1

First Flights

The first controlled flight of a heavier-than-air airplane, Kill Devil Hills, North Carolina, 17 December 1903. (Source: *W. Wright, O. Wright, and J. Daniels, 1903, US Library of Congress*.)

> Wilbur, having used his turn in the unsuccessful attempt on the 14th, the right to the first trial now belonged to me. After running the motor a few minutes to heat it up, I released the wire that held the machine to the track, and the machine started forward in the wind. Wilbur ran at the side of the machine, holding the wing to balance it on the track. Unlike the start on the 14th, made in a calm, the machine, facing a 27-mile wind, started very slowly. Wilbur was able to stay with it till it lifted from the track after a 40-foot run. One of the Life Saving men snapped the camera for us, taking a picture just as the machine had reached the end of the track and had risen to a height of about 2 feet.[1] The slow forward speed of the machine over the

[1] John Thomas Daniels, Jr. (1873–1948) snapped the iconic photograph of the Wright brothers' historic first flight. Daniels was a member of the Kill Devil Hills, North Carolina, Life Saving Station, which relied on volunteers to respond to the frequent shipwrecks in the barrier island area. The Wright's *Flyer I* made four flights on December 17, 1903, three of which were photographed. After the fourth and final flight, a gust of wind caught the airplane and Daniels grabbed a wing strut, attempting to hold the airplane down, and he was caught between the biplane wings when the *Flyer* flipped over in the wind. Although the *Flyer I* was destroyed, Daniels was unhurt, and he would later recount that he had survived the first airplane crash.

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ground is clearly shown in the picture by Wilbur's attitude. He stayed along beside the machine without any effort.

The course of the flight up and down was exceedingly erratic, partly due to the irregularity of the air, and partly to lack of experience in handling this machine. The control of the front rudder was difficult on account of its being balanced too near the center. This gave it a tendency to turn itself when started; so that it turned too far on one side and then too far on the other. As a result, the machine would rise suddenly to about ten feet, and then as suddenly dart for the ground. A sudden dart when a little over a hundred feet from the end of the track, or a little over 120 feet from the point at which it rose into the air, ended the flight. As the velocity of the wind was over 35 ft/s and the speed of the machine over the ground against this wind ten feet per second, the speed of the machine relative to the air was over 45 ft/s, and the length of the flight was equivalent to a flight of 540 feet made in calm air. This flight lasted only 12 seconds, but it was nevertheless the first in the history of the world in which a machine carrying a man had raised itself by its own power into the air in full flight, had sailed forward without reduction of speed and had finally landed at a point as high as that from which it started.

Orville Wright writing about the first successful flight of a heavier-than-air flying machine from Kill Devil Hills, North Carolina, on 17 December 1903[2]

1.1 Preflight

The history of aerospace engineering is full of firsts, such as the first balloon flight, the first heavier-than-air airplane flight, the first artificial satellite flight, the first manned spacecraft flight, and many others. The first flight is a significant achievement and milestone. It is often the culmination of years of hard work by many people, including engineers, technicians, managers, pilots, and others. A first flight may represent a first in the application of a new aerospace engineering concept or theory that is being validated by the actual flight.

As an aerospace engineer, you may have the opportunity to contribute to the first flight of a new aircraft, a new spacecraft, or a new technology. The aerospace engineer may test the vehicle, on the ground and in flight, to verify that it can perform as predicted or to improve its operating characteristics. Flight testing is the final test to be performed on the complete vehicle or system.

Aerospace engineers are involved in all facets of the design, analysis, research, development, and testing of aerospace vehicles. This encompasses many different aerospace engineering disciplines, including aerodynamics, propulsion, performance, stability, control, structures, systems, and others. Several of these fundamental disciplines of aerospace engineering are introduced in this text.

In many areas of engineering and technology, there is sometimes a perception that there is nothing left to be discovered. Aerospace engineers have indeed designed, built, and flown some of the most innovative, complex, and amazing machines known to humanity. However, there is still ample room for creativity, innovation, and opportunities for technological breakthroughs to make the skies and stars far more accessible. By the end of this textbook, you may have greatly increased your knowledge of aerospace engineering, but you may also be humbled by how much more there is to be discovered.

[2] Orville Wright, "How We Made the First Flight." (1986) Federal Aviation Administration, Office of Public Affairs, Aviation Education Program, US Department of Transportation.

1.2 The First Balloon Flight

Balloons are perhaps the earliest form of manned flying vehicles. The first recorded, manned, untethered, free flight of a hot air balloon took place on 21 November 1783, in Paris, France (Figure 1.1). The balloon, with aeronauts[3] Jean Francis Pilatre de Rozier (1754–1785) and the Marquis d'Arlandes (1742–1809) onboard, flew for about 25 minutes over the city of Paris, France, rising to an altitude of about 3000 feet (914 m) and covering a distance of about 5 miles (8.1 km). A firebox, suspended underneath an opening at the bottom of the balloon, held a fire that filled the balloon with hot air. The balloon aeronauts stood on a platform, encircling the bottom of the balloon, from which they could add fuel and tend to the fire in the firebox. This was the first free flight by mankind in an aerial vehicle. The balloon was built by Joseph (1740–1810) and Etienne (1745–1799) Montgolfier of France, who were to play a major role in the future development of balloon flight.

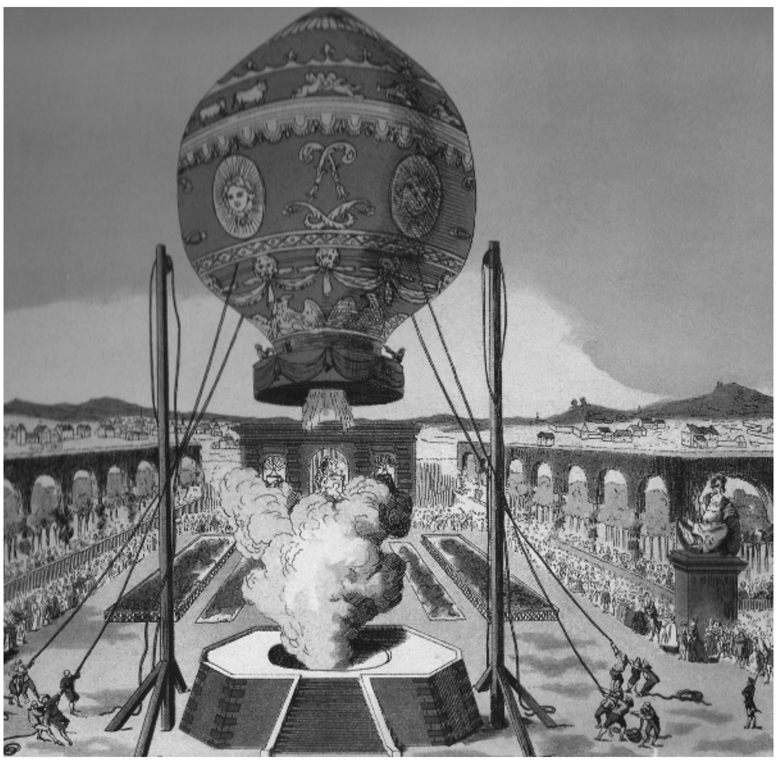

Figure 1.1 Illustration of the first manned balloon flight over Paris, France, on 21 November 1783 (Source: *Claude Louis Desrais / Prussian Cultural Heritage Foundation / Public domain*.)

[3] A person who operates or pilots a balloon or airship is called an aeronaut.

With a background in paper manufacturing, the Montgolfier brothers were supposedly inspired by seeing scraps of paper in their paper mill being lifted aloft by smoke from a fire. Based on these observations, they believed that the smoke was a new, undiscovered gas that was less dense than air, which they dubbed "Montgolfier gas." They believed that a thicker smoke contained more of this "Montgolfier gas," so they sometimes burned unusual materials, such as rotten meat and shoes, to produce as thick a smoke as possible for their balloons. They did not realize that the smoke is simply heated air and is less dense than unheated air. The brothers used a trial-and-error method, rather than one based on an understanding of the physics, in developing their balloons.

An aspect of the Montgolfier brothers' balloon development, which was insightful and may have contributed to their success, was their incremental design and flight test approach. They started with the flight of a smaller scale, 10-meter (32.8 ft) diameter, unmanned hot air balloon that was tethered to the ground and built up to flights of larger, manned balloons. The Montgolfier brothers' flight test approach was also admirable from a risk reduction standpoint. Prior to risking a balloon flight with people onboard, they flew a balloon carrying three farm animals, a sheep, aptly named Montauciel, French for "climb to the heavens," a duck, and a rooster, to assess the effects of balloon flight on living creatures. There was logic to their selection of these three particular animals. The sheep was thought to have a physiology that was similar to a human being thus, it was selected to assess the physiological effects of altitude. Since the duck was capable of flight at the balloon altitudes, it was used to assess any nonphysiological effects of balloon flight. The rooster was a non-flight-capable bird, so it was used to assess altitude effects in comparison with the duck. On 9 September 1783, the sheep, duck, and rooster made history as the first living creatures to fly in a balloon. Their balloon flight lasted about 8 minutes, ascending to an altitude of about 1500 feet (460 m) and landing safely about 2 miles (3.2 km) from their launch point.

The next incremental step was the flight of a 75 feet (22.9 m) tall, 55 feet (16.8 m) diameter, tethered balloon with a man onboard. On 15 October 1783, Etienne Montgolfier was the first person to ascend in a tethered balloon followed, later that day, by Jean Francis Pilatre de Rozier, who rode the tethered balloon to a height of about 80 feet (24.4 m), the length of the tethered line attached to the balloon. Just a little over a month later, the first free flight of a balloon was completed by de Rozier and the Marquis d'Arlandes in a Montgolfier balloon.

Ten days after the first manned hot air balloon flight, aeronauts Jacques Alexander Charles and Nicholas Louis Robert flew the first manned flight of a gas balloon on 1 December 1783, in Paris, France. Charles and Robert ascended to an altitude of about 1800 feet (550 m), covered a distance of about 25 miles (40.2 km), and were airborne for about two hours. Their rubber-coated, silk balloon was filled with flammable hydrogen gas, an attractive choice from a buoyancy standpoint, but a poor choice from a flight safety perspective. Hydrogen gas would be used in balloons and airships well into the 20th century, with many instances of catastrophic events due to its high flammability, until being replaced by helium gas. In fact, de Rozier, of hot air balloon fame, died when his hydrogen gas balloon exploded while attempting to cross the English Channel in 1785. De Rozier's balloon was a hybrid gas-and-hot air balloon, essentially a hot air balloon with an internal hydrogen gas chamber. Sadly, in addition to being one of the first persons to fly, de Rozier was also the first air crash fatality. The first manned balloon flight in the United States was in a hydrogen gas balloon, piloted by the Frenchman Jean-Pierre Blanchard (1753–1809) on 9 January 1793. Blanchard's balloon lifted off from Philadelphia, Pennsylvania, climbed to an altitude of about 5800 feet (1770 m) and landed in New Jersey.

In addition to opening up a new era in flight, balloons found military applications. Tethered balloons were used as military observation platforms by the French in the late 18th century and by armies during the US Civil War. Balloons were also used for artillery spotting in World War I.

1.3 The First Airplane Flight

At the beginning of this chapter, the iconic photograph of the first controlled, sustained flight of a heavier-than-air, powered airplane was presented. This first flight was the culmination of years of hard work by two brothers from Dayton, Ohio, Orville (1871–1948) and Wilbur (1867–1912) Wright. The brothers followed a logical and systematic engineering approach in the design, construction, and flight test of their powered airplane. They critically reviewed much of the existing technical information and data relevant to aeronautical theory and aircraft design. In several important areas, the Wright brothers determined that the state-of-the-art information was not adequate or simply incorrect, so they performed their own, independent analyses and tests to collect the data that they needed. For example, in designing the airfoil shapes for their wings and propellers, they used data collected from a wind tunnel of their own design (see Section 4.6.42). They also developed their own internal combustion aircraft engine, with the help of expert machinist, Charlie Taylor (1868–1956). The Wright brothers' determination to ensure that their airplane design was based on sound technical data was fundamental to their success.

The Wright brothers were methodical and systematic in their approach to flying and flight testing. Between 1900 and 1903, they performed extensive flight testing with gliders of their own design. Starting with unmanned, kite-like gliders, they systematically progressed to manned glider flights (Figure 1.2). The Wright brothers designed, built, and flew their first manned glider at Kitty Hawk, North Carolina, in 1900 with disappointing results. They test-flew another glider design in 1901, but this second manned glider also flew poorly. It was not until their third glider design in 1903 that the Wright brothers were satisfied with how the glider flew. These glider design iterations systematically improved the performance and flying qualities of their unpowered airplanes and the lessons learned were incorporated into their 1903-powered airplane design.

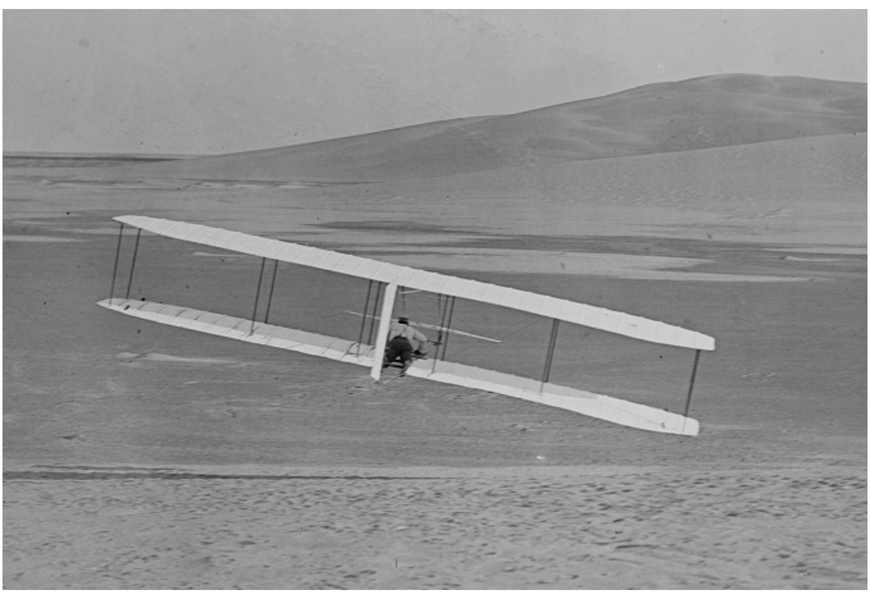

Figure 1.2 Flight of a Wright brothers-manned glider, 24 October 1902. Note the single vertical rudder on this glider as compared with the dual rudders on the 1903 Wright *Flyer I*. (Source: *O. Wright (1902) / US Library of Congress / Public domain*.)

The glider flying had another very important purpose in addition to collecting flight data for their designs; by flying these many glider flights, the Wright brothers were learning *how to fly*. They gained extensive piloting experience in how to control an aircraft in the new three-dimensional world of flight. They understood that not only must a successful heavier-than-air vehicle lift its own weight but it must also be controllable. They designed their aircraft to be controllable by the pilot in all three axes, with independent control effectors in pitch, roll, and yaw. Their airplane design had an elevator for pitch control, a rudder for yaw control, and for roll control, they used a scheme of warping or twisting of the wings.

The Wright brothers spent a considerable amount of time observing the flight of birds, and in particular, the flights of buzzards. Their observations of bird flight gave them valuable insights into how to control a flying vehicle. They observed that as birds soared and turned, the shape of their wings changed. Realizing that this wing twisting or warping was critical to the roll control of maneuvering birds, the Wright brothers incorporated the wing warping concept into their airplane designs, and finally into the design of the first successful heavier-than-air airplane. It is interesting to read the Wright brothers' description of their invention of a heavier-than-air flying machine in their original patent, as shown below. Note that they make particular mention of the stability and control aspects of their airplane.

> Be it known that we, Orville Wright and Wilbur Wright, citizens of the United States, residing in the city of Dayton, county of Montgomery, and State of Ohio, have invented certain new and useful Improvements in Flying-Machines, of which the following is a specification. Our invention relates to that class of flying machines in which the weight is sustained by the reactions resulting when one or more aeroplanes are moved through the air edge-wise at a small angle of incidence, either by the application of mechanical power or by the utilization of the force of gravity. The objects of our invention are to provide means for maintaining or restoring the equilibrium or lateral balance of the apparatus, to provide means for guiding the machine both vertically and horizontally, and to provide a structure combining lightness, strength, convenience of construction, and certain other advantages which will hereinafter appear.
>
> US patent 821,393, "Flying-Machine"
> Application filed 23 March 1903
> Patent granted 22 May 1906

The Wright brothers' successful, first powered airplane, the *Flyer I*, was a canard[4] configuration biplane with a forward-mounted, all-moving horizontal, biplane elevator and an aft-mounted, vertical, twin rudder. The all-moving nature of the elevator is clearly seen in the photograph of the *Flyer I*'s first flight, shown at the beginning of the chapter. The airplane structure was a spruce and ash wooden framework, covered with finely woven muslin cotton fabric. The wing bracing wires were 15-gauge bicycle spoke wires. The airplane had a single, four-cylinder, gasoline-fueled piston engine, capable of producing about 12 horsepower (8.9 kW). Less than half a gallon of gasoline fuel was carried onboard the airplane. There was no engine throttle, the pilot could only open or close the fuel line that supplied the engine. The engine drove two contrarotating, pusher propellers

[4] The word *canard* is literally translated from French as "duck." It is speculated that the aeronautical usage came from the French public's comparison of a 1906 airplane, designed and flown by Brazilian aviation pioneer Alberto Santos-Dumont (1873–1932), to a duck. This 1906 airplane, the *No. 14-bis*, was a biplane with a forward-mounted elevator. Santos-Dumont first flew the *No. 14-bis* on September 13, 1906, but this "powered hop" was only 23 feet (7 m) in distance. He is credited with flying the first public flight of a heavier-than-air airplane in Europe, when he flew the *No. 14-bis* on October 23, 1906, traveling a distance of 200 feet (61 m).

through a chain-drive transmission system. The propellers rotated at an average speed of about 350 rpm. The 170-pound (77-kg) engine was mounted on the right wing. To counterbalance the engine weight, the pilot was placed on the left wing. Since the Wright brothers' pilot weight of about 145 pounds (66 kg) was less than the engine weight, the right wing was about 4 inches (10 cm) longer than the left.

Unusual by today's standards, the pilot lay prone on his stomach, with his hips in a padded wooden cradle, facing toward the front-mounted elevator. The wing-warping roll control and rudder-deflection yaw control were interconnected, such that sliding of the hip cradle sideways caused the wings to warp and the rudders to deflect. A wooden lever in the pilot's left hand controlled the aircraft pitch by changing both the angle of the elevator and the camber or curvature of the elevator airfoil section. If the pilot pulled back on the lever, the elevator angle and camber were increased, thereby increasing its lift. If the pilot pushed the lever forward, the elevator angle and camber were decreased, resulting in less elevator lift. (Airfoil camber is discussed in Chapter 4.)

The *Flyer I* used a 60-foot (18.3 m) long launch rail for takeoff. The aircraft was restrained, sitting on the rail, until the pilot was ready for takeoff. He then released the restraining rope and the aircraft started its takeoff roll along the rail, riding on two modified bicycle wheel hubs. The aircraft had wooden skids for landing on the sandy ground of the Kill Devil Hills sand dunes. The *Flyer I* had a maximum airspeed of about 30 miles per hour (48 km/h) and a maximum altitude of about 30 feet (9.0 m). Selected specifications of the Wright *Flyer I* are given in Table 1.1.

After winning a coin toss, Wilbur Wright attempted the first flight of the *Flyer I* on 14 December 1903. The launch rail was placed on an incline, giving the aircraft a downhill, gravity-assisted takeoff roll. Taking off in a light wind, Wilbur pulled the *Flyer I* off the launch rail, but almost immediately stalled the aircraft, causing it to return to Earth in about three seconds. This "powered hop," with a gravity-assisted takeoff, could not be considered the first, controlled flight of a heavier-than-air airplane. The aircraft sustained some minor damage, which took three days to repair.

Table 1.1 Selected specifications of the 1903 Wright *Flyer I*.

Item	Specification
Primary function	First heavier-than-air flying machine
Manufacturer	Orville and Wilbur Wright, Dayton, Ohio
First flight	17 December 1903
Crew	1 pilot
Powerplant	In-line, 4-cylinder, water-cooled piston engine
Engine power	12 hp (8.9 kW) at 1020 rpm
Fuel capacity	0.2 gallons (0.65 l) of gasoline
Propellers	Two 2-bladed, 8 ft (2.4 m) diameter wooden propellers
Empty weight	605 lb (274 kg)
Gross weight	750 lb (341 kg)
Length	21 ft 1 in (6.43 m)
Height	9 ft 4 in (2.8 m)
Wingspan	40 ft 4 in (12.3 m)
Wing area	510 ft^2 (47.4 m^2) (upper and lower wings)
Wing loading	1.47 lb/ft^2 (7.18 kg_f/m^2)
Maximum speed	30 mph (48.3 km/h)
Stall speed	22 mph (35 km/h)
Ceiling	30 ft (9.0 m)

On 17 December 1903, it was Orville's turn to attempt the first flight. Since the winds were blowing at more than 20 mi/h (32.2 km/h), the launch rail was placed on level ground and pointed into the wind. At 10:35 am, Orville Wright made the first controlled, powered flight in a heavier-than-air airplane, with the flight lasting about 12 seconds, landing 120 feet (37 m) from the point of takeoff. The Wright brothers made four flights that day, with the final flight lasting almost a full minute. Soon after the fourth landing, a gust of wind picked up the *Flyer I* and it tumbled end-over-end across the rough and sandy terrain. The *Flyer I* was destroyed and never flew again. Quite fittingly, a part of the *Flyer I* would soar again, when a piece of its wing fabric and a piece of wood from one of its propellers were carried inside a spacesuit pocket of Neil Armstrong when he stepped onto the surface of the Moon on 20 July 1969.

1.4 The First Rotorcraft Flight

Rotorcraft are heavier-than-air aircraft that generate lift from rotating wings or spinning rotor blades. Early inspiration for the design of rotorcraft may have come from nature. There are several examples of rotating, winged seeds in nature that glide through the air as a means of dispersion. Flying seeds or samaras (a fruit with a wing) have been the interest of past and current aeronautical enthusiasts, inventors, and engineers. In 1808, aeronautical pioneer Sir George Cayley (1773–1857) wrote about the sycamore seed [1], as follows.

> I was much struck with the beautiful contrivance of the chat of the sycamore tree. It is an oval seed furnished with one thin wing, which one would at first imagine would not impede its fall but only guide the seed downward, like the feathers of an arrow. But it is so formed and balanced that it no sooner is blown from the tree than it instantly creates a rotative motion preserving the seed for the centre, and the…wing keeps it nearly horizontal, meeting the air in a very small angle like the bird's wing.

The aerodynamics of this naturally rotating wing has been studied extensively, including through the application of modern computational techniques, attempting to unlock the secrets of an example of nature's optimization of flight. The notion of a flying, rotating wing dates back to an ancient Chinese rotating toy, which was essentially a feather acting as a propeller, attached to the end of a stick. By applying rotation to the stick between the palms of one's hands and releasing the toy, the rotating feather-propeller would generate lift, making the toy fly for a short time. In 1483, Leonardo da Vinci (1452–1519) conceived of a human-carrying rotorcraft that he called an aerial screw. The da Vinci aerial screw concept did not address several critical issues in the design of a practical rotorcraft, which would not be solved for many centuries.

One of these issues was the development of a propulsion system to rotate the blades with sufficient power and yet light enough to lift the rotorcraft into the air. The propulsion issue was shared by the designers of heavier-than-air fixed-wing airplanes and would not be solved until the early 20th century with the advent of the internal combustion engine. Another issue, unique to rotary-wing aircraft, had to do with the reaction torque developed by a rotating wing. The torque imparted by the engine to the rotor blade shaft results in a reaction torque, which rotates the vehicle in the opposite direction of the blade motion. This reaction torque must be countered by some means so that the vehicle does not rotate when the rotor blades are spinning. Other issues to be solved included the high vibration environment due to the large, spinning rotor, which may lead to mechanical failure and structural metal fatigue. Many of these issues are still being actively worked on today to improve helicopter designs.

Figure 1.3 Paul Cornu's rotorcraft that made the first free-flight of a heavier-than-air rotorcraft. (Source: *PD-USGov*.)

During the early 20th century, there were many attempts at building and flying a vehicle capable of vertical flight. On 13 November 1907, about four years after the Wright brothers' first successful flight of a heavier-than-air, fixed-wing airplane, a French bicycle maker, Paul Cornu (1881–1944), flew a helicopter of his own design to a vertical height of 1 foot (30 cm) and hovered for 20 seconds, making this the first free flight of a heavier-than-air rotorcraft. Cornu's helicopter had two 20 feet (6.1 m) diameter rotors with large, low aspect ratio blades mounted on spinning spoked wheels, as shown in Figure 1.3. The opposite rotation of the rotors, located at opposite ends of the vehicle, served to counter the reaction torque. A 24-horsepower, gasoline-fueled internal combustion engine powered the rotors. In the several flights of the Cornu helicopter, it achieved a maximum vertical height of only about 6 feet (1.8 m), never rising above the region of aerodynamic ground effect, where there is increased lift and decreased drag.

The first practical helicopter design is perhaps the experimental Vought Sikorsky VS-300 helicopter, designed by helicopter pioneer Igor Sikorsky (1889–1972). The first flight of the VS-300 was on 14 September 1939, in Stratford, Connecticut, piloted by Igor Sikorsky himself. While the first flight of the VS-300 was only a few vertical inches in the air and lasted only 10 seconds, this experimental helicopter prototype, and subsequent variants, would set rotorcraft speed and endurance records (Figure 1.4). The VS-30 had a three-bladed, 28 feet (8.5 m) diameter main rotor, powered by a 75 horsepower Lycoming internal combustion engine, and weighed 1325 pounds (601 kg). For the first time, the reaction torque of the main rotor was countered using an antitorque tail rotor, an additional spinning rotor mounted vertically at the end of the fuselage. The single main rotor coupled with an antitorque tail rotor configuration became the predominant helicopter configuration, the predecessor of the modern-day helicopter.

1.5 The First Supersonic Flight

On 14 October 1947, high over the Mojave Desert in Southern California, a B-29 *Superfortress* bomber climbed into the sky carrying a unique payload attached to its belly, a bright saffron-colored (yellow-orange), experimental airplane with the words *Glamorous Glennis* painted on its nose, the name of the pilot's wife. This unique aircraft had a fuselage shaped like a 0.50-caliber bullet and a windscreen that was faired in with the fuselage to preserve its bullet shape. Prior to the first flight of a supersonic airplane, it was known that projectiles and bullets traveled at supersonic speeds. For this reason, this aircraft, the Bell X-1, manufactured by the Bell Aircraft Company, Buffalo, New York, was shaped like a bullet (Figure 1.5).

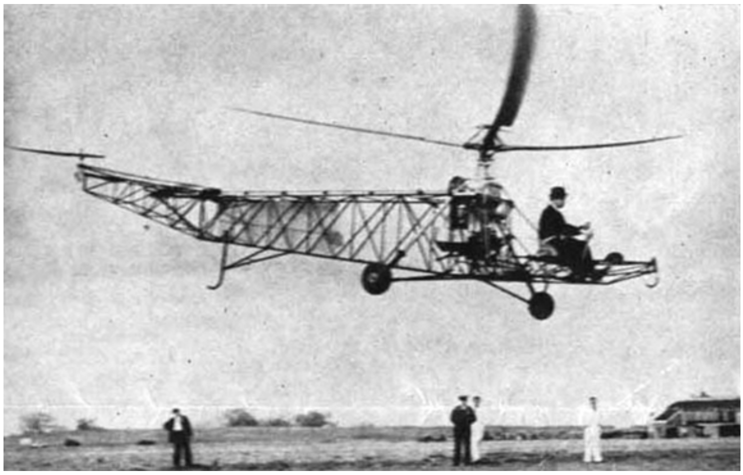

Figure 1.4 The first flight of the VS-300 helicopter, piloted by its designer, Igor Sikorsky, wearing his legendary Fedora hat. (Source: *Sikorsky Historical Archives*.)

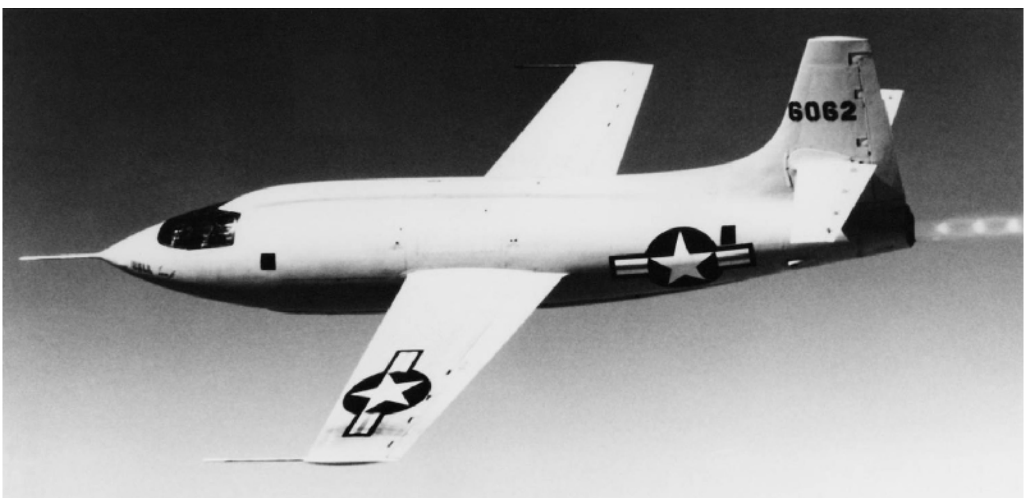

Figure 1.5 The Bell X-1, the first aircraft to fly faster than the speed of sound. (Source: *NASA / Public domain*.)

The Bell X-1 was designed to explore the then unknown regions of transonic and supersonic flight. It had very thin wings with only an 8% thickness (relative to the wing chord). The aircraft propulsion was a Reaction Motors, Inc., XLR11-RM3 4-chamber liquid rocket engine, providing about 6000 pounds (26,689 N) of sea-level thrust. The propellants in the 12,250-pound (5557-kg) rocket-powered airplane were freezing-cold liquid oxygen and diluted ethyl alcohol rocket fuel. Sitting in the single-place cockpit of this first-ever "X-plane" was Captain Charles E. "Chuck" Yeager (1923–2020), a 24-year-old US Air Force test pilot from West Virginia.

This was the 50th flight of the X-1 program and the 9th flight of the X-1 under rocket power. As the B-29 mothership approached an altitude of 20,000 feet (6096 m), just prior to the drop of the X-1 rocket plane from the B-29, the following radio transmissions were heard [2].

Tower[5]: Muroc Tower to Air Force Eight Zero, clear to drop. (*Air Force 80 is the B-29 aircraft.*)

Cardenas: Roger.

Ridley: Yeager, this is Ridley. You all set?

Yeager: Hell, yes, let's get this over with.

Ridley: Remember those stabilizer settings.
(*The X-1 had an all-moving horizontal stabilizer, a key design feature that helped make supersonic flight possible.*)

Yeager: Roger.

Cardenas: Eight Zero. Here is your countdown, 10 – 9 – 8 – 7 – 6 – 5 – 3 – 2 – 1 – Drop.
(*Cardenas had omitted "4" in the countdown. The X-1 release occurred at 10:26 a.m. as the B-29 was flying at 20,000 feet and an indicated airspeed of 250 mi/h.*)

Yeager: Firing Four (*rocket chamber #4*)… Four fired okay… will fire Two… Two on… will cut off Four… Four off… will fire Three… Three burning now… will shut off Two and fire One… One on… will fire Two again… Two on… will fire Four.
(*The Bell X-1 was powered by a Reaction Motors, Inc. XLR11 liquid rocket engine, burning ethyl alcohol and liquid oxygen. The XLR11 had four separate combustion chambers and nozzles, each producing 1,500 pounds (6,672 N) of thrust, for a total, combined thrust of 6,000 pounds (26,689 N). The thrust of each chamber could not be varied or throttled, rather the thrust was controlled by turning the individual rocket chambers on and off.*)

Ridley: How much of a drop (*in the rocket chamber pressure*)?

Yeager: About forty psi… got a rich mixture… chamber pressure down… now going up again… pressures all normal… will fire Three again… Three on… acceleration good… have had mild buffet… usual instability. Say Ridley, make a note here. Elevator effectiveness regained.
(It was known, at the time, that there would be a decrease in elevator effectiveness at transonic Mach numbers. The all-moving stabilizer was moved in small increments during the acceleration to maintain longitudinal stability and proved very effective. Yeager's comment, that elevator effectiveness was regained, was made as the X-1 accelerated through an indicated Mach number of 0.96.)

Ridley: Roger. Noted.

Yeager: Ridley! Make another note. There's something wrong with this Mach meter. It's gone screwy!
(In his post-flight, written test report, Yeager states that the needle of the Mach meter fluctuated momentarily at about Mach 0.98, then went off the scale. Based on radar tracking data, the Bell X-1 had achieved Mach 1.06.)

Ridley: If it is, we'll fix it. Personally, I think you're seeing things.

Yeager: I guess I am, Jack… will shut down again… am shutting off… shut off… still going upstairs like a bat… have jettisoned fuel and LOX… about thirty percent of each remaining… still going up… have shut down now.
(LOX is liquid oxygen.)

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[5] "Tower" is the Muroc Tower at the Muroc Army Air Field in the Mojave Desert, California, "Cardenas" is Major Robert Cardenas, the B-29 pilot, "Ridley" is Captain Jackie "Jack" Ridley, the X-1 project engineer, and "Yeager" is Captain Charles "Chuck" Yeager, the X-1 test pilot. Comments in italics are added for clarity.

Despite the disbelief and surprise of Yeager and Ridley, the Bell X-1 had indeed become the first aircraft to fly faster than the speed of sound or Mach 1. There were a total of 157 test flights of the Bell X-1, flown by 19 test pilots, with the final flight occurring on 23 October 1951. During the course of the test flights, the X-1 reached a maximum Mach number of 1.45 and a maximum altitude of 69,000 feet (21,030 m). It was the first supersonic airplane and the first in a long series of flight research "X-planes." Jack Ridley (1915–1957) also flew the Bell X-1 rocket airplane four times. He broke the sound barrier on his first X-1 flight, reaching Mach 1.23 on 11 March 1949, joining a small and exclusive club of supersonic pilots at that time. Note in the conversation above the emphasis on the aircraft's horizontal stabilizer. The all-moving horizontal stabilizer, versus the traditional fixed stabilizer and moving elevator, was an innovative flight control design feature that helped make supersonic flight a reality. The all-moving horizontal stabilizer would be incorporated into future supersonic aircraft, including modern-day supersonic aircraft.

The National Advisory Committee for Aeronautics (NACA), the forerunner to NASA, played a major role in the attainment of supersonic flight. The NACA performed extensive wind tunnel testing in an attempt to understand the effects of compressibility (to be discussed in Chapter 5); however, they were limited by the inability to duplicate transonic Mach numbers in wind tunnels. NACA aerodynamicist John Stack (1906–1972) was prominent in advocating for high-speed research aircraft to explore the aerodynamics, stability, control, and other fundamental engineering issues associated with transonic and supersonic flight. This ultimately led to the Bell X-1 program where the NACA developed the aircraft specifications and basic design, planned the overall flight research test program, and was responsible for the flight data instrumentation, collection, and analyses. The NACA pioneered many of the techniques for obtaining high-quality flight test data. Their flight planning emphasized safety, using the flight test build-up approach, where the flight data was used to verify it was safe to continue to the next test points in the flight envelope. The X-1 flight tests were conducted at the Muroc Army Air Field in the Mojave Desert of Southern California. The NACA created the Muroc Flight Test Unit on 7 September 1947 to support the Bell X-1 flight tests, staffed by a total of 27 personnel. This small flight research station in the middle of the Mojave desert would steadily grow in size, eventually becoming the NASA Dryden (now Armstrong) Flight Research Center and the Air Force Flight Test Center (now the Air Force Test Center) on Edwards Air Force Base in California. These flight test organizations have played a major role in the research and flight testing of many of the X-planes that have been flown and discussed in this text.

1.6 The First Rocket Flights

Rocket propulsion is perhaps the earliest form of flight propulsion, dating back to the 11th or 12th century, when the Chinese launched gunpowder-filled bamboo tubes as a form of fireworks. Sometime later, they attached these rudimentary solid rocket motors to arrows, creating a rocket-powered weapon of sorts. The arrow shaft provided some flight stability, although the accuracy of these rocket-powered arrows was probably poor. Much later, in the early 19th century, solid propellant rockets were developed in England by William Congreve (1772–1828). These rockets had a range of about 3000 yards (2743 m), likely with poor accuracy. Congreve's rockets were used by the British in the War of 1812, including being fired at American troops in Baltimore's Fort McHenry, as immortalized by the words, "the rockets' red glare," in the American national anthem, the *Star Spangled Banner*. Although rockets were developed for military uses in the 18th and 19th centuries, the most significant advancements in rocket propulsion took place in the 20th century. Great strides in rocket propulsion were made during the 20th century, most notably in Russia, Germany, and the United States.

One of the earliest rocket propulsion visionaries, especially of the potential applications of rockets to space travel, was Konstantin Tsiolkovsky (1857–1935), a Russian schoolteacher. In 1903,

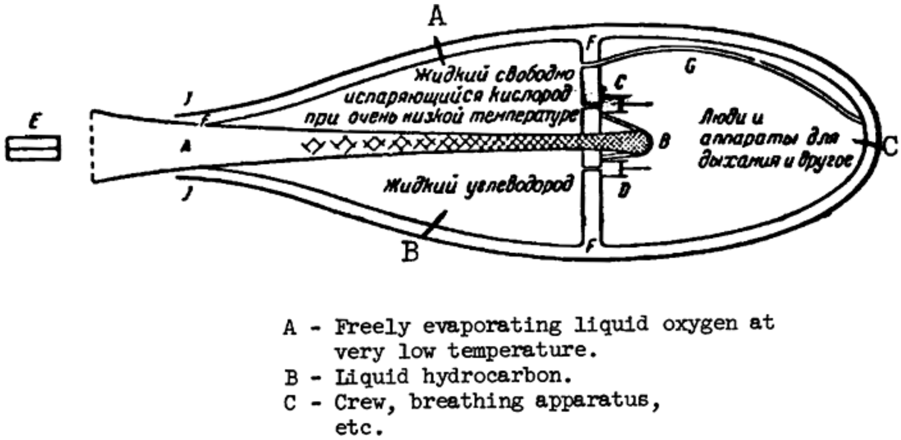

Figure 1.6 Sketch of a liquid propellant rocket by Konstantin Tsiolkovsky. (Source: *Blagonravov, A.A. [3].*)

Tsiolkovsky published a paper titled "Exploration of Space with Reaction Devices," [3] where he discussed the use of rockets to escape the orbit of the Earth. One of Tsiolkovsky's sketches of a liquid propellant rocket is shown in Figure 1.6. Tsiolkovsky was the first to publish the rocket equation, which relates the burnout velocity of a rocket to the rocket engine's exhaust velocity and the initial-to-final mass ratio of the rocket (the rocket equation is discussed in Section 10.5.1). In 1929, Tsiolkovsky published the idea of multistage rockets, a concept that makes spaceflight into Earth orbit and beyond realizable (multistage rockets and rocket staging are discussed in Section 10.5.4). Tsiolkovsky's rocket concepts included the use of liquid oxygen and liquid hydrogen as propellants. In addition to his significant achievements in rocket science, Tsiolkovsky contributed to early aviation, including designing a monoplane in 1894 and constructing the first Russian wind tunnel in 1897.

In the United States, Robert Hutchings Goddard (1882–1945) pioneered the development of rocket propulsion. Goddard was born at a time when airplanes and spacecraft were not commonplace. He was 11 years old when the Wright brothers made their historic first flight of a heavier-than-air airplane. When Goddard was 17, he climbed a cherry tree in his backyard to prune its dead branches. Resting in its branches, he gazed up at the sky and imagined what could be. He later wrote, in an autobiographical account, of the inspiration that he felt while gazing up at the sky in that cherry tree.

> On the afternoon of 19 October 1899, I climbed a tall cherry tree and, armed with a saw which I still have, and a hatchet, started to trim the dead limbs from the cherry tree. It was one of the quiet, colorful afternoons of sheer beauty which we have in October in New England, and as I looked towards the fields at the east, I imagined how wonderful it would be to make some device which had even the possibility of ascending to Mars. I was a different boy when I descended the tree from when I ascended for existence at last seemed very purposive.[6]

The purpose, to which Goddard alluded, was his decision to dedicate his life to making spaceflight a reality. For the rest of his life, Goddard privately observed that day, October 19, as the Anniversary Day of his inspiration. In 1907, he began his lifelong research and testing of rockets in earnest, as an undergraduate physics student at the Worchester Polytechnic Institute, Massachusetts. After earning his PhD in Physics from Clark University in Worchester, Massachusetts, he accepted a

[6] Goddard, Robert H., *The Papers of Robert H. Goddard, Including the Reports to the Smithsonian Institution and the Daniel and Florence Guggenheim Foundation: 1925–1937*, McGraw-Hill, 1970.

research fellowship at Princeton University in 1912. In addition to possessing exceptional academic skills, Goddard was a prolific inventor, obtaining 214 patents over his career, some of these granted after his death.

Goddard was granted two significant patents in 1914, one described a solid-propellant, multistage rocket and the other, a rocket containing gasoline and liquid nitrous oxide, or in other words, a liquid-propellent rocket. In the fall of 1914, Goddard returned to Clark University, where he conducted experiments with different types of solid propellant rockets, much of this at his own expense. He performed static ground tests of the rocket engines, carefully measuring their thrust and efficiency. (A static ground test is a test of the rocket engine that is performed with the engine securely mounted in a test stand on the ground. The engine is fired statically, meaning that it cannot move. The engine is instrumented so that data is collected about the operation of the engine and its systems. A load cell, or other force-measuring device, is often attached to the rocket so that the thrust force may be measured. Today, static ground tests of rocket engines are a standard, engineering practice.)

In 1916, Goddard built a vacuum tube apparatus to show that the efficiency of a rocket increased with decreasing external pressure. It was a misconception of Goddard's time that a rocket would not produce thrust in the vacuum of space. According to this misconception, Newton's third law of action with equal and opposite reaction required that the rocket exhaust gas have something to push against. It was thought that the vacuum of space could not provide the equal and opposite reaction to the rocket exhaust gas that was required to propel the rocket. The error in this reasoning is that the equal and opposite reaction is from the rocket, not the vacuum, reacting to the exhaust gas. Using the vacuum tube apparatus, Goddard was the first to prove that a rocket produces thrust in the vacuum of space. (Goddard obtained several patents, an "Apparatus for Vacuum Tube Transportation" and "Vacuum Tube Transportation Systems," which were visionary ideas of very high-speed transportation using magnetic levitation, or maglev, vehicles traveling inside vacuum tubes.)

During this time, Goddard made some significant advances in the design of rockets. He had the rare ability to transform his theoretical understanding into practical engineering, that is, real flight hardware. To increase the thrust and efficiency of his rockets, he understood several key design requirements. He realized that the rocket exhaust velocity and the rocket's propellant mass fraction, the mass of the propellant relative to the rocket's total mass, must both be as high as possible. To increase the rocket exhaust velocity, Goddard used a converging-diverging exhaust nozzle, called a de Laval nozzle. Using this exhaust nozzle, he was able to accelerate the flow exiting the nozzle to supersonic speeds, as high as Mach 7. (Supersonic nozzles are discussed in Chapters 5 and 6.)

Based on the substantial progress that he was making and the fact that he was unable to continue self-funding all of his research, Goddard started submitting research-funding proposals to sponsors such as the Smithsonian Institution and others. In his 1916 proposal to the Smithsonian Institution, he included a paper he had written that detailed his solid propellant rocket experiments, his mathematical theories of rocket propulsion, and his vision of using rockets to explore the Earth's atmosphere and beyond. He provided a quantitative analysis of launching a rocket to the Moon with a payload of flash powder, which would explode upon impact on the Moon. He calculated that a multistage rocket, with an initial launch mass of 6436 pounds (2919 kg), could deliver a payload of 2.67 lb (1.21 kg) of flash powder to the surface of the Moon. He calculated that this amount of flash powder would make a flash just visible from an Earth-bound, high-power telescope, confirming the rocket's impact on the Moon. The Smithsonian was impressed with Goddard's proposal and, in 1917, awarded him a $5000 grant.

Later, in 1919, the Smithsonian published Goddard's paper as Publication No. 2540 of the Smithsonian Miscellaneous Collections, titled "A Method of Reaching Extreme Altitudes" [4]. This publication has become one of the most significant scientific contributions to the development of rocket propulsion. Unfortunately, at the time of its publication, it was not viewed as such. The public at large still thought that the idea of space travel was a fanciful dream without much scientific basis. In fact, the US government as well as the US military did not see much use for either spaceflight or Goddard's rockets. To make matters worse, the press ridiculed Goddard's ideas of flying rockets to the Moon. This led to Goddard's distrust of the press and his penchant to work in secrecy, sentiments that he would have for the rest of his life.

By 1921, Goddard was conducting experiments with liquid propellants. He successfully ground tested the first liquid propellant rocket engine, using gasoline and liquid oxygen, in November 1923. Initially pursuing a pump-fed engine design, where mechanical pumps are used to move the propellants from their tanks to the combustion chamber, proved to be problematic. Goddard abandoned the pump-fed system and decided to use a pressure-fed system, where a high-pressure, inert gas, such as nitrogen, is used to push the propellants from their tanks into the combustion chamber. On 6 December 1925, Goddard conducted a static test of a liquid-propellant rocket engine, with a pressure-fed system, in a laboratory at Clark University in Worcester, Massachusetts. The rocket engine fired for 27 seconds, lifting its own weight in the test stand, proving the feasibility of a liquid-propellant rocket engine.

The configuration of Goddard's first liquid-propellant rocket is shown in Figure 1.7. The combustion chamber and exhaust nozzle were located at the top of the rocket and the two, cylindrical propellant tanks were at the bottom. Goddard chose this arrangement in his early rocket designs

Figure 1.7 Robert Goddard's 1928 liquid-propellant rocket. Goddard is holding the trapezoidal launch frame of the rocket. (Source: *NASA / Public domain*.)

because he thought that the rocket would be more stable in flight with this configuration. This early Goddard design lacked any aerodynamic fairings over the rocket nose or body and had no fins for stability. The liquid oxygen tank, below the exhaust nozzle, was protected from the hot exhaust by a conical-shaped exhaust shield, with an asbestos fabric covering. The gasoline and liquid oxygen lines ran from their respective tanks to the combustion chamber along the left and right sides of the rocket. The propellant-feed lines also served as structural supports for the rocket. The rocket engine ignitor was mounted at the top of the rocket, above the combustion chamber. The high-pressure gas generated by the boil-off of the liquid oxygen was the pressurant gas that was used to move the propellants to the combustion chamber. Goddard adopted today's conventional rocket configuration, with the combustion chamber and nozzle at the base of the rocket, in his later designs.

In 1926, Goddard was ready to conduct flight tests of his liquid-propellant rockets. He moved his operation to a farm owned by a distant relative, about 2 miles from Clark University. The farm offered a remote setting for conducting rocket launches, with less chance of an errant rocket crashing and hurting people or property. Despite its remote location, the neighbors still complained about the noise from the rockets. On 26 March 1926, the first flight of a liquid-propellant rocket occurred. The 10-foot (3.048 m)-long, gasoline and liquid oxygen-propellant rocket reached a maximum altitude of about 41 feet (12.5 m) and ended its two-and-a-half second flight in a cabbage field, about 184 feet (56.1 m) from its launch point. Since his youth, Goddard avidly wrote in his daily diary. On the auspicious day of the first flight of a liquid-propellant rocket, he, rather succinctly, wrote the following.

> 16 March 1926
>
> Went to Auburn with S[achs] in am. E[sther] and Mr. Roope[7] came out at 1 pm. Tried rocket at 2:30. It rose 41 ft, & went 184 ft, in 2.5 secs, after the lower half of nozzle had burned off.[8]

The next day, Goddard wrote about the previous day's first liquid-propellant rocket flight with a bit more fanfare.

> 17 March 1926
>
> The first flight with a rocket using liquid propellants was made yesterday at Aunt Effie's farm[9] in Auburn. The day was clear and comparatively quiet. The anemometer on the Physics lab was turning leisurely when Mr. Sachs and I left in the morning, and was turning as leisurely when we returned at 5:30 pm. Even though the release was pulled, the rocket did not rise at first, but the flame came out, and there was a steady roar. After a number of seconds it rose, slowly until it cleared the frame, and then at express train speed, curving over to the left, and striking the ice and snow, still going at a rapid rate. It looked almost magical as it rose, without any appreciably greater noise or flame, as if it said "I've been here long enough; I think I'll be going somewhere else, if you don't mind." Esther said that it looked like a fairy or an aesthetic dancer, as it started off. The sky was clear, for the most part, with large shadowy white clouds, but late in the afternoon, there was a large pink cloud in the west, over which the sun shone. One of the surprising things was the absence of smoke, the lack of a very loud roar, and the smallness of the flame.[10]

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[7] In addition to Goddard, three other people witnessed the first flight of a liquid-propellant rocket: Esther Goddard, his wife and photographer, Henry Sachs, the crew chief, and Percy Roope, an Assistant Professor of Physics at Clark University.
[8] Goddard, Robert H., (1926, Mach 16), Diary entry, Clark University Archives and Special Collections.
[9] Aunt Effie was Effie Ward, a distant relative of Robert Goddard. Her farm was in a rural area, about two miles from Clark University in Worcester, Massachusetts. This site, of the first flights of a liquid-propellent rocket, is now part of a golf course.
[10] Goddard, Robert H., (1926, Mach 17), Diary entry, Clark University Archives and Special Collections.

In 1930, Goddard moved his rocket flight test operation to remote Roswell, New Mexico, where he had plenty of open space and a clear, dry climate conducive to year-round testing. Today, New Mexico is the location of the White Sands Missile Range, the US Army's rocket test range. Covering almost 3200 square miles (8300 km^2), it is the largest military installation in the United States.

Goddard continued to design and build larger and more powerful rockets, integrating design improvements and technology advancements with each new model. Soon, Goddard's rockets resembled the more conventional configuration that is common today. Goddard's A-series rocket had an aerodynamic nose cone, a cylindrical body with a smooth aluminum skin that covered the internal tanks, a nozzle at the base of the rocket, and thin, highly swept tail fins. An A-series rocket was the first rocket to fly faster than the speed of sound on 8 March 1935. Goddard was responsible for significant advancements in rocket guidance and control, including the invention of a steering system using gyroscope-controlled, movable vanes in the exhaust and another using a movable or gimbaled exhaust nozzle, forerunners of systems in use today. He continually developed innovations in rocket propulsion technology, including eventually building turbopumps for pump-fed propellant feed systems. Goddard was the first to launch a scientific payload in a rocket, consisting of a barometer, a thermometer, and a camera.

Between 1926 and 1941, Goddard launched 34 rockets, reaching altitudes of about 8500 feet (2590 m) and speeds of about 550 miles per hour (885 km/h). He performed many more static ground tests than flight tests, using a methodical, engineering approach to improve the designs. Many of the ground and flight tests ended with failures of the engine, nozzle, guidance system, or other components; however, Goddard was never deterred. He always believed that important lessons were learned from any test results, a noteworthy perspective for anyone involved with ground or flight testing.

Robert Goddard was a true visionary, recognizing the incredible potential of rockets for atmospheric research, ballistic missiles, and space travel. Unfortunately, the US government, the US military, and the public were blind to this vision. Another aerospace visionary, Charles Lindbergh (1902–1974), took great interest in Goddard's work and personally helped with obtaining funds for his rocket research. Overall, Goddard's research and testing of rockets received meager funding and support throughout his career and he received little recognition for his work. Today, Robert Goddard is rightfully considered the father of rocket propulsion. Much like the Wright brothers' first flight, Goddard's first flight was a fledgling step of remarkable consequence. It would ultimately shape the future of rocketry and affect all of humanity. A short four years after Goddard's first flight, the first man to set foot on the Moon was born, destined to fly 238,900 miles (384,500 km) from the Earth to the Moon atop a 363 foot (111 m) tall, 6.5 million-pound (2.9 million kg) *Saturn V* rocket, a rocket that could trace its roots back to Robert Goddard's first liquid-propellant rocket.

1.7 The First Hypersonic Flight

In the 1940s, the United States developed the *WAC Corporal*, the first sounding rocket, specifically designed for upper atmospheric research. Designed and built by the Douglas Aircraft Company and the California Institute of Technology's Guggenheim Aeronautical Laboratory, the *WAC Corporal* was 16 feet, 2 inches (4.9 m) in length, 12 inches (30 cm) in diameter, and weighed about 665 pounds (300 kg). The rocket had an Aerojet liquid-propellant rocket engine, delivering about 1500 pounds (340 N) of thrust for 47 seconds. The rocket was not stabilized and was unguided (with some references stating that *WAC* was an acronym for "without attitude control"). Later versions of the *WAC Corporal* incorporated stabilization and guidance systems. Upon reaching its peak altitude, the nosecone of the rocket separated and fell back to Earth for recovery of scientific instruments and recording equipment. The *WAC Corporal* was launched using a *Tiny Tim* solid propellent booster, capable of producing about 50,000 pounds (11,200 N) of thrust for 0.6 seconds. The first flight of a fully operational *WAC Corporal* occurred on 11 October 1945 at the White Sands proving ground, New Mexico (later to be renamed the White Sands Missile Range). The rocket reached an altitude of about 230,000 feet (43.5 miles, 70 km).

Later, the liquid-propellant, upper stage of the *WAC Corporal* was mated to a much larger V-2 rocket and renamed the *Bumper-WAC* rocket. The V-2 rocket was about 45 feet (13.7 m) in length and had a thrust of about 55,000 pounds (245,000 N) at launch. After launch, the V-2 rocket engine burned for about one minute, before the *WAC Corporal* second stage was ignited, which burned for about 45 seconds. The *Bumper-WAC* was so named because of the “bump” in altitude provided by the V-2 rocket. A total of eight flights of the *Bumper-WAC* rocket were conducted, six from the White Sands proving ground, New Mexico and two from Cape Canaveral, Florida. The two Cape Canaveral launches were the first ever conducted from this fledgling rocket launch complex. The first *Bumper-WAC* flight from White Sands was on 13 May 1948, reaching a maximum altitude of about 80 miles (129 km, 422,400 ft) and a maximum speed of about 2740 mi/h (4410 km/h, 4019 ft/s). On 24 February 1949, the fifth *Bumper-WAC* flight from White Sands (see Figure 1.8) reached an altitude of 244 miles (393 km) and a maximum speed of 5150 mi/h (8290 km/h), making it the first manmade object to fly at hypersonic speed, in excess of Mach 5 (hypersonic flight is the subject of Chapter 9).

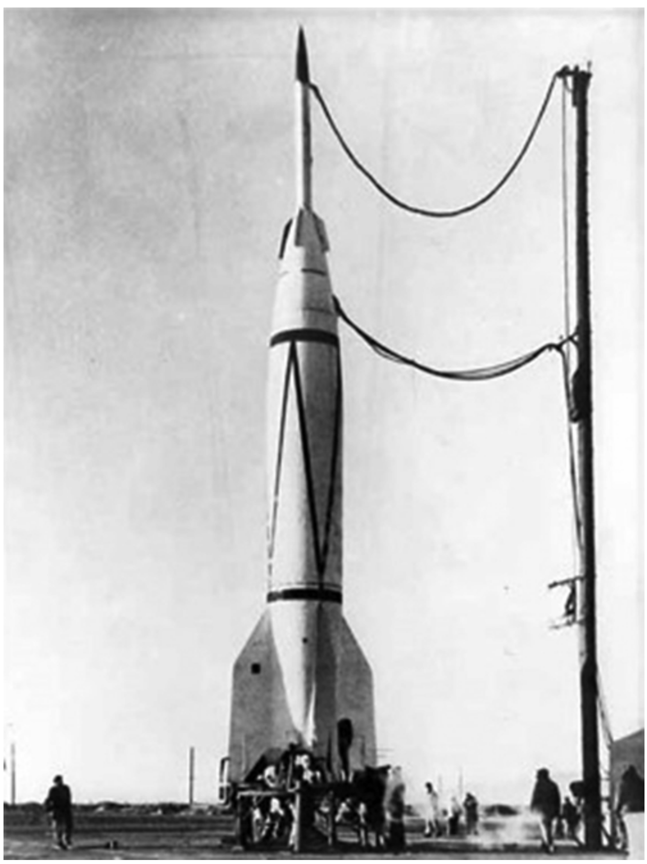

Figure 1.8 The *Bumper-WAC Corporal* rocket on the launch pad. (Source: *NASA / Public domain*.)

1.8 The First Spaceflight

Robert Goddard was not alone in his quest to make rocket flight a reality. Across the Atlantic Ocean, Wernher von Braun (1912–1977) and his team of German rocket scientists and engineers were busy at the Peenemunde Army Research Center, on a small Baltic Sea island on the northern coast of Germany, developing the world's first long-range, guided ballistic missile with a liquid-propellant rocket engine. The German scientists and engineers were aware of Goddard's work and monitored it closely. The German efforts culminated in the development of the V-2 rocket, which was used as a weapon against the Allied forces during World War II. Recall that the V-2 was the first stage of the *Bumper-WAC* shown in Figure 1.8. Over 3000 V-2 rockets were launched by the Germans against Allied targets, many in London, England, during the war. On 3 October 1942, a V-2 rocket, launched from Peenemunde, soared to an altitude of 190 kilometers (118 mi, 623,400 ft), becoming the first manmade object to reach the edge of space.

The German-developed V-2 liquid-propellant rocket was substantially larger than Goddard's rockets. The V-2 rocket airframe had a length of 14 meters (45 ft 11 in), diameter of 1.65 meters (5 ft 5 in), and wingspan of 3.56 meters (11 ft 8 in). With a total launch weight of 12,500 kilograms (27,600 lb), the V-2 carried 3800 kilograms (8400 lb) of fuel, comprised of a 75% ethanol–25% water mixture, 4900 kilograms (10,800 lb) of liquid oxygen, and a 1000-kilogram warhead (2200 lb). The V-2 could reach speeds of 5700 km/h (3540 mi/h) and altitudes of over 200 kilometers (124 mi, 656,000 ft). The missile had a maximum range of about 320 kilometers (200 mi).

The V-2 rocket was technologically advanced for its time. In addition to the liquid-propellant rocket engine technology, the rocket incorporated advancements in the areas of supersonic aerodynamics, stability, control, guidance, and navigation. The liquid rocket engine had a pump-fed propellant feed system, where the fuel and oxidizer pumps were driven by a steam turbine. The steam to drive the turbine was generated by the combustion of hydrogen peroxide with a sodium permanganate catalyst. The propellant tanks were made of a lightweight aluminum-magnesium alloy. The alcohol–water mixture fuel was used as a coolant for the combustion chamber and nozzle. The fuel was pumped behind the combustion chamber walls, cooling the chamber and heating the fuel. The heated fuel was then sprayed into the combustion chamber. Fuel was also sprayed inside the nozzle, providing film cooling of the nozzle walls. Steering control of the rocket was provided by a combination of movable rudders on the tail fins and movable guide vanes in the rocket engine exhaust. An automatic gyroscope control system was used for vehicle stabilization. Early V-2 rockets used a simple type of analog computer for guidance and navigation; however, later versions used a ground-transmitted, radio signal guide beam.

After World War II, many of the German scientists and engineers who had been involved in the V-2 development, including von Braun, were brought to the United States. Many of these rocket scientists and engineers were located in Huntsville, Alabama, laying the foundations for what would become the US Army Redstone Arsenal and the NASA Marshall Spaceflight Center. von Braun would later lead the major efforts to develop the *Saturn V* rocket engines that would take a man to the Moon. Accompanying the German personnel were significant amounts of V-2 rocket hardware and components, including complete rocket vehicles. These captured V-2 rockets were studied and launched on test flights by the United States from the White Sands Missile Range in New Mexico.

On 24 October 1946, a V-2 rocket, launched from White Sands, carried a small 35-mm motion picture camera, taking black-and-white photographs every 1.5 seconds during its flight. The photographs were not telemetered back to Earth; rather the camera film was recovered from a

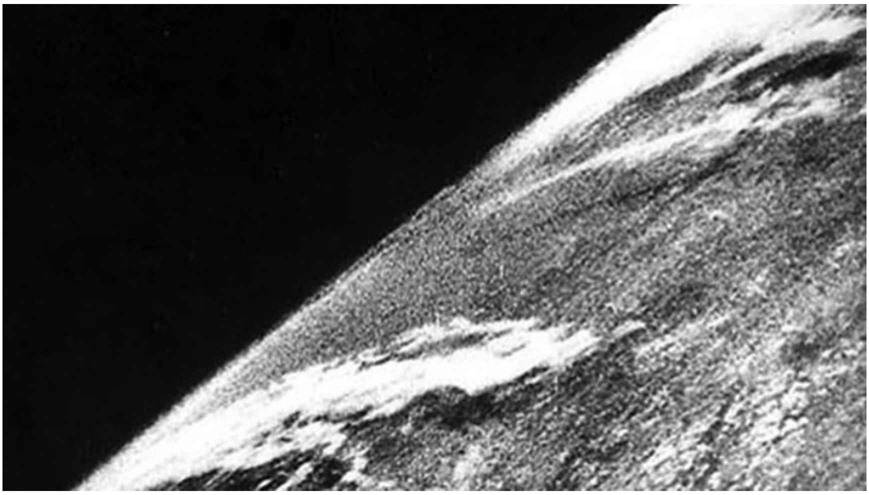

Figure 1.9 The first photograph of the Earth taken from space during a V-2 rocket flight on 24 October 1946. (Source: *US Army / Wikimedia Commons / Public domain.*)

protective case after the rocket crashed back to Earth. The rocket reached an altitude of 65 miles (105 km, 343,200 ft), where it took the first photograph of the Earth from space, shown in Figure 1.9. Today, photographs of the Earth from space are commonplace; however, this first, grainy picture of the Earth from space gave us the first perspective of our planet from the new frontier of space.

1.9 The First Orbital Spaceflight

The first spacecraft to be placed into Earth orbit was the *Sputnik 1* (Russian for *Satellite 1*), launched by the Soviet Union on 4 October 1957 (see Figure 1.10). *Sputnik* became the Earth's first artificial satellite as opposed to a natural satellite, such as the Moon. For a spacecraft to be placed into low Earth orbit, defined as an altitude of 1200 miles (2000 km) or less, it must attain an orbital velocity of about 17,000 miles per hour (27,360 km/h).

Sputnik had a simple spherical shape about the size of a beach ball, 22.8 inches (57.9 cm) in diameter, and weighed 184 pounds (83.5 kg). It was launched into an elliptical, low Earth orbit, with an apogee (point in the orbit that is the farthest from the Earth) of 584 miles (940 km) and a perigee (point in the orbit that is the closest to the Earth) of 143 miles (230 km), completing an orbit about every 96 minutes (also known as the orbital period).

Sputnik broadcast radio pulses, using four external antennae, which were detected by radio receivers on the ground. In addition to demonstrating the ability to launch an artificial satellite into low Earth orbit, *Sputnik* provided scientific data about the Earth's upper atmosphere. The drag on the satellite in its orbit provided data about the atmospheric density, while the attenuation of the broadcast radio signals provided information about the ionosphere. The satellite remained in orbit for about three months, before the atmospheric drag brought it into the thicker regions of the

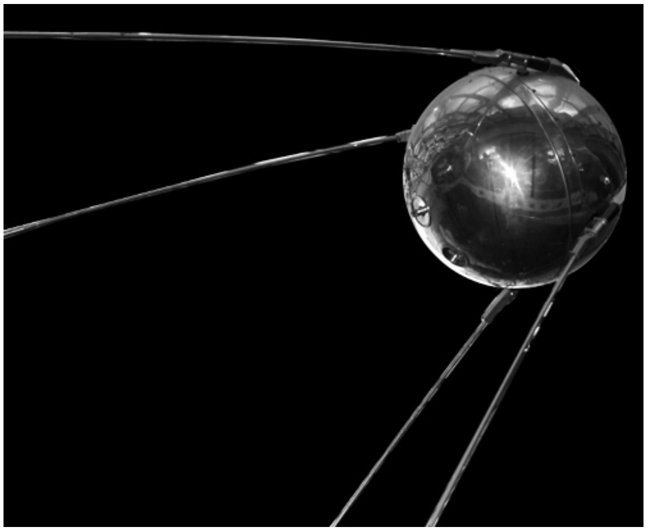

Figure 1.10 The Russian *Sputnik 1*, the first artificial Earth satellite. (Source: *NASA / Public domain*.)

atmosphere, where it burned up. This first satellite was visible in the night sky, as it raced around the Earth every 96 minutes, broadcasting its radio pulses; the space age had begun.

In the United States, plans were in work to develop the first American Earth satellite; however, the *Sputnik* launch caught all of America by surprise. There was a firestorm of political, scientific, and emotional turmoil over the concern that the Soviet Union was technologically ahead of the United States and that they would use this advantage to control space. There was also much concern that the Soviet Union had the capability to launch intercontinental ballistic missiles, armed with nuclear weapons, across the globe. Thus, *Sputnik* had not only started the space age but had also set off the space race between the United States and the Soviet Union. As a side note, a significant event that occurred, due to this new space race, was the creation of the National Aeronautics and Space Administration (NASA) on 1 October 1958, from its predecessor, the National Advisory Committee on Aeronautics (NACA).

Prior to *Sputnik*, the American effort to launch an artificial satellite into low Earth orbit resided with the *Vanguard* program, led by the Naval Research Laboratory in Washington, D.C. The *Vanguard* program was ultimately successful in placing several artificial satellites into Earth orbit; however, they were not the first to place an American satellite into orbit. *Vanguard 1* was successfully launched and placed into Earth orbit on 17 March 1958, the fourth manmade satellite to orbit the Earth after *Sputnik 1*, *Sputnik 2* (on November 3, 1957), and *Explorer 1* (discussed below). The *Vanguard 1* spherically shaped satellite was 6.44 inches (16.4 cm) in diameter and weighed 3.2 pounds (1.47 kg). It was placed into an elliptical orbit with an apogee of 2387 miles (3841 km), perigee of 409 miles (659 km), and an orbital period of 132.8 minutes. Despite its small size, the *Vanguard 1* satellite had some impressive scientific achievements, including obtaining data to prove that the Earth is not a perfect sphere, but rather, more pear-shaped. It was also the first solar-powered satellite. Amazingly, the *Vanguard 1* is still in orbit today, albeit non-functional, making it the oldest manmade satellite still in Earth orbit. It is expected to remain in Earth orbit into the 22nd century.

After *Sputnik*, the United States initiated the *Explorer* project to place an artificial satellite into low Earth orbit. The *Explorer 1* satellite was the top stage of its rocket launch vehicle. The aft end of the satellite was the burnt-out fourth stage of the rocket and the forward end was the satellite instrumentation section (see Figure 1.11). The *Explorer 1* had a total weight of 30.7 pounds (13.9 kg) with the instrumentation section weighing 18.4 pounds (8.35 kg). As shown in Figure 1.11, the instrumentation section had substantial instrumentation, containing a nose cone temperature probe, a cosmic ray detector, an internal temperature sensor, micrometeorite erosion gauges, external temperature sensors, a micrometeorite ultrasonic microphone detector, and low-power and high-power data transmitters. There were two different types of antennae on the satellite, two fiberglass slot antennae on the cylindrical satellite body and four flexible, whip-wire antennae located around the circumference in a turnstile arrangement. The satellite was spun about its longitudinal axis at 750 revolutions per minute, which kept the flexible wire antennae extended.

The *Explorer 1* satellite was built by the California Institute of Technology's Jet Propulsion Laboratory (JPL), under the direction of William H. Pickering (1910–2004). The satellite instrumentation was designed and built by James A. van Allen (1914–2006) of the University of Iowa. The satellite's *Jupiter-C* launch vehicle, a modified *Redstone* ballistic missile, was designed by a team led by Wernher von Braun at the US Army Redstone Arsenal in Huntsville, Alabama. The success of the *Explorer 1* satellite is a tribute to the combined contributions of these three great scientists and the teams that they led (see Figure 1.12).

A little less than four months after the success of *Sputnik 1*, on 31 January 1958, the United States successfully placed *Explorer 1* into low Earth orbit. The small satellite went around the Earth in an elliptical orbit with an apogee of 1575 miles (2535 km), a perigee of 224 miles (361 km), and an

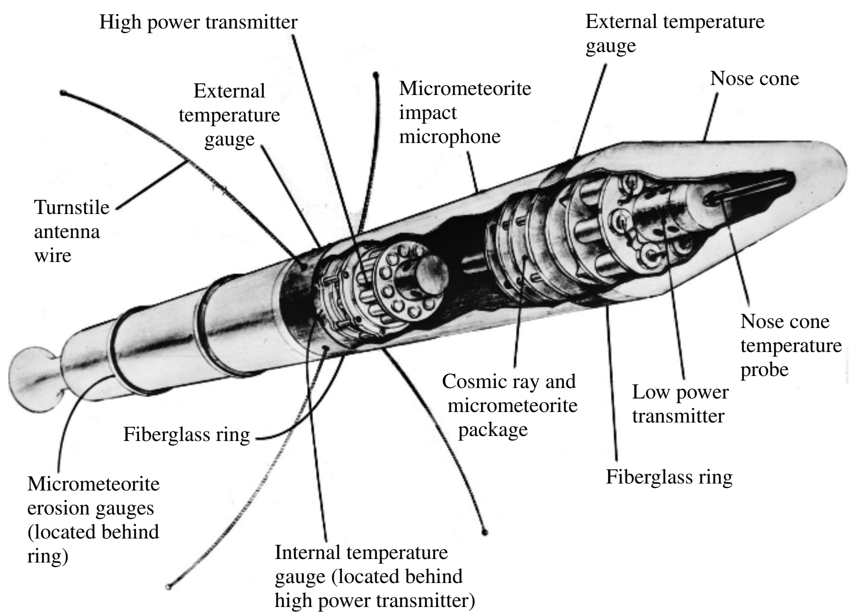

Figure 1.11 *Explorer 1*, the first artificial Earth satellite launched by the United States. (Source: *NASA / Wikimedia Commons / Public domain / https://commons.wikimedia.org/wiki/File:Explorer1Structure.jpg*.)

Figure 1.12 Dr. William H. Pickering, Dr. James A. van Allen, and Dr. Wernher von Braun hold up a full-scale model of *Explorer 1*. The modest size of the *Explorer 1* satellite may be appreciated in this photo. (Source: *NASA / Public domain*.)

orbital period of 114.9 minutes. *Explorer 1* is credited with collecting the scientific data that led James van Allen to the discovery of the radiation belt that surrounds the Earth and now bears his name.

Orbiting Earth satellites have transformed our world by providing us with a variety of previously unavailable capabilities and perspectives. Earth satellites have revolutionized many areas, including weather prediction, Earth observation, communications, and navigation. Satellites are placed into a variety of Earth orbits, including very high orbits, called geostationary orbits, where they may remain over the same spot on the Earth (various types of Earth orbits are discussed in Chapter 10). Since the success of these early satellites, literally thousands of artificial satellites have been placed in Earth orbit. Of these, perhaps several hundred are currently operational, many have re-entered the atmosphere and burned up, while others are no longer operational and have become space debris. In fact, there is so much space debris or space "junk" orbiting the Earth that it has to be tracked so that collisions may be avoided with operational spacecraft, including manned spacecraft (orbital debris is discussed in Section 10.2).

1.10 The First Manned Spaceflights

Less than four years after the successful launch of the first artificial satellite into Earth orbit, the Soviet Union achieved another space first, launching the first human being into space. On 12 April 1961, the first manned spacecraft, *Vostok 1* (see Figure 1.13), entered low Earth orbit with 27-year-old Soviet cosmonaut Yuri Gagarin onboard. Gagarin and the *Vostok 1* completed a single Earth orbit, making it the shortest manned orbital flight in history, with a flight time from launch to landing of 108 minutes.

The entire flight of *Vostok 1* was controlled by either automatic systems or ground control, even though there were manual controls that could be operated by Gagarin. Since this was the first time that a human being was exposed to the space environment, including the effects of weightlessness, it was unknown whether there would be adverse reactions on the human body, incapacitating the cosmonaut. Therefore, it was decided that automatic systems or ground control would be the safest option. In fact, the manual controls were locked during the mission, requiring a code to unlock them. The unlock code was sealed in an envelope, to be opened by Gagarin in the event of an emergency.

The *Vostok 1* spacecraft consisted of a spherical capsule attached to a service module. The single cosmonaut sat in an aircraft-type ejection seat in the spherical capsule, which had three small porthole windows. The spherical capsule was 2.3 meters (7.5 ft) in diameter and weighed about 2400 kilograms (5300 lb). The service module contained the batteries for electrical power, consumables for life support, instrumentation and telemetry systems, attitude control system, and the retrorocket propulsion system to slow the vehicle for return to Earth. The spherical capsule was separated from the service module for the descent back to Earth, but the cosmonaut did not remain in the capsule for the landing. At an altitude of about 7 kilometers (23,000 ft), Gagarin ejected from the capsule and parachuted to the ground. Parachutes were used for the capsule's final descent and the capsule was recovered on the ground. The spherical capsule was covered with an ablative material to protect it from the intense temperatures generated during entry to the Earth's atmosphere.

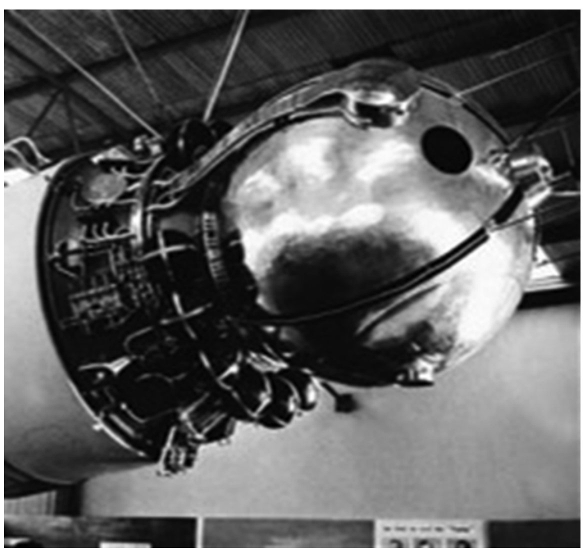

Figure 1.13 The Russian *Vostok 1*, the spacecraft that carried the first man into space, cosmonaut Yuri Gagarin. (Source: *NASA / Public domain*.)

Ablation is a method of thermal protection where a material coating is allowed to vaporize or melt away. Heat is absorbed in the chemical transformations and phase changes of the material during ablation and is carried away from the vehicle by the flow of the vaporized material into the free-stream flow.

Twenty-five days after Gagarin's flight in *Vostok 1*, the United States launched the world's second manned spacecraft, the *Mercury Freedom 7*, on 5 May 1961 (Figure 1.14). The first American in space was Alan B. Sheppard, Jr. (1923–1998), who completed a suborbital flight, lasting 15 minutes and 28 seconds, to an altitude of over 187 km (116 miles). This was followed by another suborbital flight with Virgil I. Grissom (1926–1967) piloting the *Mercury* spacecraft, *Liberty Bell 7*, on 21 July 1961. John H. Glenn, Jr. (1921–2016) became the first American to orbit the Earth on 20 February 1962 with the flight of the *Mercury Friendship 7* spacecraft. Glenn and *Friendship 7* completed three orbits of the Earth with the flight lasting four hours and 55 minutes. The orbit of *Friendship 7* had a perigee of 98.8 miles (159 km) and an apogee of 165 miles (265 km). These three astronauts were in the first group of seven astronauts selected by NASA. They each named their *Mercury* spacecraft, adding the number "7," at the end of the name, to represent their group of seven. The *Mercury* spacecraft would fly a total of 16 times, with six of those being manned spaceflights.

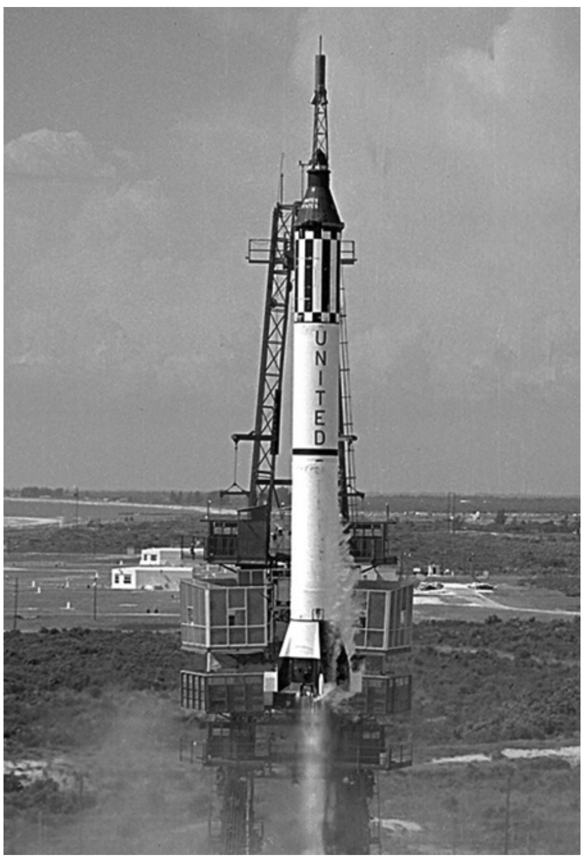

Figure 1.14 Launch of the *Mercury-Redstone* rocket and the *Mercury* spacecraft, *Freedom 7*, with astronaut Alan Shepard aboard, the first American in space. (Source: *NASA / Public domain*.)

The legacy of *Vostok* and *Mercury* designs would be imprinted on future Soviet and American spacecraft designs, respectively, for many years to come.

1.11 The First Flight on Mars

The first flight of a powered aircraft on another planet, Mars, was performed by the NASA *Ingenuity* helicopter on 19 April 2021 (see Figure 1.15). The *Ingenuity* helicopter was launched from Cape Canaveral, Florida, on its journey to Mars on 30 July 2020, strapped to the belly of the *Perseverance* rover. The rover and helicopter landed on Mars, 6½ months later, on 18 February 2021. *Ingenuity* made its first flight on Mars two months later.

The *Ingenuity* helicopter was designed by a team led by the NASA JPL in collaboration with AeroVironment, the NASA Ames Research Center, and the NASA Langley Research Center. The helicopter had a box-shaped, rectangular body with dimensions of 195 mm × 163 mm × 136 mm (7.68 in × 6.42 in × 5.35 in), suspended below a pair of coaxial, counter-rotating rotor blades. The rotor blade diameter measured 1.21 meters (4.0 ft). *Ingenuity* had a total height of 0.49 meter (1.61 ft). Since the density of the Martian atmosphere is about 1/100th that of the Earth's atmosphere at sea level, the rotor blades were larger, with airfoil shapes specially designed for the low density, to enable flight on Mars. The rotor spun at 10 times the rotational rate, between about 2400 and 2900 revolutions per minute, that would be needed on Earth. The helicopter landing gear was comprised of four tubular legs made of carbon fiber composite material. *Ingenuity* had a total weight of 3.97 pounds (1.80 kg) in Earth's gravity while weighing about 60% less, only 1.5 pounds (0.68 kg) in the reduced gravity of Mars. Power was supplied by a solar panel, mounted atop the rotor blades, charging six lithium-ion batteries. The batteries provided sufficient power for a 90-second flight in a single Martian solar day or sol (about 24 hours and 40 minutes). The helicopter

Figure 1.15 NASA *Ingenuity* helicopter on the surface of Mars, 6 April 2021. The image was taken by the *Perseverance* Mars rover. The tread marks from the wheels of the *Perseverance* rover are visible to the right of the helicopter. (Source: *NASA / JPL-Caltech / ASU / MSSS / Public domain*.)

was designed to fly autonomously since the up to 20-minute time delay, in transmitting radio signals between Earth and Mars, made real-time remote control flight impractical.

Ingenuity flew its final flight on Mars on 18 January 2024. While the helicopter was visibly upright and in communication with Earth, it appears that one or more of its rotor blades were damaged during its last landing making it incapable of future flight. Initially designed as a technology demonstrator that would fly no more than five test flights over 30 days, the first Mars helicopter flew a total of 72 flights over 3 years. It reached a maximum altitude of 78.7 feet (24 m), a maximum ground speed of 22.4 miles per hour (10 m/s), and traveled a total of about 10.5 miles (17 km). During its flight time over Mars, *Ingenuity* flew as an aerial scout to assist with planning of the ground treks of the *Perseverance* rover, conducted aerial scientific data collection, and in its final phase, performed flight tests to better understand the aerodynamics of flight on Mars.

1.12 The First Flight Beyond Our Solar System

During the 1970s, the United States launched a series of deep-space probes on trajectories to fly by our Solar System's outer planets and then continue beyond our Solar System. Two of the most successful of these space probes are the *Voyager 1* and *2*, designed to fly by the gas giant planets in our outer Solar System [5]. The *Voyager* spacecraft were designed and built by NASA's JPL in Pasadena, California. Each spacecraft weighed about 1600 pounds (720 kg) and was nuclear-powered by radioisotope thermoelectric generators (to be discussed in Chapter 10). A 30-centimeter diameter, gold-plated, copper disk was attached to each *Voyager* space probe with inscriptions of symbols showing the location of the Earth and recordings of greetings, images, music, and sounds of nature from Earth.

Launched in August 1977, *Voyager 2* flew past Jupiter in July 1979 and Saturn in August 1981. After performing flybys of Jupiter and Saturn, *Voyager 2* became the first spacecraft to fly by the planets Uranus and Neptune, in January 1986 and August 1989, respectively. *Voyager 1* (Figure 1.16) was launched in September 1977, two weeks after *Voyager 2*. Although being launched after *Voyager 2*, *Voyager 1* was on a faster trajectory, passing *Voyager 2* in December 1977. *Voyager 1* performed a Jupiter flyby in March 1979 and discovered the first volcanic activity on another world, the active volcanos on the Jupiter moon, Io. *Voyager 1* flew past Saturn in November 1980, making a close approach to Saturn's moon, Titan.

In 1989, the *Voyager 1* primary mission to fly by the outer planets was complete, and on 1 January 1990, the *Voyager* Interstellar Mission began with the goal of exploring beyond the outer planets, past the Sun's sphere of influence and into interstellar space. On 17 February 1998, *Voyager 1* became the most distant manmade object from Earth at a distance of 69.4 AU[11] [6]. *Voyager 1* flew past the heliosphere, the outermost atmospheric layer of the Sun, on 25 August 2012, and became the first manmade object to leave our solar system and enter interstellar space. As of August 2024, *Voyager 1* was 164.7 AU from the Earth, moving at a velocity of over 38,000 miles per hour (17 km/s) relative to the Sun. Amazingly, the *Voyager 1* spacecraft is still in communication with the NASA Deep Space Network, sending data back to Earth from four of its still-operating instruments: a cosmic ray telescope, a low-energy charged particle experiment, a magnetometer, and a plasma wave experiment. *Voyager 1* is on a trajectory to fly by the star *Gliese 445* in the northern part of the

[11] An astronomical unit, or AU, is a unit of distance equal to the average distance between the Earth and the Sun, about 149.6 million km (93 million mi). The International Astronomical Union (IAU) defines the AU as exactly 149,597,870,700 m.

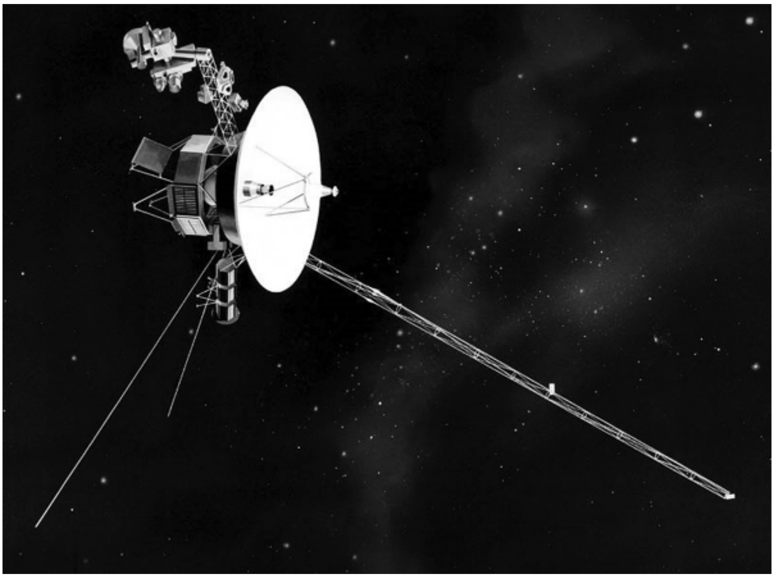

Figure 1.16 The first manmade object to leave our solar system, the *Voyager 1* spacecraft. (Source: *NASA / Public domain*.)

giraffe-shaped constellation *Camelopardalis*, 17.6 light-years[12] from Earth. If *Voyager 1* survives its interstellar journey, it will reach *Gliese 445* in about 40,000 years.

Thus, we close our look at some of the first flights of aerospace vehicles that fly through air or space. It is truly amazing how far we have come in a relatively short time, from the 12-second, powered flight of a wood- and fabric-covered biplane that landed 120 feet from its takeoff point to the flight of a sophisticated space probe into the far reaches of interstellar space, billions, perhaps trillions, of miles from our home planet.

1.13 Organization of the Book

Aerospace engineering encompasses the fields of aeronautical and astronautical engineering. As a broad generalization, the aeronautical field tends to deal with vehicles that fly through the sensible atmosphere, that is, aircraft. Astronautics deals with vehicles that operate in the airless space environment, that is, spacecraft. Aerospace engineering may be considered a merging of these two fields to include aircraft, spacecraft, and other vehicles that operate in both the air and space environments.

The material in the text is organized in a building-block fashion as shown in Figure 1.17. In Chapter 1, the first flights of various aircraft and spacecraft have been described, from the first fledgling flights of hot air balloons to spaceflights beyond our solar system. These first flights may provide the reader with valuable insights into the development and evolution of aerospace engineering.

Several introductory concepts in aerospace engineering and flight tests are introduced in Chapter 2. The reader is introduced to aircraft, including the fixed-wing airplane, the rotary-wing helicopter, the lighter-than-air vehicle, and the unmanned aerial vehicle. The description of the

[12] A light year is the distance light travels in one year, about 5.88 trillion miles (9.46 trillion km).

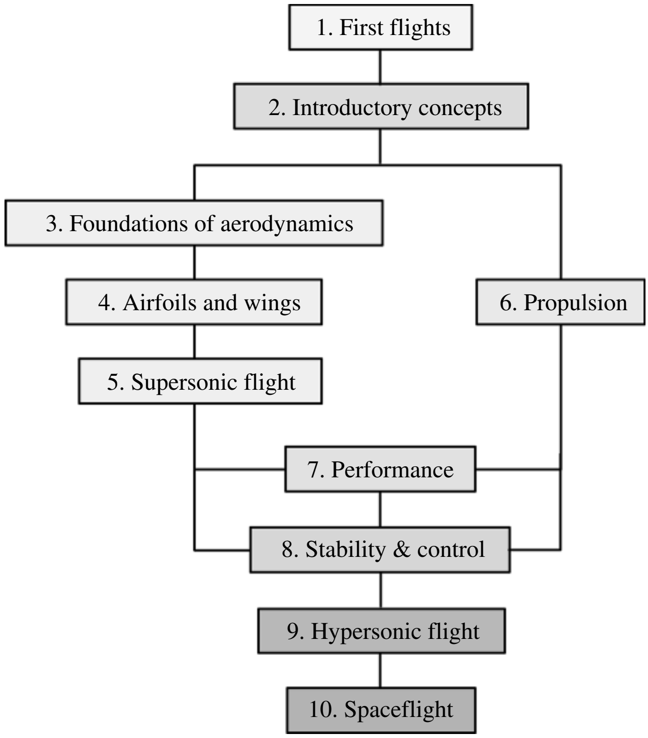

Figure 1.17 Organization of the text.

different types of spacecraft is reserved for Chapter 10. Basic aerospace engineering fundamentals and concepts are described, including the regimes of flight, the four forces acting on aircraft, and the flight envelope. The properties of the Earth's atmosphere are discussed, which is used for analyses in many of the following chapters. Basic flight test concepts are introduced, including the different types of flight tests, the flight test process, and the use of flight test techniques.

The fundamental disciplines of aerodynamics and propulsion are discussed in Chapters 3 through 6. The study of aerodynamics provides the theories and tools required to analyze the flow of air over aerospace vehicles, the flow that produces aerodynamic forces such as lift and drag. Chapter 3 covers the foundations of aerodynamics, including the fundamental physical properties of fluids, the types of aerodynamic flows, and an explanation of the fundamental aerodynamic forces of lift and drag. Airfoils and wings, the aerodynamic surfaces that enable aircraft flight, are described in detail in Chapter 4. Supersonic flight is covered in Chapter 5 with an explanation of the speed of sound, shock and expansion waves, and supersonic airfoils and wings. Aerospace propulsion is the subject of Chapter 6, where we learn about the devices that generate the thrust force to propel aerospace vehicles both in the atmosphere and in space. A deeper understanding of how thrust is produced is provided, regardless of the type of propulsion system.

The study of performance, in Chapter 7, builds upon an overall understanding of aerodynamics and propulsion, as shown graphically in Figure 1.17. Performance deals with the motion of the vehicle caused by the aerodynamic forces (lift and drag) and propulsive force (thrust) acting upon it. Performance seeks to determine how fast, how high, how far, and for how long a vehicle may fly.

In Chapter 8, the study of stability and control also builds upon the fundamental disciplines of aerodynamics and propulsion. Stability and control deal with the motion of the vehicle caused by the aerodynamic and propulsive moments acting on it. We investigate the vehicle's stability when disturbed from its equilibrium condition and seek to understand the impacts of various vehicle configurations and geometries. We also look at the means by which the vehicle may be controlled throughout its flight regime.

Chapters 9 and 10 introduce two new complete chapters, one on hypersonic flight and the other on spaceflight. Chapter 9 discusses flight at hypersonic speeds of Mach 5 and higher. The aerodynamics, propulsion, and design of the vehicles, unique to hypersonic flight, are discussed in detail. The final Chapter 10 discusses the space environment, different types of spacecraft, space access systems, space launch, orbital mechanics, and the atmospheric entry of spacecraft from Earth orbit.

Many examples of ground and flight testing are integrated throughout the text, in sections titled Ground Test Techniques and Flight Test Techniques. Several of the flight test techniques are described in a unique manner, by placing the reader "in the cockpit" of different aircraft as the test pilot or flight test engineer. In this way, the reader may obtain an intimate knowledge of the engineering concepts, test techniques, and in-flight data collection by "flying" the flight test technique. A collateral benefit of this approach is that the reader becomes familiar with several different types of aircraft.

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