Magnificent Flying Machine— A Cathedral to Technology

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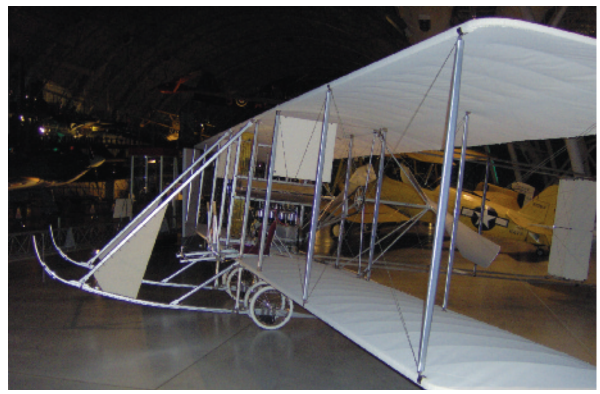
Wayne Hale

Certain physical objects become icons of their time. Popular sentiment transmutes shape, form, and outline into a mythic embodiment of the era so that abstracted symbols evoke even the hopes and aspirations of the day. These icons are instantly recognizable even by the merest suggestion of their shape: a certain wasp-waisted soft drink bottle epitomizes America of the 1950s; the outline of a gothic cathedral evokes the Middle Ages of Europe; the outline of a steam locomotive memorializes the American expansion westward in the late 19th century; a clipper ship under full sail idealizes global trade in an earlier part of that century. America's Space Shuttle has become such an icon, symbolizing American ingenuity and leadership at the turn of the 21st century. The outline of the delta-winged Orbiter has permeated the public consciousness. This stylized element has been used in myriad illustrations, advertisements, reports, and video snippets—in short, everywhere. It is a fair question to ask why the Space Shuttle has achieved such status.



Top: 1928 Ford Tri-Motor; above: 1909 Wright "Model B." Smithsonian National Air and Space Museum, Washington, DC. (photos by Wayne Hale)

The first great age of space exploration culminated with the historic lunar landing in July 1969. Following that achievement, the space policymakers looked back to the history of aviation as a model for the future of space travel. The Space Shuttle was conceived as a way to exploit the resources of the new frontier. Using an aviation analogy, the shuttle would be the Douglas DC-3 of space. That aircraft is generally considered to be the first commercially successful air transport. The shuttle was to be the first commercially successful *space* transport. This impossible leap was not realized, an unrealistic goal that appears patently obvious in retrospect, yet it haunts the history of the shuttle to this day. Much of the criticism of the shuttle originates from this overhyped initial concept.

In fact, the perceived relationship between the history of aviation and the promise of space travel continues to motivate space policymakers. In some ways, the analogy that compares space with aviation can be very illustrative. So, if an unrealistic comparison for the shuttle is the leap from the 1903 Wright Flyer to the DC-3 transport of 1935 in a single technological bound, what is a more accurate comparison?

If the first crewed spacecraft of 1961—either Alan Shepard's Mercury or Yuri Gagarin's Vostok—are accurately the analog of the Wright brothers' first aircraft, the Apollo spacecraft of 1968 should properly be compared with the Wright brothers' 1909 "Model B"—their first commercial sale. The "B" was the product of 6 years of tinkering, experimentation, and adjustments, but were only two major iterations of aircraft design. In much the same way, Apollo was the technological inheritor of two iterations of spacecraft design in 7 years. The Space Shuttle of 1981—coming 20 years after the first spaceflights—could be compared with the aircraft of the mid 1920s. In fact, there is a good analogy in the history of aviation: the Ford Tri-Motor of 1928.

The Ford Tri-Motor was the leap from experimental to operational and had the potential to be economically effective as well. It was a huge improvement in aviation—it was revolutionary, flexible, and capable. The vehicle carried passengers and the US mail.

Admiral Richard Evelyn Byrd used the Ford Tri-Motor on his historic flyover of the North Pole. But the Ford Tri-Motor was not quite reliable enough, economical enough, or safe enough to fire off a successful and vibrant commercial airline business; just like the Space Shuttle.

Lower left: 1903 Wright Flyer; right: Douglas aircraft DC-3 of 1935. Smithsonian National Air and Space Museum, Washington, DC. (photos by Wayne Hale)

But here the aviation analogy breaks down. In aviation history, advances are made not just because of the passage of calendar time but because there are hundreds of different aircraft designs with thousands of incremental technology advances tested in flight between the “B” and the Tri-Motor.

Even so, the aviation equivalent compression of decades of technological advance does not do justice to the huge technological leap from expendable rockets and capsules to a reusable, winged, hypersonic, cargo-carrying spacecraft. This was accomplished with no intermediate steps. Viewed from that perspective, the Space Shuttle is truly a wonder. No doubt the shuttle is but one step of many on the road to the stars, but it was a giant leap indeed.

That is what this book is about: not what might have been or what was impossibly promised, but what was actually achieved and what was actually delivered. Viewed against this background, the Space Shuttle was a tremendous engineering achievement—a vehicle that enabled nearly routine and regular access to space for hundreds of people, and a profoundly vital link in scientific advancement. The vision of this book is to take a clear-eyed look at what the shuttle accomplished and the shuttle’s legacy to the world.

Superlative Achievements of the Space Shuttle

For almost half a century, academic research, study, calculations, and myriad papers have been written about the problems and promises of controlled, winged hypersonic flight through the atmosphere. The Space Shuttle was the largest, fastest, winged hypersonic aircraft in history. Literally everything else had been a computer model, a wind tunnel experiment, or some subscale vehicle launched on a rocket platform. The shuttle flew at 25 times the speed of sound; regularly. The next fastest crewed vehicle—the venerable X-15—flew at its peak at seven times the speed of sound. Following the X-15, the next fastest crewed vehicle was the military SR-71, which could achieve three times the speed of sound. Both the X-15 and the SR-71 were retired years ago. Flight above about Mach 2 is not practiced today. If the promise of regular, commercial hypersonic flight is ever to come to fruition, the lessons learned from the shuttle will be an important foundation. For example, the specifics of aerodynamic control change significantly with these extreme speeds. Prior to the first flight, computations for the shuttle were found to be seriously in error when actual postflight data were reviewed. Variability in the atmosphere at extreme altitudes would have gone undiscovered except for the regular passage of the shuttle through regions unnavigable any other way. Serious engineering obstacles with formidable names—hypersonic boundary layer transition, for example—must be understood and overcome, and cannot be studied in wind tunnels or computer simulations. Only by flight tests will real data help us understand and tame these dragons of the unknown ocean of hypersonic flight.

The second X-15 rocket plane (56-6671) is shown with two external fuel tanks, which were added during its conversion to the X-15A-2 configuration in the mid 1960s.

Most authorities agree that getting back safely from Earth orbit is a more difficult task than achieving Earth orbit in the first place. All the tremendous energy that went into putting the spacecraft into orbit must be cancelled out. For any vehicle’s re-entry into Earth’s atmosphere, this is principally accomplished by air friction—turning kinetic energy into heat. Objects entering the Earth’s atmosphere are almost always rapidly vaporized by the friction generated by the enormous velocity of space travel. Early spacecraft carried huge and bulky ablative heat shields, which were good for one use only. The Space Shuttle Orbiter was completely reusable, and was covered with Thermal Protection Systems from nose to tail. The thermal shock standing 9 mm (0.3 in.) off the front of the wing leading edge exceeded the temperature of the visible surface of the sun: 8,000°C (14,000°F). At such an extreme temperature, metals don’t melt—they boil. Intense heating went on for almost half an hour during a normal deceleration from 8 km (5 miles) per second to full stop. Don’t forget that weight was at a premium. A special carbon fiber cloth impregnated with carbon resin was molded to an aerodynamic shape. This was the

This view of the suspended Orbiter Discovery shows the underside covered with Thermal Protection System tiles.

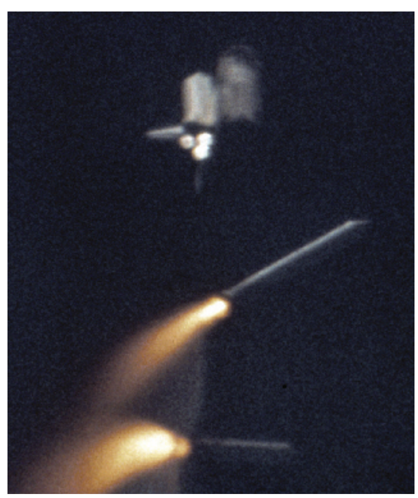
so-called reinforced carbon-carbon on the wing leading edge and nose cone. This amazing composite was only 5 mm (0.2 in.) thick, but the aluminum structure of the Orbiter was completely reliant on the reinforced carbon-carbon for protection. In areas of the shuttle where slightly lower peak temperatures were experienced, the airframe was covered with silica-based tiles. These tiles were mostly empty space but provided protection from temperatures to 1,000°C (2,000°F). Extraordinarily lightweight but structurally robust, easily formed to whatever shape needed, over 24,000 tiles coated the bottom and sides of the Orbiter. In demonstrations of the tile's effectiveness, a technician held one side of a shuttle tile in a bare hand while pointing a blowtorch at the opposite side. These amazing Thermal Protection Systems—all invented for the shuttle—brought 110 metric tons (120 tons) of vehicle, crew, and payload back to Earth through the inferno that is re-entry.

Nor is the shuttle's imaginative navigation system comparable to any other system flying. The navigation system kept track of not only the shuttle's position during re-entry, but also the total energy available to the huge glider. The system managed energy, distance, altitude, speed, and even variations in the winds and weather to deliver the shuttle precisely to the runway threshold. The logic contained in the re-entry guidance software was the hard-won knowledge from successful landings.

So much for re-entry. All real rocket scientists know that propulsion is problem number one for space travel. The shuttle excelled in both solid- and liquid-fueled propulsion elements.

The reusable Solid Rocket Booster (SRB) motors were the largest and most powerful solid rocket motors ever flown. Solid rockets are notable for their high thrust-to-weight ratio and the SRB motors epitomized that. Each one developed a thrust of almost 12 meganewtons (3 million pounds) but weighed only 600,000 kg (1.3 million pounds) at ignition (with weight decreasing rapidly after that). This was the equivalent motive power of 36,000 diesel locomotives that together would weigh 26 billion kg (57 billion pounds). The shuttle's designers were grounded in aviation in the 1950s and thought of the SRB motors as extreme JATO bottles—those small solid rockets strapped to the side of overloaded military transports taking off from short airfields. (JATO is short for jet-assisted takeoff, where "jet" is a generic term covering even rocket engines.) Those small, strap-on solid rocket motors paled in comparison with the SRB motors—some JATO bottles indeed. Within milliseconds of ignition, the finely tuned combustion processes inside the SRB motor generated internal pressure of over 7 million pascals (1,000 pounds per square inch [psi]). The thrust was "throttled" by the shape in which the solid propellant was cast inside the case. This was critical because thrust had to be reduced as the shuttle accelerated through the speed of maximum aerodynamic pressure. For the first 50 years of spaceflight, these reuseable boosters were the largest solid rockets ever flown.

The Solid Rocket Boosters operated in parallel with the main engines for the first 2 minutes of flight to provide the additional thrust needed for the Orbiter to escape the gravitational pull of the Earth. At an altitude of approximately 45 km (24 nautical miles), the boosters separated from the Orbiter/External Tank, descended on parachutes, and landed in the Atlantic Ocean. They were recovered by ships, returned to land, and refurbished for reuse. The boosters also assisted in guiding the entire vehicle during initial ascent. Thrust of both boosters was equal to over 2 million kg (over 5 million pounds).



Development of the liquid-fueled Space Shuttle Main Engine was considered an impossible task in the mid 1970s. Larger liquid-fueled rockets had been developed—most notably the Saturn V first-stage engines, the famous F-1 engine that developed three times the thrust of the shuttle main engines. But the F-1 engines burned kerosene rather than hydrogen and their "gas mileage" was much lower than the shuttle main engines. In fact, no more efficient, liquid-fueled rocket engines have ever been built. Getting to orbit requires enormous amounts of energy. The "mpg" rating of these main engines was unparalleled in the history of rocket manufacture. The laws of thermodynamics define the maximum efficiency of any "heat engine," whether it is the gasoline engine that powers an automobile, or a big power plant that generates electricity, or a rocket engine. Different thermodynamic "cycles" have different possible efficiencies. Automobile engines operating on the Otto cycle typically are 15% of the maximum theoretical efficiency. The shuttle main engines operating on the rocket cycle achieved 99.5% of the maximum theoretical efficiency.

To put the power of the main engines in everyday terms: if your car engine developed the same power per pound as these engines, your automobile would be powered by something about the size and weight of a loaf of bread. And it would cost less than $100.00. More efficient engines have never been made, no matter what measure is used: horsepower to weight, horsepower to cost. Nor is the efficiency standard likely to ever be exceeded by any other chemical rocket.

So far, this has been about the basic problem in any journey—getting there and getting back. But the shuttle was a space truck, a heavy-lift launch vehicle in the same class as the Saturn V moon rocket. In fact, over half of all the mass put in Earth orbit—and that includes all rockets from all the nations of the world from 1957 until 2010—was put there by the shuttle. Think of that. The shuttle lofted more mass to Earth orbit than all the Saturn Vs, Saturn Is, Atlases, Deltas, Protons, Zenits, and Long Marches, etc., combined. And what about all the mass brought safely home from space? Ninety-seven percent came home with the shuttle. The Space Shuttle deployed some of the heaviest-weight upper stages for interplanetary probes. The largest geosynchronous satellites were launched by the shuttle. What a truck. What a transportation system.

And Science?

How much science was accomplished by the Space Shuttle? Start with the study of the stars. What has the shuttle done for astronomy? It brought us closer to the heavens. Shuttle had mounted telescopes operated directly by the crew to study the heavens. Not only did the shuttle launch the Compton Gamma Ray Observatory, the crew saved it by fixing its main antenna. Astronauts deployed the orbiting Chandra X-ray Observatory and the international polar star probe Ulysses. A series of astronomy experiments, under the moniker SPARTAN, studied comets, the sun, and galactic objects. The Solar Maximum Satellite enabled the study of our sun. And the granddaddy of them all, the Hubble Space Telescope, often called the most productive scientific instrument of all time, made discoveries that have rewritten the textbooks on astronomy, astrophysics, and cosmology—all because of shuttle.

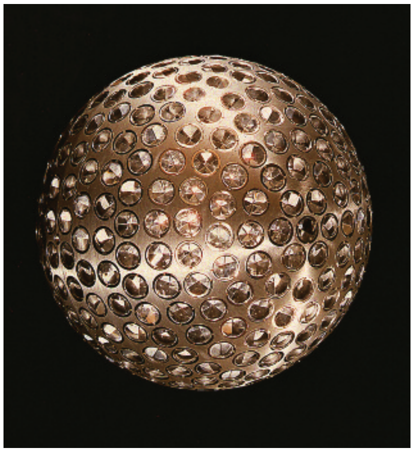
Don't forget planetary science. Not only has Hubble looked deeply at most of the planets, but the shuttle also launched the Magellan radar mapper

Backdropped by a cloud-covered part of Earth, Space Shuttle Discovery approaches the International Space Station during STS-124 (2008) rendezvous and docking operations. The second component of the Japan Aerospace Exploration Agency's Kibo laboratory, the Japanese Pressurized Module, is visible in Discovery's cargo bay.

to Venus and the Galileo mission to Jupiter and its moons.

In Earth science, two Spacelab Atmospheric Laboratory for Applications and Science missions studied our own atmosphere, the Laser Geodynamic Satellite sphere monitors the upper reaches of the atmosphere and aids in mapping, and three Space Radar Laboratory missions mapped virtually the entire land mass of the Earth to a precision previously unachievable. The Upper Atmosphere Research satellite was also launched from the shuttle, as was the Earth Radiation Budget Satellite and a host of smaller nanosatellites that pursued a variety of Earth-oriented topics. Most of all, the pictures and observations made by the shuttle crews using cameras and other handheld instruments provided long-term observation of the Earth, its surface, and its climate.

Satellite launches and repairs were a highlight of shuttle missions, starting with the Tracking and Data Relay Satellites that are the backbone for communications with all NASA satellites—Earth resources,

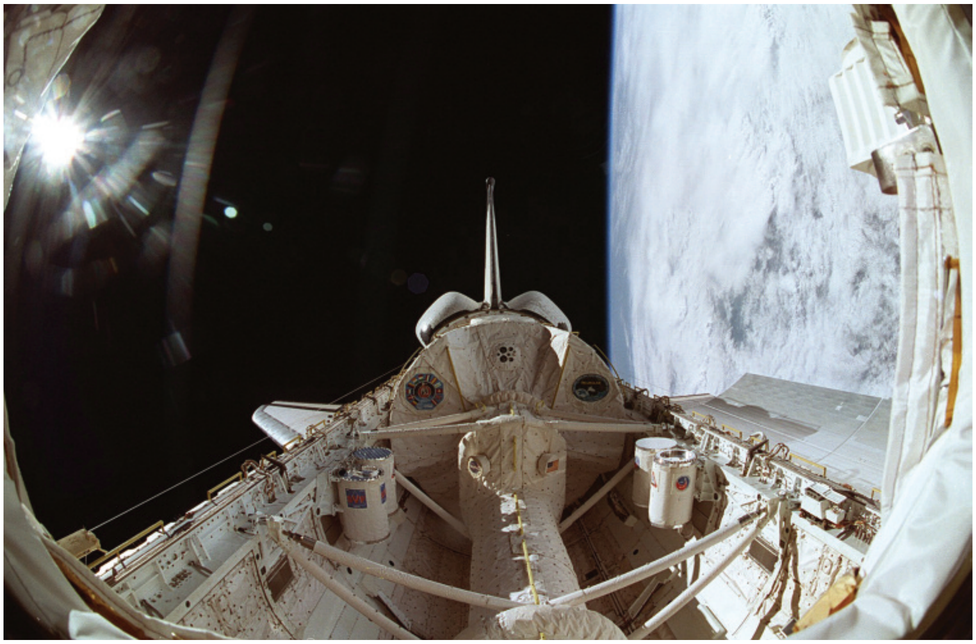


Laser Geodynamic Satellite dedicated to high-precision laser ranging. It was launched on STS-52 (1992).

astronomical, and many more. Communications satellites were launched early in the shuttle's career but were reassigned to expendable launches for a variety of reasons. Space repair and recovery of satellites started with the capture and repair of the Solar Maximum Satellite in 1984 and continued with satellite recovery and repair of two HS-376 communications satellites in 1985 and the repair of Syncom-IV that same year. The most productive satellite repair involved five repetitive shuttle missions to the Hubble Space Telescope to upgrade its systems and instruments on a regular basis.

Biomedical research also was a hallmark of many shuttle missions. Not only were there six dedicated Spacelab missions studying life sciences, but there were also countless smaller experiments on the effects of microgravity (not quite zero gravity) on various life forms: from microbes and viruses, through invertebrates and insects, to mammals, primates, and finally humans. This research yielded valuable insight in the workings of the human body, with ramifications for general medical care and disease cure and prevention. The production of pharmaceuticals in space has been investigated with mixed success, but practical production requires lower cost transportation than the shuttle provided.

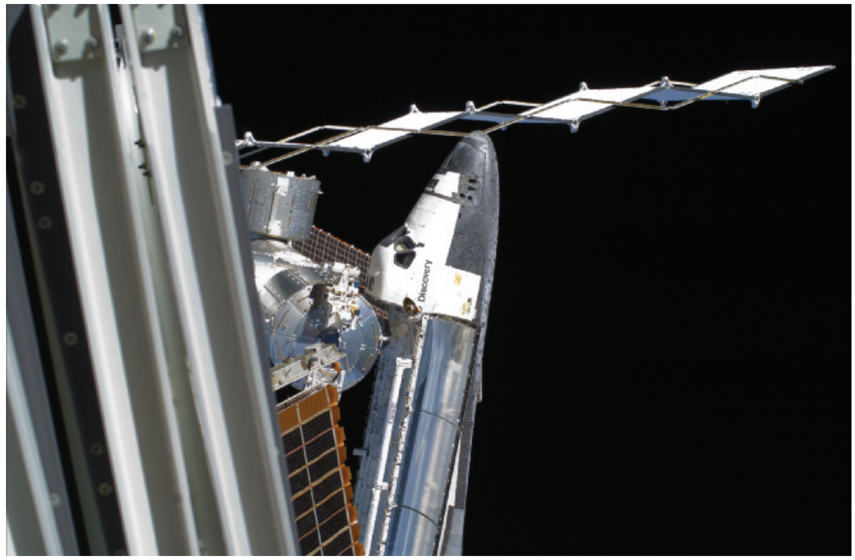
Finally, note that nine shuttle flights specifically looked at materials science questions, including how to grow crystals in microgravity, materials processing of all kinds, lubrication, fluid mechanics, and combustion dynamics—all without the presence of gravity.



View from the Space Shuttle Columbia's cabin of the Spacelab science module, hosting 16 days of Neurolab research. (STS-90 [1998] is in the center.) This picture clearly depicts the configuration of the tunnel that leads from the cabin to the module in the center of the cargo bay.

Spacewalks

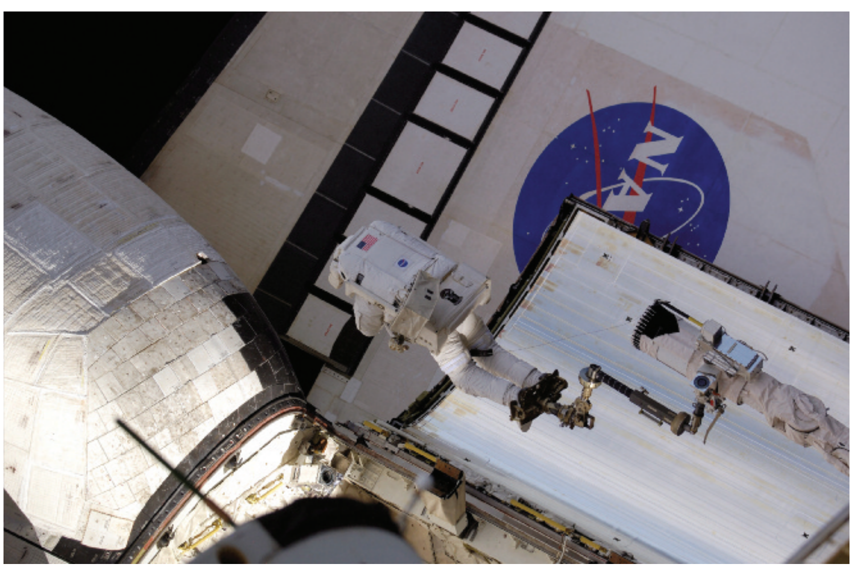
Of all the spacewalks (known as extravehicular activities) conducted in all the spaceflights of the world, more than three-quarters of them were based from the Space Shuttle or with shuttle-carried crew members at the International Space Station (ISS) with the shuttle vehicle attached and supporting. The only "untethered" spacewalks were executed from the shuttle. Those crew members were buoyed by the knowledge that, should their backpacks fail, the shuttle could swiftly come to their rescue.



Space Shuttle Discovery docked to the International Space Station is featured in this image photographed by one of the STS-119 (2009) crew members during the mission's first scheduled extravehicular activity.

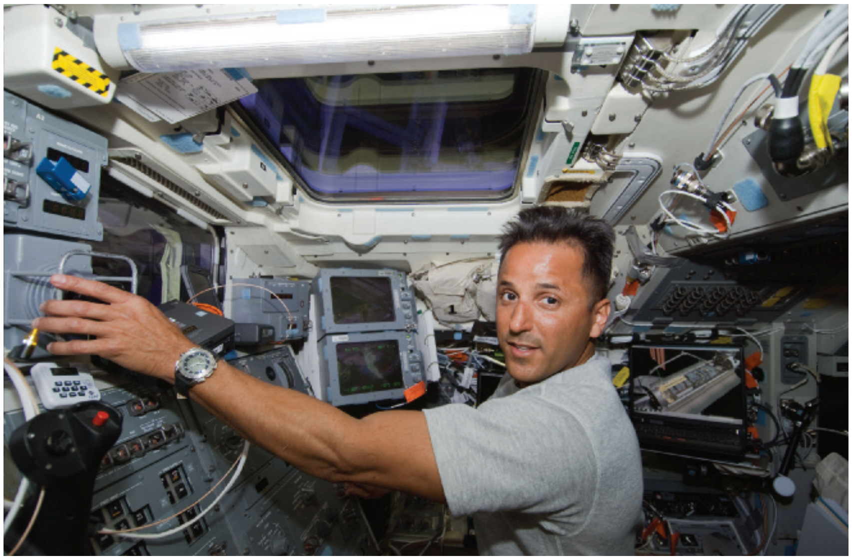
The final and crowning achievement of the shuttle was to build the ISS. The shuttle was always considered only part of the future of space infrastructure. The construction and servicing of space stations was one of the design goals for the shuttle. The ISS—deserving of a book in its own right—is the largest space international engineering project in the history of the world. The ISS and the Space Shuttle are two sides of the same coin: the ISS could not be constructed without the shuttle, and the shuttle would have lost a major reason for its existence without the ISS. In addition to the scientific accomplishments of the ISS and the engineering marvel of its construction, the ISS is important as one of the shining examples of the power of international cooperation for the good of all humanity. The shuttle team was always international due to the Canadian contributions of the robot arm, the international payloads, and the international spacefarers. But participation in the construction of the ISS brought international cooperation to a new level, and the entire shuttle team was transformed by that experience.

Anchored to a foot restraint on Space Shuttle Atlantis' remote manipulator system robotic arm, Astronaut John Olivas, STS-117 (2007), moves toward Atlantis' port orbital maneuvering system pod that was damaged during the shuttle's climb to orbit. During the repair, Olivas pushed the turned-up portion of the thermal blanket back into position, used a medical stapler to secure the layers of the blanket, and pinned it in place against adjacent thermal tile.



The Astronauts

In the final analysis, space travel is all about people. In 133 flights, the Space Shuttle provided nearly 850 seats to orbit. Many people have been to orbit more than once, so the total number of different people who have flown to space on all spacecraft (Vostok, Mercury, Voskhod, Gemini, Soyuz, Apollo, Shenzhou, and the shuttle) in the last 50 years is just under 500. Of that number, over 400 have flown on the Space Shuttle. Almost three times as many people flew to space on the



Astronaut Joseph Acaba, STS-119 (2009), works the controls of Space Shuttle Discovery's Shuttle Robotic Arm on the aft flight deck during Flight Day 1 activities.

shuttle than on all other vehicles from all countries of the world combined. If the intent was to transform space and the opening of the frontier to more people, the shuttle accomplished this. Fliers included politicians, officials from other agencies, scientists of all types, and teachers. Probably most telling, these spacefarers represented a multiplicity of ethnicities, genders, and citizenships. The shuttle truly became the people's spaceship.

Fourteen people died flying on the shuttle in two accidents. They too represented the broadest spectrum of humanity. In 11 flights, Apollo lost no astronauts in space—although Apollo 13 was a very close call—and only three astronauts in a ground accident. Soyuz, like shuttle, had two fatal in-flight accidents but lost only four souls due to the smaller carrying capacity. The early days of aviation were far bloodier, even though the altitudes and energies were a fraction of those of orbital flight.

How Do We Rate the Space Shuttle?

Did shuttle have the power of thousands of diesel locomotives? Was it the most efficient rocket system ever built? Certainly it was the only winged space vehicle that flew from orbit as a hypersonic glider. And it was the only reusable space vehicle ever built except for the Soviet Buran ("Snowflake"), which was built to be reusable but only flew once. Imitation is the sincerest form of flattery; the Buran was the greatest compliment the shuttle ever had.

In the 1940s and early 1950s, the world's experimental aircraft flew sequentially faster and higher. The X-15 even allowed six people to earn their astronaut wings for flying above 116,000 m (380,000 ft) in a parabolic suborbital trajectory. If the exigencies of the Cold War—the state of conflict, tension, and competition that existed between the United States and the Soviet Union and their respective allies from the mid 1940s to the early 1990s—had not forced a rapid entry into space on the top of intercontinental ballistic missiles, a far different approach to spaceflight would most likely have occurred with air-breathing winged vehicles flying to the top of the atmosphere and then smaller rocket stages to orbit. But that buildup approach didn't happen. Some historians think such an approach would have provided a more sustainable approach to space than expendable intercontinental ballistic missile-based launch systems. Hypersonic flight continues to be the subject of major research by the aviation community. Plans to build winged vehicles that can take off horizontally and fly all the way to Earth orbit are still advanced as the "proper" way to travel into space. Time will tell if these dreams become reality.

No matter the next steps in space exploration, the legacy of the Space Shuttle will be to inspire designers, planners, and astronauts. Because building a Space Shuttle was thought to be impossible, and yet it flew, the shuttle remains the most remarkable achievement of its time—a cathedral of technology and achievement for future generations to regard with wonder.

The sun radiates on Space Shuttle Atlantis as it is positioned to head for space on mission STS-115 (2006).