Thermoelectric Generator (RTG) to generate electrical power. Electrical power is sent through power conditioning equipment before it passes through a power distribution unit over an electrical bus to other spacecraft components. Batteries are typically connected to the bus via a battery charge regulator, and the batteries are used to provide electrical power during periods when primary power is not available, for example when a Low Earth Orbit (LEO) spacecraft is eclipsed by the Earth.

Thermal control

Spacecraft must be engineered to withstand transit through the Earth's atmosphere and the space environment. They must operate in a vacuum with temperatures potentially ranging across hundreds of degrees Celsius as well as (if subject to reentry) in the presence of plasmas. Material requirements are such that either high melting temperature, low density materials such as beryllium and reinforced carbon-carbon or (possibly due to the lower thickness requirements despite its high density) tungsten or ablative carbon/carbon composites are used. Depending on mission profile, spacecraft may also need to operate on the surface of another planetary body. The thermal control subsystem can be passive, dependent on the selection of materials with specific radiative properties. Active thermal control makes use of electrical heaters and certain actuators such as louvers to control temperature ranges of equipments within specific ranges.

A launch vehicle, like this Proton rocket, is typically used to bring a spacecraft to orbit.

Propulsion

Spacecraft may or may not have a propulsion subsystem, depending upon whether or not the mission profile calls for propulsion. The *Swift* spacecraft is an example of a spacecraft that does not have a propulsion subsystem. Typically though, LEO spacecraft (for example *Terra (EOS AM-1)* include a propulsion subsystem for altitude adjustments (called drag make-up maneuvers) and inclination adjustment maneuvers. A propulsion system is also needed for spacecraft that perform momentum management maneuvers. Components of a conventional propulsion subsystem include fuel, tankage, valves, pipes, and thrusters. The TCS interfaces with the propulsion subsystem by monitoring the temperature of those components, and by preheating tanks and thrusters in preparation for a spacecraft maneuver.

Structures

Spacecraft must be engineered to withstand launch loads imparted by the launch vehicle, and must have a point of attachment for all the other subsystems. Depending upon mission profile, the structural subsystem might need to withstand loads imparted by entry into the atmosphere of another planetary body, and landing on the surface of another planetary body.

Payload

The payload is dependent upon the mission of the spacecraft, and is typically regarded as the part of the spacecraft "that pays the bills". Typical payloads could include scientific instruments (cameras, telescopes, or particle detectors, for example), cargo, or a human crew.

Ground segment

The ground segment, though not technically part of the spacecraft, is vital to the operation of the spacecraft. Typical components of a ground segment in use during normal operations include a mission operations facility where the flight operations team conducts the operations of the spacecraft, a data processing and storage facility, ground stations to radiate signals to and receive signals from the spacecraft, and a voice and data communications network to connect all mission elements.

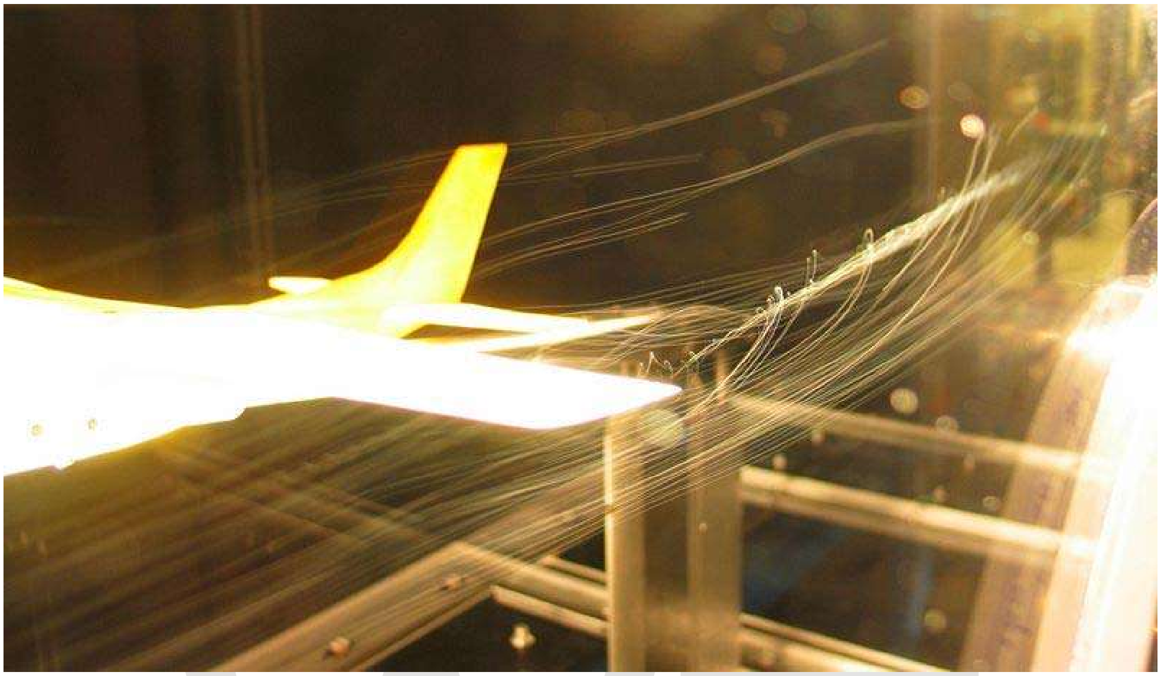
Launch vehicle

The launch vehicle propels the spacecraft from the Earth's surface, through the atmosphere, and into an orbit, the exact orbit being dependent upon mission configuration. The launch vehicle may be expendable or reusable.

Chapter- 6

Wind Tunnel

NASA wind tunnel with the model of a plane.


A model Cessna with helium-filled bubbles showing streamlines of the wingtip vortices.

A **wind tunnel** is a research tool used in aerodynamic research. It is used to study the effects of air moving past solid objects.

Theory of operation

Wind tunnels were first proposed as a means of studying vehicles (primarily airplanes) in free flight. The wind tunnel was envisioned as a means of reversing the usual paradigm: instead of the air's standing still and the aircraft moving at speed through it, the same effect would be obtained if the aircraft stood still and the air moved at speed past it. In that way a stationary observer could study the aircraft in action, and could measure the aerodynamic forces being imposed on the aircraft.

Later, wind tunnel study came into its own: the effects of wind on manmade structures or objects needed to be studied, when buildings became tall enough to present large surfaces to the wind, and the resulting forces had to be resisted by the building's internal structure. Determining such forces was required before building codes could specify the required strength of such buildings.

Still later, wind-tunnel testing was applied to automobiles, not so much to determine aerodynamic forces *per se* but more to determine ways to reduce the power required to move the vehicle on roadways at a given speed. In these studies, the interaction between the road and the vehicle plays a significant role, and this interaction must be taken into consideration when interpreting the test results. In an actual situation the roadway is moving relative to the vehicle but the air is stationary relative to the roadway, but in the wind tunnel the air is moving relative to the roadway, while the roadway is stationary relative to the test vehicle. Some automotive-test wind tunnels have incorporated moving belts under the test vehicle in an effort to approximate the actual condition.

Measurement of aerodynamic forces

Ways that air velocity and pressures are measured in wind tunnels:

- air velocity through the test section is determined by Bernoulli's principle. Measurement of the dynamic pressure, the static pressure, and (for compressible flow only) the temperature rise in the airflow
- direction of airflow around a model can be determined by tufts of yarn attached to the aerodynamic surfaces
- direction of airflow approaching an aerodynamic surface can be visualized by mounting threads in the airflow ahead of and aft of the test model
- dye, smoke, or bubbles of liquid can be introduced into the airflow upstream of the test model, and their path around the model can be photographed
- pressures on the test model are usually measured with beam balances, connected to the test model with beams or strings or cables
- pressure distributions across the test model have historically been measured by drilling many small holes along the airflow path, and using multi-tube manometers to measure the pressure at each hole
- pressure distributions can more conveniently be measured by the use of pressure-sensitive paint, in which higher local pressure is indicated by lowered fluorescence of the paint at that point
- pressure distributions can also be conveniently measured by the use of pressure-sensitive pressure belts, a recent development in which multiple ultra-miniaturized pressure sensor modules are integrated into a flexible strip. The strip is attached to the aerodynamic surface with tape, and it sends signals depicting the pressure distribution along its surface.
- pressure distributions on a test model can also be determined by performing a **wake survey**, in which either a single pitot tube is used to obtain multiple readings downstream of the test model, or a multiple-tube manometer is mounted downstream and all its readings are taken (often by photograph).

History of wind tunnels

The First Wind Tunnels

English military engineer and mathematician Benjamin Robins (1707–1751) invented a whirling arm apparatus to determine drag and did some of the first experiments in aviation theory.

Sir George Cayley (1773–1857) also used a whirling arm to measure the drag and lift of various airfoils. His whirling arm was 5 feet long and attained top speeds between 10 and 20 feet per second.

However, the whirling arm does not produce a reliable flow of air impacting the test shape at a normal incidence. Centrifugal forces and the fact that the object is moving in its own wake mean that detailed examination of the airflow is difficult. Francis Herbert Wenham (1824–1908), a Council Member of the Aeronautical Society of Great Britain, addressed these issues by inventing, designing and operating the first enclosed wind tunnel in 1871. Once this breakthrough had been achieved, detailed technical data was rapidly extracted by the use of this tool. Wenham and his colleague Browning are credited with many fundamental discoveries, including the measurement of l/d ratios, and the revelation of the beneficial effects of a high aspect ratio.

Carl Rickard Nyberg used a wind tunnel when designing his *Flugan* from 1897 and onwards.

In a classic set of experiments, the Englishman Osborne Reynolds (1842–1912) of the University of Manchester demonstrated that the airflow pattern over a scale model would be the same for the full-scale vehicle if a certain flow parameter were the same in both cases. This factor, now known as the Reynolds Number, is a basic parameter in the description of all fluid-flow situations, including the shapes of flow patterns, the ease of heat transfer, and the onset of turbulence. This comprises the central scientific justification for the use of models in wind tunnels to simulate real-life phenomena. However, there are limitations on conditions in which dynamic similarity is based upon the Reynolds number alone.

Replica of the Wright brothers' wind tunnel.

German aviation laboratory, 1935

The Wright brothers' use of a simple wind tunnel in 1901 to study the effects of airflow over various shapes while developing their Wright Flyer was in some ways revolutionary. It can be seen from the above, however, that they were simply using the accepted technology of the day, though this was not yet a common technology in America.

Subsequent use of wind tunnels proliferated as the science of aerodynamics and discipline of aeronautical engineering were established and air travel and power were developed.

The US Navy in 1916 built one of the largest wind tunnels in the world at that time at the Washington Navy Yard. The inlet was almost 11 feet in diameter and the discharge part was 7 feet in diameter. A 500 hp electric motor drove the paddle type fan blades.

Wind tunnels were often limited in the volume and speed of airflow which could be delivered.

World War Two Wind Tunnels

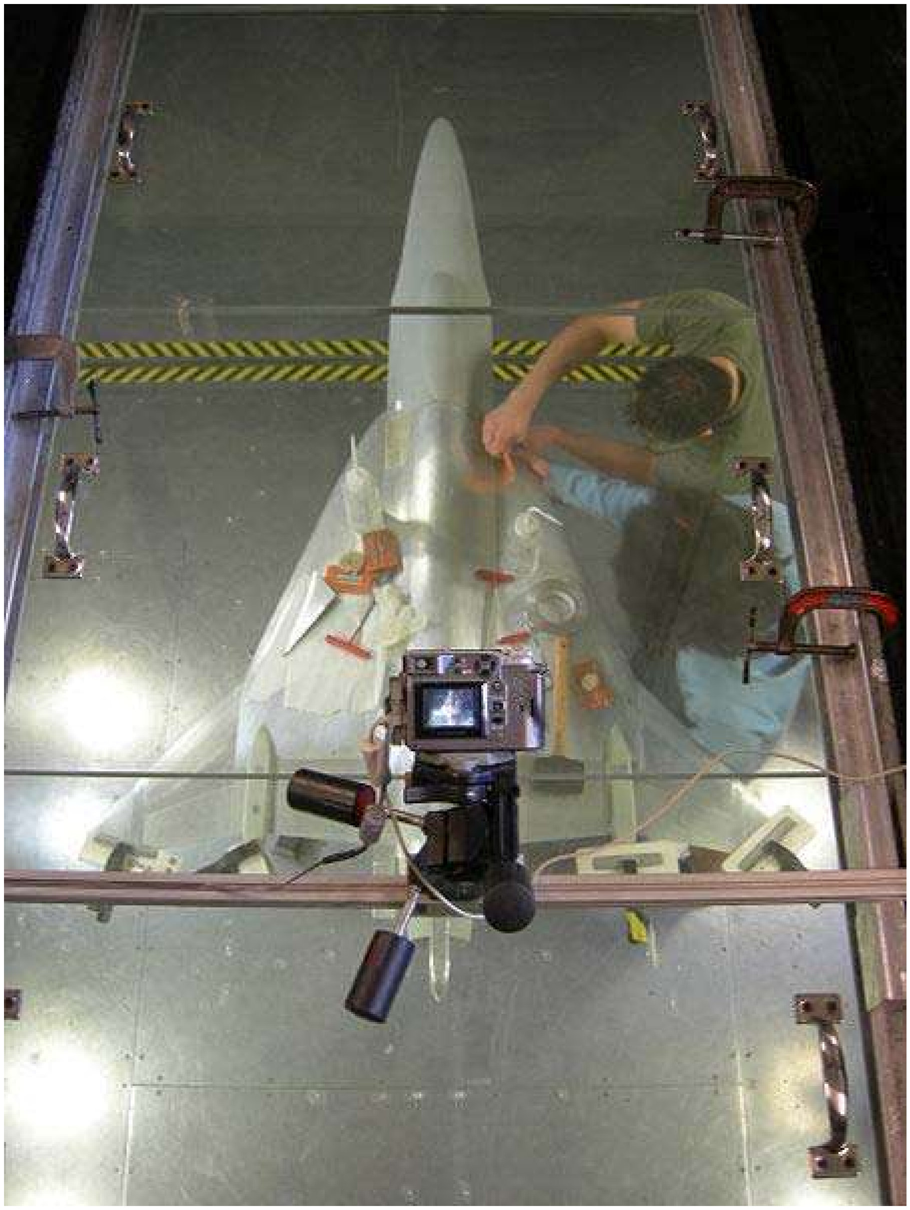
In 1941 the US constructed one of the largest wind tunnels at that time at Wright Field in Dayton, Ohio. This wind tunnel starts at 45 feet and narrows to 20 feet in diameter. Two 40 foot fans were driven by a 40,000hp electric motor. Large scale aircraft models could be tested at air speeds of 400mph.

The wind tunnel used by German scientists at Peenemünde prior to and during WWII is an interesting example of the difficulties associated with extending the useful range of large wind tunnels. It used some large natural caves which were increased in size by excavation and then sealed to store large volumes of air which could then be routed through the wind tunnels. This innovative approach allowed lab research in high-speed regimes and greatly accelerated the rate of advance of Germany's aeronautical engineering efforts. By the end of the war, Germany had at least three different *supersonic* wind tunnels, with one capable of Mach 4.4 (heated) airflows.

Post World War Two Wind Tunnels

Later research into airflows near or above the speed of sound used a related approach. Metal pressure chambers were used to store high-pressure air which was then accelerated through a nozzle designed to provide supersonic flow. The observation or instrumentation chamber ("test section") was then placed at the proper location in the throat or nozzle for the desired airspeed.

For limited applications, Computational fluid dynamics (CFD) can augment or possibly replace the use of wind tunnels. For example, the experimental rocket plane SpaceShipOne was designed without any use of wind tunnels. However, on one test, flight threads were attached to the surface of the wings, performing a wind tunnel type of test during an actual flight in order to refine the computational model. It should be noted that, for situations where external turbulent flow is present, CFD is not practical due to limitations in present day computing resources. For example, an area that is still much too complex for the use of CFD is determining the effects of flow on and around structures, bridges, terrain, etc.



Preparing a model in the Kirsten Wind Tunnel, a subsonic wind tunnel at the University of Washington

The most effective way to simulative external turbulent flow is through the use of a boundary layer wind tunnel.

There are many applications for boundary layer wind tunnel modeling. For example, understanding the impact of wind on high-rise buildings, factories, bridges, etc. can help building designers construct a structure that stands up to wind effects in the most efficient manner possible. Another significant application for boundary layer wind tunnel modeling is for understanding exhaust gas dispersion patterns for hospitals, laboratories, and other emitting sources. Other examples of boundary layer wind tunnel applications are assessments of pedestrian comfort and snow drifting. Wind tunnel modeling is accepted as a method for aiding in Green building design. For instance, the use of boundary layer wind tunnel modeling can be used as a credit for Leadership in Energy and Environmental Design (LEED) certification through the U.S. Green Building Council.

Fan blades of Langley Research Center's 16 foot transonic wind tunnel in 1990, before it was mothballed in 2004.

Wind tunnel tests in a boundary layer wind tunnel allow for the natural drag of the Earth's surface to be simulated. For accuracy, it is important to simulate the mean wind speed profile and turbulence effects within the atmospheric boundary layer. Most codes and standards recognize that wind tunnel testing can produce reliable information for designers, especially when their projects are in complex terrain or on exposed sites.

In the USA many wind tunnels have been decommissioned in the last 20 years, including some historic facilities. Pressure is brought to bear on remaining wind tunnels due to declining or erratic usage, high electricity costs, and in some cases the high value of the real estate upon which the facility sits. On the other hand CFD validation still requires wind-tunnel data, and this is likely to be the case for the foreseeable future. Studies have been conducted and others are under way to assess future military and commercial wind tunnel needs, but the outcome remains uncertain. . More recently an increasing use of jet-powered, instrumented unmanned vehicles ["research drones"] have replaced some of the traditional uses of wind tunnels

How it works

Six-element external balance below the Kirsten Wind Tunnel

Air is blown or sucked through a duct equipped with a viewing port and instrumentation where models or geometrical shapes are mounted for study. Typically the air is moved through the tunnel using a series of fans. For very large wind tunnels several meters in diameter, a single large fan is not practical, and so instead an array of multiple fans are used in parallel to provide sufficient airflow. Due to the sheer volume and speed of air movement required, the fans may be powered by stationary turbofan engines rather than electric motors.

The airflow created by the fans that is entering the tunnel is itself highly turbulent due to the fan blade motion (when the fan is **blowing** air into the test section **-** when it is **sucking** air out of the test section downstream, the fan-blade turbulence is not a factor), and so is not directly useful for accurate measurements. The air moving through the tunnel needs to be relatively turbulence-free and laminar. To correct this problem, closely-spaced vertical and horizontal air vanes are used to smooth out the turbulent airflow before reaching the subject of the testing.

Due to the effects of viscosity, the cross-section of a wind tunnel is typically circular rather than square, because there will be greater flow constriction in the corners of a square tunnel that can make the flow turbulent. A circular tunnel provides a smoother flow.

The inside facing of the tunnel is typically as smooth as possible, to reduce surface drag and turbulence that could impact the accuracy of the testing. Even smooth walls induce some drag into the airflow, and so the object being tested is usually kept near the center of the tunnel, with an empty buffer zone between the object and the tunnel walls. There are correction factors to relate wind tunnel test results to open-air results.

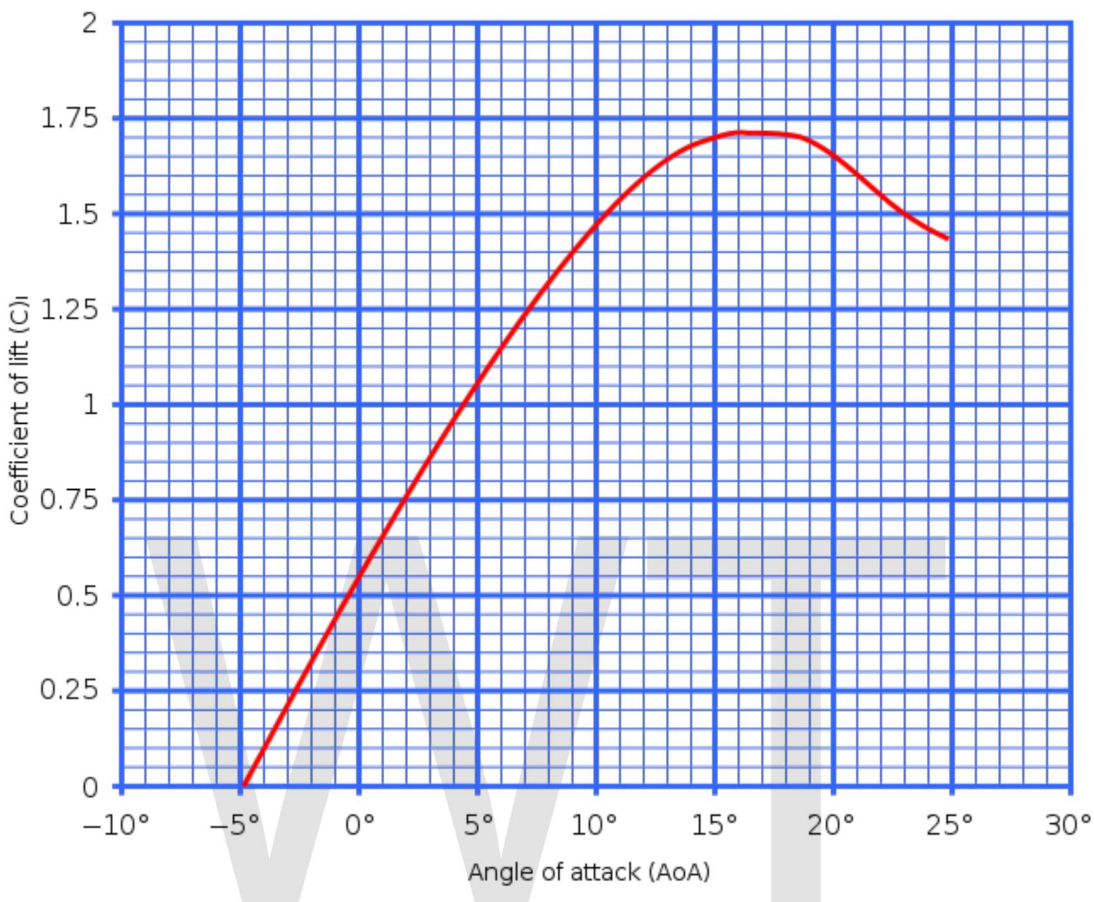
Lighting is usually recessed into the circular walls of the tunnel and shines in through windows. If the light were mounted on the inside surface of the tunnel in a conventional manner, the light bulb would generate turbulence as the air blows around it. Similarly, observation is usually done through transparent portholes into the tunnel. Rather than simply being flat discs, these lighting and observation windows may be curved to match the cross-section of the tunnel and further reduce turbulence around the window.

Various techniques are used to study the actual airflow around the geometry and compare it with theoretical results, which must also take into account the Reynolds number and Mach number for the regime of operation.

Pressure measurements

Pressure across the surfaces of the model can be measured if the model includes pressure taps. This can be useful for pressure-dominated phenomena, but this only accounts for normal forces on the body.

Force and moment measurements



A typical lift coefficient versus angle of attack curve.

With the model mounted on a force balance, one can measure lift, drag, lateral forces, yaw, roll, and pitching moments over a range of angle of attack. This allows one to produce common curves such as lift coefficient versus angle of attack (shown).

Note that the force balance itself creates drag and potential turbulence that will affect the model and introduce errors into the measurements. The supporting structures are therefore typically smoothly shaped to minimize turbulence.

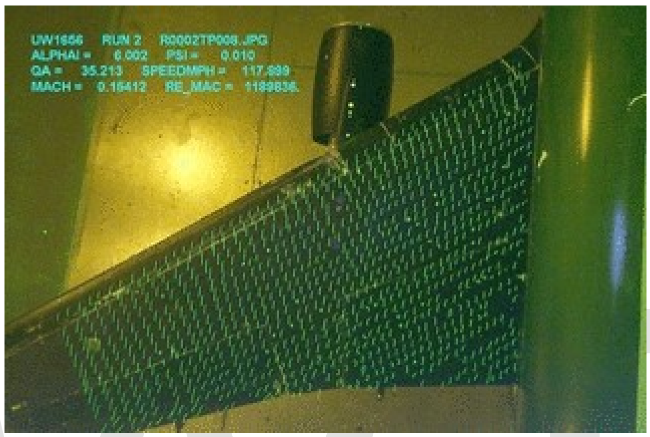
Flow visualization

Because air is transparent it is difficult to directly observe the air movement itself. Instead, multiple methods of both quantitative and qualitative flow visualization methods have been developed for testing in a wind tunnel.

Qualitative methods

- Smoke
- Tufts

Tufts are applied to a model and remain attached during testing. Tufts can be used to gauge air flow patterns and flow separation.

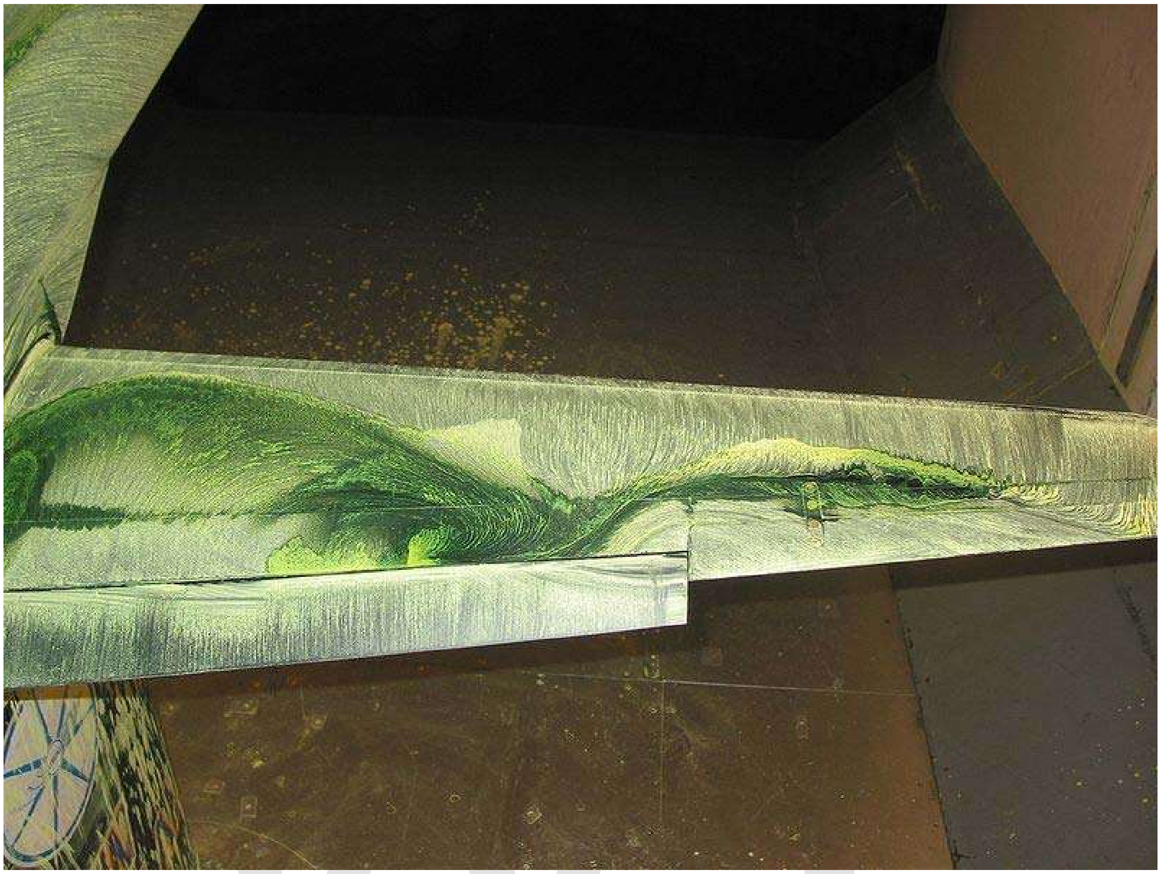


Compilation of images taken during an alpha run starting at 0 degrees alpha ranging to 26 degrees alpha. Images taken at the Kirsten Wind Tunnel using fluorescent mini-tufts. Notice how separation starts at the outboard wing and progresses inward. Notice also how there is delayed separation aft of the nacelle.

Fluorescent mini-tufts attached to a wing in the Kirsten Wind Tunnel showing air flow direction and separation. Angle of attack ~ 12 degrees, speed ~120 Mph.

- Evaporating suspensions

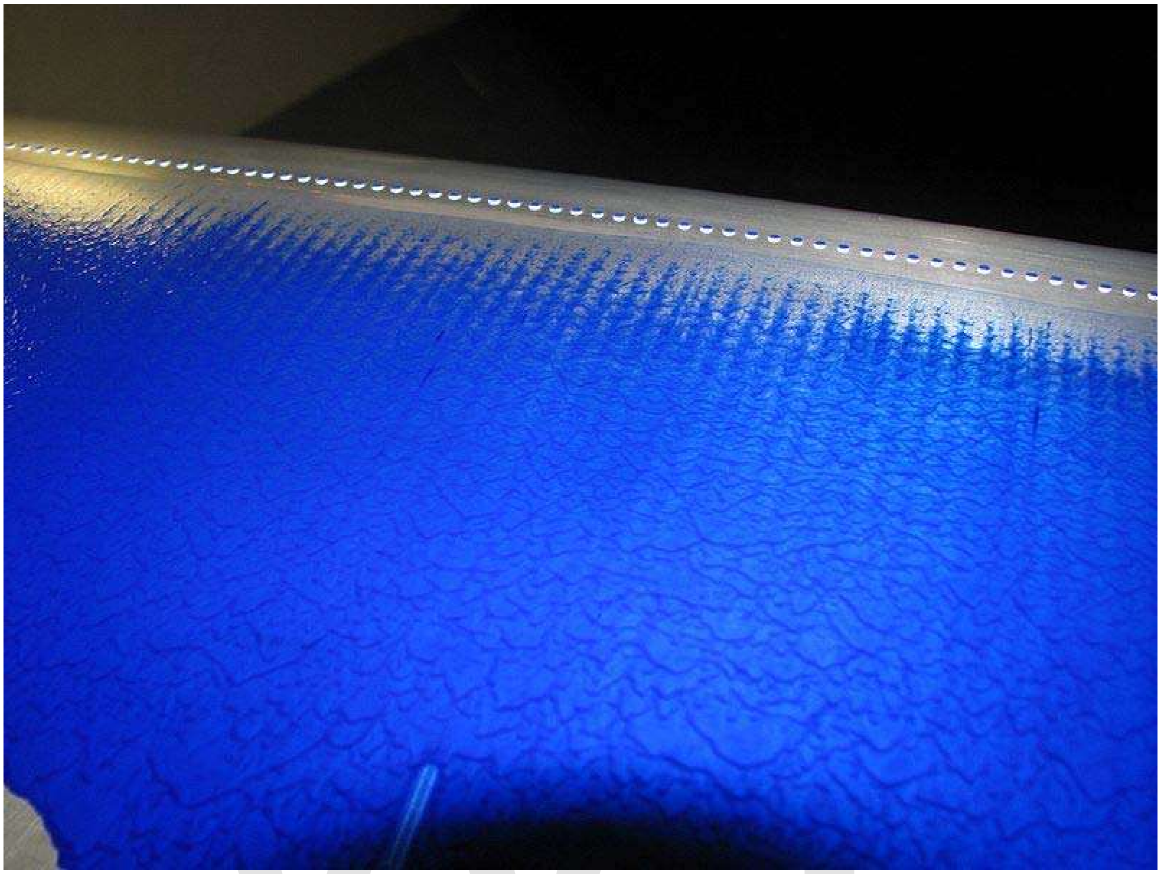
Evaporating suspensions are simply a mixture of some sort or fine powder, talc, or clay mixed into a liquid with a low latent heat of evaporation. When the wind is turned on the liquid quickly evaporates leaving behind the clay in a pattern characteristic of the air flow.



China clay on a wing in the Kirsten Wind Tunnel showing reverse and span-wise flow.

- Oil

When oil is applied to the model surface it can clearly show the transition from laminar to turbulent flow as well as flow separation.



Oil flow vis on straight wing in the Kirsten Wind Tunnel. Trip dots can be seen near the leading edge.

- Sublimation

If the air movement in the tunnel is sufficiently non-turbulent, a particle stream released into the airflow will not break up as the air moves along, but stay together as a sharp thin line. Multiple particle streams released from a grid of many nozzles can provide a dynamic three-dimensional shape of the airflow around a body. As with the force balance, these injection pipes and nozzles need to be shaped in a manner that minimizes the introduction of turbulent airflow into the airstream.

High-speed turbulence and vortices can be difficult to see directly, but strobe lights and film cameras or high-speed digital cameras can help to capture events that are a blur to the naked eye.

High-speed cameras are also required when the subject of the test is itself moving at high speed, such as an airplane propeller. The camera can capture stop-motion images of how the blade cuts through the particulate streams and how vortices are generated along the trailing edges of the moving blade.

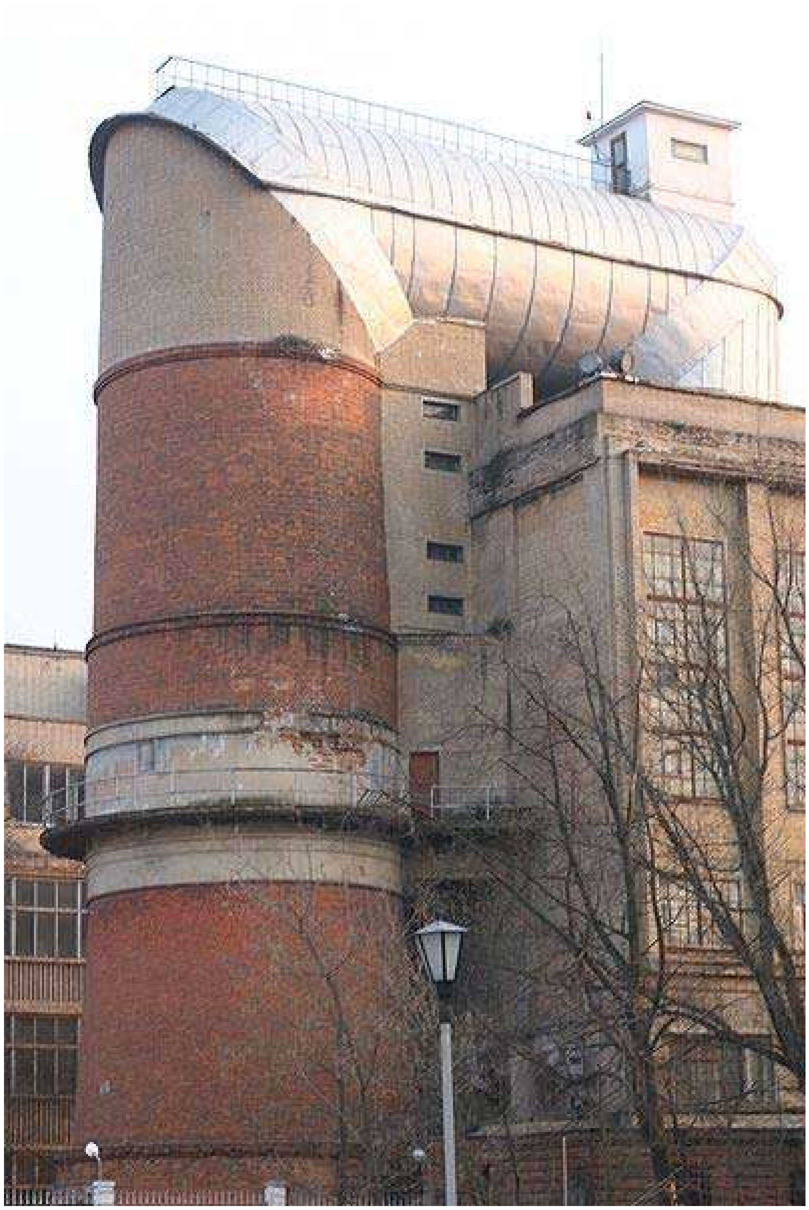
Wind tunnel classification

There are many different kinds of wind tunnels, an overview is given in the figure below:

- Low speed wind tunnel
- High speed wind tunnel
- Supersonic wind tunnel
- Hypersonic wind tunnel
- Subsonic and transonic wind tunnel

List of wind tunnels

- Modine Wind Tunnels, Climatic Wind Tunnel Testing, Large Truck and Automotive
- AeroDyn Wind Tunnel, Full Scale NASCAR Racecars
- A2 Wind Tunnel, Full scale general purpose
- Eight-Foot High Speed Tunnel
- Full Scale 30- by 60-Foot Tunnel
- Trisonic Wind Tunnel
- Unitary Plan Wind Tunnel
- Wind Shear's Full Scale, Rolling Road, Automotive Wind Tunnel
- Variable Density Tunnel



Vertical wind tunnel T-105 at TsAGI used for aircraft testing (built in 1941)

Aquadynamic Flume

The aerodynamic principles of the wind tunnel work equally on watercraft, except the water is more viscous and so imposes a greater forces on the object being tested. A looping flume is typically used for underwater aquadynamic testing. The interaction between 2 different types of fluids means that pure windtunnel testing is only partly relevant. However, a similar sort of research is done in a towing tank

Low-speed Oversize Liquid Testing

Air is not always the best test medium to study small-scale aerodynamic principles, due to the speed of the air flow and airfoil movement. A study of fruit fly wings designed to understand how the wings produce lift was performed using a large tank of mineral oil and wings 100 times larger than actual size, in order to slow down the wing beats and make the vortices generated by the insect wings easier to see and understand.

Wind Tunnel Testing for Wind Engineering

In Wind Engineering, Wind Tunnel Tests are often used to measure the velocity around, and forces or pressures upon structures. Usually very tall buildings, buildings with unusual or complicated shapes (such as a tall building with a parabolic or a hyperbolic shape), cable suspension bridges or cable stayed bridges are analysed in specialized atmospheric boundary layer wind tunnels. These feature a long upwind section to accurately represent the wind speed and turbulence profile acting on the structure. Wind tunnel tests provide the necessary design pressure measurements for use in the dynamic analysis of the structure.