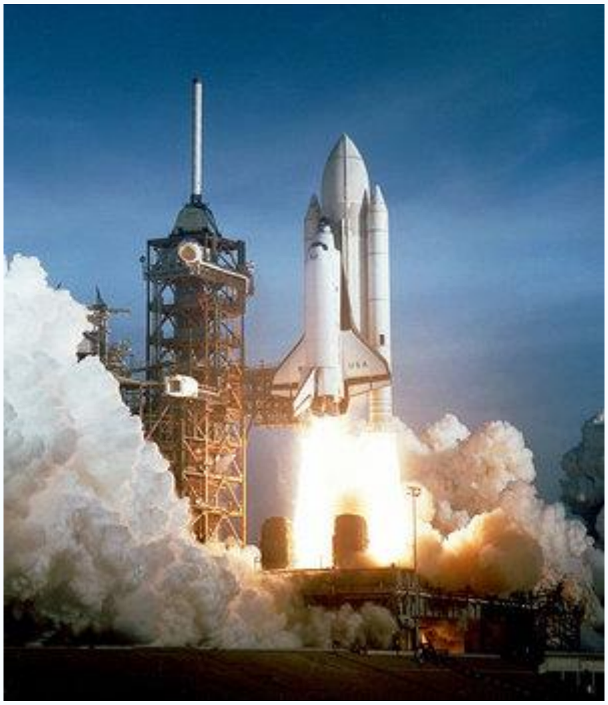
Space Shuttle program



The Space Shuttle *Columbia* seconds after engine ignition, 1981 (NASA). For the first two missions only, the external fuel tank spray-on foam insulation (SOFI) was painted white. Subsequent missions have featured an unpainted tank thus exposing the orange/rust colored foam insulation. This resulted in a weight saving of over 1,000 lb (450 kg), a savings that translated directly to added payload capacity to orbit.

NASA's **Space Shuttle**, officially called **Space Transportation System** (**STS**), is the United States government's sole manned launch vehicle currently in service. The winged shuttle orbiter is launched vertically, carrying usually five to seven astronauts and up to about 22,700 kg (50,000 lbs) of payload into low earth orbit. When its mission is complete, it reenters the earth's atmosphere and makes an unpowered gliding horizontal landing, usually on a runway at Kennedy Space Center.

The Space Shuttle orbiter was manufactured by North American Rockwell, now part of the Boeing Company. Martin Marietta (now part of Lockheed Martin) designed the external fuel tank and Morton Thiokol (now part of Alliant Techsystems (ATK)) designed the solid rocket boosters.

The Shuttle is the first orbital spacecraft designed for partial reusability. It carries large payloads to various orbits, provides crew rotation for the International Space Station (ISS), and performs servicing missions. While the vehicle was designed with the capacity to recover satellites and other payloads from orbit and return them to Earth, this capacity has not been used often; it is, however, an important use of the Space Shuttle in the context of the ISS program, as only very small amounts of experimental material, hardware needing to be repaired, and trash can be returned by Soyuz. Each Shuttle was designed for a projected lifespan of 100 launches or 10-years operational life.

The program started in the late 1960s and has dominated NASA's manned operations since the mid-1970s. According to the Vision for Space Exploration, use of the Space Shuttle will be focused on completing assembly of the ISS in 2010, after which it will be replaced by the yet-to-be-developed Crew Exploration Vehicle (CEV). However, following the STS-114 return-to-flight mission in August

2005, the Shuttle program is currently grounded pending repairs and the solution of outstanding safety issues.

Further aggravating the shuttle's return to space, also in August 2005, the Space Shuttle external tank construction site, Michoud Assembly Facility located in New Orleans, Louisiana was damaged by Hurricane Katrina, with all work shifts cancelled up to September 26, 2005. This could potentially set back further Shuttle flights by more than two months.

The NASA Chief Administrator Michael Griffin has recently suggested the decision to develop the Space Shuttle and International Space Station was a mistake by saying, "It is now commonly accepted that was not the right path. We are now trying to change the path while doing as little damage as we can." [1]

Space Shuttles

American

- *Enterprise* (test)
- *Pathfinder* (mockup)
- *Columbia* (destroyed 2003)
- *Challenger* (destroyed 1986)
- *Discovery* (active)
- *Atlantis* (active)
- *Endeavour* (active)
- *Explorer* (mockup)

Soviet/ Russian

- *Buran* (retired, destroyed 2002)
- *Ptichka* (unfinished)
- 2.01 (unfinished)
- 2.02 (dismantled)
- 2.03 (dismantled)
- *Baikal* (hoax)

Development

Postage stamp depicting shuttle program

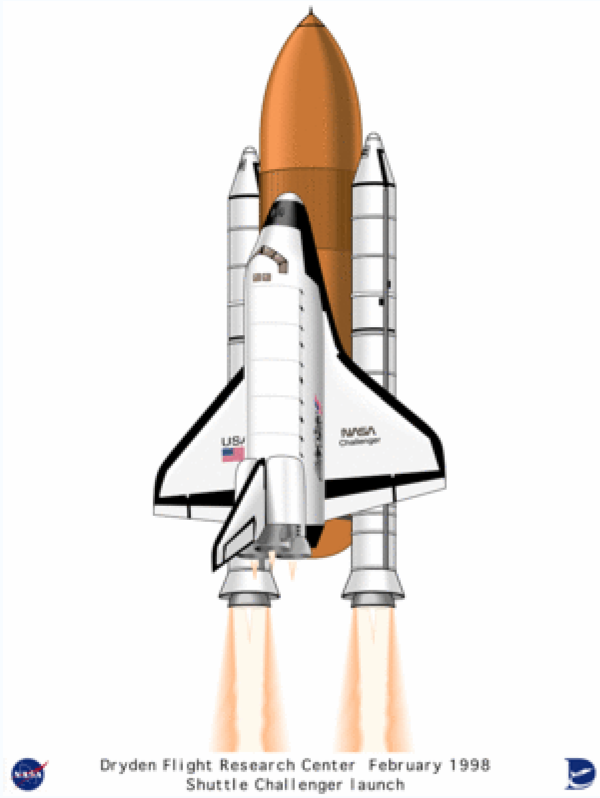
The Shuttle program was launched on January 5, 1972, when President Richard M. Nixon announced that NASA would proceed with the development of a reusable, low-cost Space Shuttle system.

The project was already to take longer than originally anticipated due to the year-to-year funding caps. Nevertheless, work started quickly and several test articles were available within a few years.

Most notable among these was the first complete Orbiter, originally to be known as *Constitution*. However, a massive write-in campaign from fans of the *Star Trek* television series convinced the White House to change the name to *Enterprise*. Amid great fanfare, the *Enterprise* was rolled out on September 17, 1976, and later conducted a successful series of glide-approach and landing tests that were the first real validation of the design.

The first fully functional Shuttle Orbiter, built in Palmdale, California, was the *Columbia*, which was delivered to Kennedy Space Center on March 25, 1979, and was first launched on April 12, 1981—the 20th anniversary of Yuri Gagarin's space flight—with a crew of two. *Challenger* was delivered to KSC in July 1982, *Discovery* was delivered in November 1983, and *Atlantis* was delivered in April 1985. The Shuttle was meant to visit Space Station Freedom, announced in 1984, an ambitious and much-delayed project later downsized and merged into the International Space Station program. *Challenger* was destroyed in an explosion during launch on January 28, 1986, with the loss of all seven astronauts on board. *Endeavour* was built to replace it (using spare parts originally intended for the other Orbiters) and delivered in May 1991. *Columbia* was lost, with all seven crew members, during reentry on February 1, 2003, and has not been replaced.

Description



Reusable Orbiter (center), External Tank (copper colored object at top center), Boosters (to the right and left of External Tank)

The shuttle system is composed of three main assemblies: the winged orbiter, the large external tank (ET), and the two solid rocket boosters (SRBs).

Two key elements of the orbiter are the Space Shuttle Main Engines (SSMEs) and thermal protection system (TPS).

The orbiter contains both astronauts and cargo. The SSMEs are attached to the orbiter. The external tank contains the 2 million liters (526,000 gallons) of liquid hydrogen and liquid oxygen propellant that feeds the SSMEs. The ET is discarded and burns up on reentry. The ET is made of aluminum-lithium alloy. The orbiter structure is made primarily from aluminum alloy, although the engine thrust structure is made from titanium.

The SRBs contain the solid fuel that provides about 71% of the vehicle's liftoff thrust. The SRBs burn until 150,000 feet (45.7 km), and are then jettisoned to parachute back for reuse. The SRB cases are made of steel.

The Thermal Protection System is composed of various materials, depending on the amount of heat. The hottest areas are on the wing leading edges and nose, which are protected by reinforced carbon/carbon. The underbelly and much of the fuselage sides is protected by silica tiles. Lower temperature areas on the upper surfaces are protected by flexible thermal blankets. Unlike previous space vehicles which used insulation that burned off during reentry and couldn't be reused, the orbiter thermal protection can be reused up to 100 times with only minor repairs.

The orbiter crew cabin has three levels: the flight deck, the mid-deck, and the utility area. The flight deck is highest, where the commander and pilot sit, surrounded by many switches and controls. Two additional astronauts are usually positioned on the flight deck behind the commander and pilot. The three other crew members are positioned in the mid-deck, which is below the flight deck.

The galley, toilet, sleep locations, and storage lockers are found in the mid-deck. The side hatch for entering/exiting the vehicle is also located there, as is the airlock hatch into the payload bay. Astronauts pass through the airlock hatch to don their space suits.

The orbiter has a large 60 by 15 ft (18 by 4.6 m) payload bay, filling most of the fuselage. The payload bay doors have heat radiators mounted on their inner surfaces, and so are kept open for thermal control while the Shuttle is in orbit. Thermal control is also maintained by adjusting the orientation of the Shuttle relative to Earth and Sun. Inside the payload bay is the Remote Manipulator System, also known as the Canadarm, a robot arm used to retrieve and deploy payloads. Until the loss of *Columbia*, the Canadarm had been used only on those missions where it was needed. Since the arm is a crucial part of the Thermal Protection Inspection procedures now required for Shuttle flights, it will probably be included on all future flights.

Computerized fly-by-wire digital flight control

The shuttle was one of the earliest aircraft to use a computerized fly-by-wire digital flight control system. This means no mechanical or hydraulic linkages connect the pilot's control stick to the control surfaces or reaction control system thrusters. For more details on fly-by-wire flight control systems, see the Wikipedia article fly-by-wire.

A primary concern with digital fly-by-wire systems is reliability. Since the shuttle had one of the first digital fly-by-wire systems, much research went into the shuttle computer system. The shuttle uses five identical redundant IBM 32-bit general purpose computers (GPCs), model AP-101, constituting a type of embedded system. Four computers run specialized software called the Primary Avionics Software System (PASS). A fifth backup computer runs separate software called the Backup Flight System (BFS). Collectively they are called the shuttle Data Processing System (DPS).

The design goal of the shuttle DPS is fail operational/fail safe reliability. After a single failure the shuttle can continue the mission. After two failures it can land safely.

The four general purpose computers operate essentially in lockstep, checking each other. If one computer fails the three functioning computers "vote" it out of the system. This isolates it from vehicle control. If a second computer of the three remaining fails, the two functioning computers vote it out. If the rare case of two our of four computers simultaneously failing (a two-two split), one group is picked at random.

The Backup Flight System (BFS) is separately developed software running on the fifth computer, used only if the entire four-computer primary system fails. The BFS was created because although the four primary computers are hardware redundant, they all run the same software, so a generic software problem could crash all of them. This should never happen, as embedded system avionic software is developed under totally different conditions than commercial software. For example the number of code lines is tiny relative to a commercial operating system, changes are only made infrequently and with extensive testing, and many programming and test personnel work on the small amount of computer code. However in theory it can fail, so the BFS exists for that contingency.

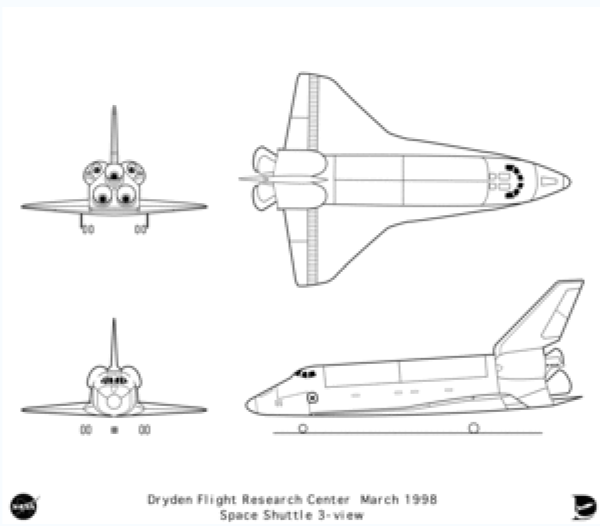
The software for the shuttle computers are written in a high-level language called HAL/S, somewhat similar to PL/1. It is specifically designed for a real time embedded system environment.

The IBM AP-101 computers originally had about 424 kilobytes of magnetic core memory each. The CPU could process about 400,000 instructions per second. They have no hard disk drive, but load software from tape cartridges.

In 1990 the original computers were replaced with an the upgraded model AP-101S, which has about 2.5 times the memory capacity (about 1 megabyte) and three times the processor speed (about 1.2 million instructions per second). The memory was changed from magnetic core to semiconductor with battery backup.

Other improvements

Internally the Shuttle remains largely similar to the original design, with the exception of the improved avionics computers. In addition to the computer upgrades, the original vector graphics monochrome cockpit displays were replaced with modern raster color displays, similar to contemporary airliners like the Airbus A320. This is called a "glass cockpit". In the Apollo-Soyuz Test Project tradition, programmable calculators are carried as well (originally the HP-41C). With the coming of the Space Station, the Orbiter's internal airlocks are being replaced with external docking systems to allow for a greater amount of cargo to be stored on the Shuttle's mid-deck during Station resupply missions.



Shuttle Orbiter, showing Shuttle main engines

The Space Shuttle Main Engines have had several improvements to enhance reliability and power. This explains phrases such as "Main engines throttling up to 104%." This does not mean the engines are being run over limit. The 100% figure is the power level for the original main engines. The actual engine contract requirement was for 109%. The original flight engines could handle 102%. The 109% number was finally reached in flight hardware with the Block II engines in 2001. The normal max throttle is 104%, with 106% and 109% available for abort emergencies.

For STS-1 and STS-2 the external tank was painted white to protect the insulation that covers much of the tank, but improvements and testing showed that it was not required. The 600lbs saved by not painting the tank results in an almost 600lb increase in payload capability to orbit. Additional weight was saved by removing some of the internal "stringers" in the hydrogen tank that proved unnecessary. The resulting "light-weight external tank" has been used on the vast majority of Shuttle missions. STS-91 saw the first flight of the "super light-weight external tank". This version of the tank is made of the 2195 Aluminum-Lithium alloy. It weighs 7,500 lb (3.4 t) less than the last run of lightweight tanks. As the Shuttle cannot fly unmanned, each of these improvements has been "tested" on operational flights.

The SRBs (Solid Rocket Boosters) have undergone improvements as well. Notable is the adding of a third O-ring seal to the joints between the segments, which occurred after the *Challenger* accident.

A number of other SRB improvements were planned in order to improve performance and safety, but never came to be. These culminated in the considerably simpler, lower cost, probably safer and better performing **Advanced Solid Rocket Booster** which was to have entered production in the early to mid-1990s to support the Space Station, but was later cancelled to save money after the expenditure of $2.2 billion. The loss of the ASRB program forced the development of the SLWT, which provides some of the increased payload capability, while not providing any of the safety improvements. In addition the Air Force developed their own much lighter single-piece design using a filament-wound system, but this too was cancelled.

A cargo-only, unmanned variant of the Shuttle has been variously proposed and rejected since the 1980s. It is called the Shuttle-C and would trade re-usability for cargo capability with large potential savings from reusing technology developed for the Space Shuttle.

Components

The Space Shuttle consists of three main components: the reusable Orbiter itself, a large, brown, expendable external fuel tank, and a pair of white, reusable solid-fuel booster rockets. The fuel tank and booster rockets are jettisoned during ascent, so only the Orbiter goes into orbit.

- The reusable Orbiter Vehicle (**OV**), with a large payload bay and three main engines (fed from the external tank) and an orbital maneuvering system with two smaller engines (used after jettisoning the external tank). There are currently three orbiters, rotated between missions.
- A large expendable external fuel tank (**ET**) containing liquid oxygen and liquid hydrogen (at the forward and aft ends, respectively) for the three main engines of the Orbiter; it is discarded 8.5 minutes after launch at an altitude of 60 nautical miles (111 km) and breaks up in the atmosphere upon reentry. The pieces fall in the ocean and are not recovered.
- A pair of reusable solid-fuel rocket boosters (**SRB**); the propellant consists mainly of ammonium perchlorate (oxidizer, 70% by weight) and aluminum (fuel, 16 %). They are used to help boost the shuttle during the first two minutes of flight. They are separated two minutes after launch at a height of 36 nautical miles (67 km) and are recovered after landing in the ocean, their fall slowed by parachutes.

Initial plans for the so-called Space Transportation System included space tugs and extra fuel tanks for the orbital-maneuvering-system engines, among many other concepts. None of this hardware has actually ever been built.

Technical data

Space Shuttle *Atlantis* transported by a Boeing 747 Shuttle Carrier Aircraft (SCA), 1998 (NASA)

- System stack height: 184.2 ft (56.14 m)
- Orbiter length: 122.17 ft (37.236 m)
  - Wingspan: 78.06 ft (23.79 m)
- Gross liftoff: 4.5 million lb (2,040,000 kg)
  - ET: 1.7 million lb (751,000 kg)
  - SRBs: 1.3 million lb (590,000 kg) each (x 2)
  - Orbiter: 240,000 lb (109,000 kg)
- Total liftoff thrust: 7.82 million lbf (34.8 MN)
  - SSMEs: 400,000 lbf (1.8 MN) each (x 3) = 1.2 million lbf (5.3 MN)
  - SRBs: 3.30 million lbf (14.7 MN) each (x 2) = 6.61 million lbf (29.4 MN)
- Maximum landing: 230,000 lb (104,000 kg)
- Maximum theoretical launch payload: 63,500 lb (28,800 kg)
- Maximum payload ever launched: approx. 50,000 lb (22,680 kg)
- Operational altitude: 100 to 520 nmi (185 to 1000 km)
- Maximum altitude achieved: 340 nmi (630 km)
- Speed: 25,404 ft/s (7743 m/s, 27 875 km/h, 17 321 mi/h)
- Passenger capacity: 10 Astronauts (crews other than 5 to 7 are uncommon)

Normal ascent

Initially the main engines are ignited and computers verify their operation for several seconds; if successful, the SRBs are ignited and the vehicle is then committed to takeoff. The SRBs cannot be turned off once ignited, and afterwards the shuttle must take off, no matter what.

Shuttle launch of Atlantis at sunset in 2001. The sun is behind the camera, and the shadow of the plume is cast across the vault of the sky, intersecting the moon.

At takeoff the vast majority (~71%) of the thrust is provided by the SRBs. Shortly after clearing the tower the Shuttle rotates so that the vehicle is below the main tank and SRBs. The vehicle climbs in a progressively flattening arc, accelerating as the weight of the SRBs and main tank decrease. To achieve orbit requires expending much more energy in a horizontal direction than in a vertical direction. This isn't visually obvious since the vehicle rises vertically and is out of sight for most of the horizontal acceleration. Orbital velocity at the 380 km (236 miles) altitude of the International Space Station is 7.68 km per second, or 17,180 mph, roughly equivalent to Mach 23.

Around a point called "max-q", where the aerodynamic forces are at their maximum, the main engines are temporarily throttled back to avoid overspeeding and hence overstressing the Shuttle (particularly vulnerable parts such as the wings).

126 seconds after launch, explosive bolts release the SRBs and small separation rockets push them laterally away from the vehicle. The SRBs parachute back to the ocean to be reused. The Shuttle then begins accelerating to orbit on the Space Shuttle Main Engines. The vehicle at that point in the flight has a thrust to weight ratio of less than one — the main engines actually have insufficient thrust to exceed the force of gravity, and the vertical speed given to it by the SRBs temporarily decreases. However, as the burn continues, the weight of the propellant reduces, the ever-lighter vehicle produces more and more acceleration until the thrust to weight ratio exceeds 1 again and the vehicle can hold itself up.

The vehicle continues to climb and takes on a somewhat nose-up angle to the horizon — it uses the main engines to gain and then maintain altitude whilst it accelerates horizontally towards orbit.

Finally, in the last tens of seconds of the main engine burn, the mass of the vehicle is low enough that the engines must be throttled back to limit vehicle acceleration to 3g, largely for astronaut health and comfort.

Before complete depletion of propellant (running dry would destroy the engines) the main engines are shutdown, and the empty external tank is released by firing explosive bolts. The tank then falls to largely burn up in the atmosphere, with some fragments falling into the Indian Ocean.

At this point the Shuttle is still slightly suborbital, since the trajectory intersects the atmosphere. The Shuttle then fires the OMS engines to circularize the orbit and avoid reentry.

Ascent abort modes

There are five abort modes available during ascent, plus pad aborts. These are classified as intact aborts and contingency aborts [2]. The choice of abort mode depends on estimates of what the orbiter's situation would be at the time of main engine cutoff (TMECO). The abort modes cover a wide range of potential problems, but the most common expected problem is SSME failure, creating inability to either cross the Atlantic or achieve orbit, depending on timing and number of failed engines. Other possible non-engine failures possibly necessitating an abort include multiple Auxiliary power unit (APU) failure, cabin leak, and external tank leak (ullage leak).

Pad abort

The SSMEs can be shut down on the pad as long as the SRBs have not ignited. This is called a "pad abort", and has happened five times, on STS-41-D, STS-51-F, STS-55, STS-51, and STS-68. It has always happened under computer (not human) control, caused by computers sensing a problem with the SSMEs after starting but before the SRBs ignite. The SRBs cannot be turned off once ignited, and afterwards the shuttle is committed to take off, no matter what.

Intact abort modes

There are four intact abort modes. Intact aborts are designed to provide a safe return of the orbiter to a planned landing site.

- Return To Launch Site (RTLS) — has never been tried, but would involve turning the Shuttle around while continuing to burn the SSMEs, jettisoning the ET, and gliding to a landing at Kennedy Space Center.
- East Coast Abort Landing (ECAL) — involves landing at predetermined locations on the east coast of North America in the U.S. and Canada. This has never occurred.
- Transoceanic Abort Landing (TAL) — involves landing at predetermined locations in Africa and western Europe. This has never occurred.
- Abort to Orbit (ATO) — occurs when the intended orbit cannot be reached but a stable alternate orbit is possible. This occurred on STS-51-F mission; required mission replanning, but the mission was nevertheless declared a success.
- Abort Once Around (AOA) — occurs when entering a stable orbit is not possible. This has never occurred.

Contingency abort mode

Contingency aborts are designed to permit flight crew survival following more severe failures when an intact abort is not possible. A contingency abort would generally result in a ditch operation.

To the extent that the hydrogen and oxygen are not needed, they are used up deliberately to allow the ET to be discarded safely.

The designated sites for ECAL are Bangor, Maine, Wilmington, North Carolina; MCAS Cherry Point, North Carolina; NAS Oceana; Wallops Flight Facility; Dover Air Force Base; Atlantic City, New Jersey; Gabreski, New York; Otis ANGB; Pease International Airport (all USA); Halifax; Stephenville; St John's; Gander; and Goose Bay (all Canada).

A TAL would be declared between roughly T+2:30 minutes (liftoff plus 2 minutes, 30 seconds) and Main Engine Cutoff (MECO), about T+8:30 minutes. The Shuttle would then land at a predesignated friendly airstrip in Africa or Europe. Potential sites include Istres Air Base in France; Banjul International Airport in The Gambia; and Zaragoza Air Base and Morón Air Base in Spain. Prior to a Shuttle launch, two of them are selected depending on the flight plan, and staffed with standby personnel in case they are used. The list of TAL sites has changed over time; most recently Ben Guerir Air Base in Morocco was eliminated due to terrorism concerns. Past TAL sites have included Kano, Nigeria; Easter Island (for Vandenberg launches); Rota, Spain; Casablanca, Morocco; and Dakar, Senegal.

Emergency landing sites for the Orbiter include Lajes, Beja, (both Portugal), Keflavík (Iceland), Shannon International Airport (Ireland), RAF Fairford (UK), Köln Bonn Airport (Germany), Ankara (Turkey), Riyadh (Saudi Arabia), Diego Garcia (British Indian Ocean Territory).

Were the Orbiter unable to reach a runway, it could ditch in water, or could land on terrain other than a landing site. It would be unlikely for the flight crew still on board to survive. However, for ascent abort scenarios where controlled gliding flight is achievable, a bailout is possible. For more details, see below heading "Post-Challenger abort enhancements".

In the two disasters, things went wrong so fast that little could be done. In the case of Challenger, the SRBs were still burning as they tore free from the rest of the stack, one likely impacting the external tank. The orbiter disintegrated almost instantly from aerodynamic stresses as the stack broke up. The Columbia disaster occurred high in the atmosphere during reentry. Even if the crew had been able to bail out, they would have been killed by the heat generated by the friction of the air.

Post-Challenger abort enhancements

Before the Challenger disaster, STS-51-L, only very limited ascent abort options existed. Only a single SSME failure was survivable prior to about T+350 seconds into the ascent. Two or three failed SSMEs prior to that would mean loss of crew and vehicle (LOCV), since no bailout option existed. Two or three failed SSMEs while the SRBs are firing would have probably overstressed the struts attaching the orbiter to the external tank, causing vehicle breakup. For that reason an RTLS abort wasn't possible for two or three failed SSMEs. Studies showed an ocean ditching was not survivable. Furthermore losing a second or third SSME most anytime *during* an RTLS abort was a LOCV.

After STS-51-L, numerous abort enhancements were added. A two-out SSME is now survivable for the crew throughout the ascent, and the vehicle could survive and land for large portions of the ascent. A three-out SSME is survivable for the crew for most of the ascent, although three failed SSMEs before T+90 seconds is questionable. However it's conceivable a three-out SSME just after liftoff might be survivable, since the SRBs provide enough thrust and steering authority to continue the ascent until a bailout or RTLS. The struts attaching the orbiter to the external tank were beefed up to better endure a multiple SSME failure.

A significant enhancement was bailout capability. This isn't ejection as with a fighter plane, but an Inflight Crew Escape System. The vehicle is put in a stable glide on autopilot, the hatch is blown, and the crew slides out a pole to clear the orbiter's left wing. They would then parachute to earth or the sea. While this may at first appear only usable under rare conditions, in actuality there are many failure modes where reaching an emergency landing site isn't possible yet the vehicle is still intact and under control. This almost happened on STS-51-F when a single SSME failed at about T+345 seconds. A second SSME almost failed due to a spurious temperature reading, inhibited only by a quick-acting flight controller. If the second SSME failed within about 20 seconds of the first, there would have been insufficient energy to cross the Atlantic. Without bailout ability the entire crew would have been lost. After the Challenger loss, those types of failures are survivable.

Another post-Challenger enhancement was East Coast Abort Landings (ECAL). High inclination launches (all ISS missions) can now reach an east coast emergency runway under certain conditions.

Numerous other abort refinements were added, mainly involving improved software for managing vehicle energy in various abort scenarios. These enable a greater chance of reaching an emergency runway for various SSME failure scenarios.

Ejection escape systems

An ejection escape system, sometimes called a launch escape system has been discussed many times for the shuttle. After the Challenger and Columbia losses, great interest was expressed in this. All previous US manned space vehicles had launch escape systems, although none were ever used. Modified Lockheed SR-71 ejection seats were installed on the first four shuttle flights (all two man missions), and removed afterward. Ejection seats were not further developed for the shuttle for several reasons:

- Very difficult to eject seven crew members when three or four are on the middeck (roughly the center of the forward fuselage), surrounded by substantial vehicle structure
- Limited ejection envelope. Ejection seats only work up to about Mach 3 and 90,000 feet. That constitutes a very limited portion of the shuttle's operating envelope
- No help during Columbia-type reentry accident. Ejecting during a reentry accident would be fatal due to the high temperatures and wind blast at high Mach speeds

An alternative to ejection seats is a capsule or cabin escape system where the crew ejects in protective capsules, or the entire cabin is ejected. Such systems have been used on several military aircraft. The B-58 Hustler and XB-70 Valkyrie used capsule ejection. Certain versions of the General Dynamics F-111 and Rockwell B-1 bomber used cabin ejection.

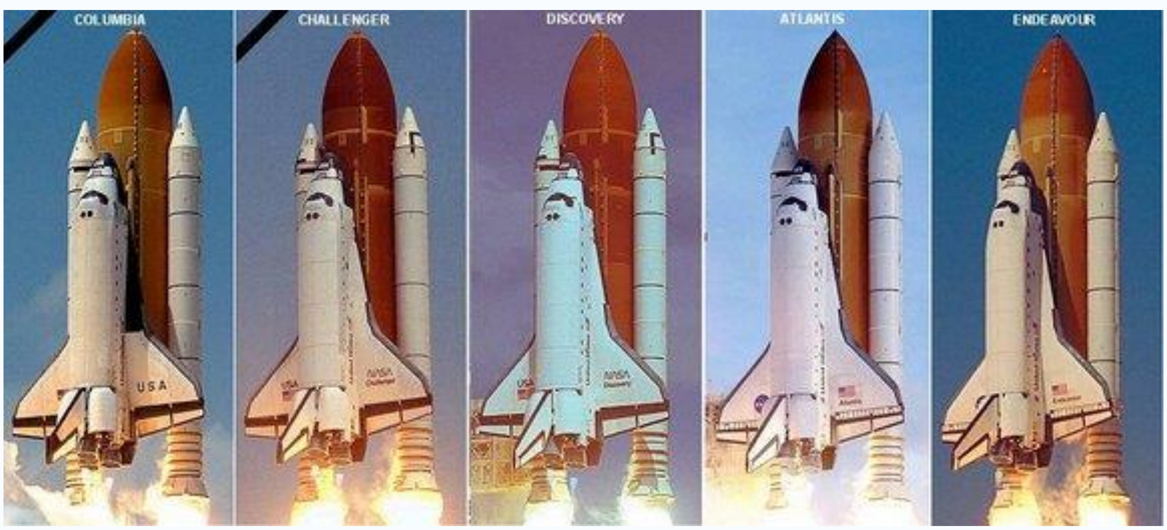
Like ejection seats, capsule ejection for the shuttle would be difficult because there's no easy way to exit the vehicle. Several crewmembers sit in the middeck, surrounded by substantial vehicle structure.

Cabin ejection would work for a much larger portion of the flight envelope than ejection seats, as the crew would be protected from temperature, wind blast, and lack of oxygen or vacuum. In theory an ejection cabin could be designed to withstand reentry, although that would entail additional cost, weight and complexity. Cabin ejection wasn't pursued for several reasons:

- Major modifications required to shuttle, likely taking several years. During much of the period the vehicle would be unavailable.
- Cabin ejection systems are heavy, thus incurring a significant payload penalty
- Cabin ejection systems are much more complex than ejection seats. They require devices to cut cables and conduits connecting the cabin and fuselage. The cabin must have aerodynamic stabilization devices to avoid tumbling after ejection. The large cabin weight mandates a very large parachute, with a more complex extraction sequence. Air bags must deploy beneath the cabin to cushion impact or provide flotation. To make on the pad ejections feasible the separation rockets would have to be quite large. In short, many complex things must happen in a specific timed sequence for cabin ejection to work, and in a situation where the vehicle might be disintegrating. If the airframe twisted or warped preventing cabin separation, or debris damaged the landing airbags, stabilization, or any other cabin system, the occupants would likely not survive
- Added risk due to many large pyrotechnic devices. Even if not needed, the many explosive devices needed to separate the cabin entail some risk of premature or uncommanded detonation
- Cabin ejection is much more difficult, expensive and risky to retrofit on a vehicle not initially designed for it. If the shuttle was initially designed with a cabin escape system, that might have been more feasible
- Cabin/capsule ejection systems have a spotty success record, likely because of the complexity. This was one reason the F-111 and B-1 cabin ejection was changed to conventional ejection seats for later aircraft versions.

Operations, applications and accidents

Shuttles



From left to right: *Columbia*, *Challenger*, *Discovery*, *Atlantis* and *Endeavour*. Not illustrated: *Enterprise* and *Pathfinder*.

Individual Orbiters are both named, in a manner similar to ships, and numbered using the NASA Orbiter Vehicle Designation system. Whilst all three are externally very similar, they have minor internal differences; new equipment is fitted on a rotating basis as they are maintained, and the newer Orbiters tend to be structurally lighter.

- Handling test article designed with no spaceflight capability whatsoever:
    - *Pathfinder* (**Orbiter Simulator**, no series number)

- Main propulsion test article, with no spaceflight capability whatsoever:
    - *MPTA-ET* (*External Tank*) which is now attached to *Pathfinder*
    - *MPTA-098* suffered major damage due to engine failure.

- Structural test article, with no spaceflight capability:
    - *STA-099* which became *Challenger*

- Test vehicle suitable only for glide/landing tests, with no spaceflight capability without major refit:
    - *Enterprise* (OV-101)

- Lost in accidents (see below):
    - *Challenger* (OV-099, ex-STA-099) - destroyed after liftoff - January 28, 1986
    - *Columbia* (OV-102) - destroyed during reentry February 1, 2003

- In use:
    - *Atlantis* (OV-104)
    - *Discovery* (OV-103)
    - *Endeavour* (OV-105)

Applications

- Crew rotation of the ISS
- Manned servicing missions, such as to the Hubble Space Telescope (HST)
- Manned experiments in LEO
- Carry to LEO:
    - Large satellites — these have included the HST
    - Components for the construction of the ISS
    - Supplies
- Carry satellites with a booster, the Payload Assist Module (PAM-D) or the Inertial Upper Stage (IUS), to the point where the booster sends the satellite to:
    - A higher Earth orbit; these have included:
        - Chandra X-ray Observatory
        - Many TDRS satellites
        - Two DSCS-III (Defense Satellite Communications System) communications satellites in one mission
        - A Defense Support Program satellite
    - An interplanetary orbit; these have included:
        - Magellan probe
        - Galileo spacecraft
        - Ulysses probe

Flight statistics (as of August 25, 2005)

Shuttle	Flight days	Orbits	Distance -mi-	Distance -km-	Flights	Longest flight -days-	Crews	EVAs	Mir/ISS docking	Sat. dep. †
Columbia	300.74	4,808	125,204,911	201,497,772	28	17.66	160	7	0 / 0	8
Challenger	62.41	995	25,803,940	41,527,416	10	8.23	60	6	0 / 0	10
Discovery	255.84	4,027	104,510,673	168,157,672	31	13.89	192	28	1 / 5	26
Atlantis	220.40	3,468	89,908,732	144,694,078	26	12.89	161	21	7 / 6	14
Endeavour	206.60	3,259	85,072,077	136,910,237	19	13.86	130	29	1 / 6	3
Total	**1,045.99**	**16,557**	**430,500,333**	**692,787,174**	**114**	***17.66**	**703**	**91**	**9 / 17**	**61**

† Satellites deployed
* This was flight STS-80, during November 1996.

Accidents

Two Shuttles have been destroyed in 114 missions, both with the loss of the entire crew of seven:

- *Challenger* — lost 73 seconds after liftoff, January 28, 1986; see STS-51-L.
- *Columbia* — lost during reentry, February 1, 2003; see Space Shuttle *Columbia* disaster.

This gives a 2% death rate per astronaut per flight.

While the technical details of the accidents are quite different, the organizational problems show remarkable similarities. In both cases events happened which were not planned for or anticipated. In both cases, junior engineers were greatly concerned about possible problems, but these concerns were not properly communicated to or understood by senior NASA managers. In both cases the vehicle gave ample warning beforehand of abnormal problems. A heavily layered, procedure-oriented bureaucratic structure inhibited necessary communication and action. In both cases a mind set among senior managers developed that concerns had to be objectively proven rather than simply suspected.

In the case of Challenger, an O-ring which should not have eroded at all did, in fact, erode on earlier shuttle launches. Instead of finding out why, managers felt because it had not previously eroded by more than 30%, that this was not a hazard as there was a factor of three safety margin. Morton Thiokol designed and manufactured the SRBs, and during a pre-launch conference call with NASA, the Thiokol engineer most experienced with the O-rings pleaded repeatedly to cancel or reschedule the launch. He raised concerns that the unusually cold temperatures would stiffen the O-rings, preventing a complete seal. Unfortunately NASA and Thiokol senior managers overruled him and allowed the launch to proceed. Challenger's O-ring eroded completely through, with fatal results.

Columbia failed because of damaged thermal protection from foam debris that broke off the external tank during ascent. The foam had not been designed or expected to break off, but had been observed in the past to do so without incident. The original shuttle operational specification said the orbiter thermal protection tiles were designed to withstand virtually *no* debris hits at all. Over time NASA managers gradually accepted more tile damage, similar to how O-ring damage was accepted. The Columbia Accident Investigation Board called this tendency the ""normalization of deviance" -- a gradual acceptance of abnormal events simply because they haven't been catastrophic to date.

Retrospect


A Space Shuttle lands like a glider.

Costs

While the Shuttle has been a reasonably successful launch vehicle, it has been unable to meet its goal of radically reducing flight launch costs, as the average launch expenditures during its operations up to 2005 accumulates to $1.3 billion [3], a rather large figure compared to the initial projections of $10 to $20 million. The total cost of the program has been $145 billion as of early 2005 ($112 billion of which was incurred while the program was operational) and is estimated at $174 billion when the Shuttle retires in 2010. NASA's budget for 2005 allocates 30%, or $5 billion, to Space Shuttle operations. [4]

The original mission of the Shuttle was to operate at a high flight rate, at low cost, and with high reliability. It was intended to improve greatly on the previous generation of single-use manned and unmanned vehicles. Although it did operate as the world's first reusable crew-carrying spacecraft, it did not improve on those parameters in any meaningful way, and is considered by some to have failed in its original purpose.

Although the design is radically different from the original concept, the project was still supposed to meet the upgraded USAF goals, and to be much cheaper to fly in general. One reason behind this apparent failure appears to be inflation. During the 1970s the U.S. suffered from severe inflation, driving up costs about 200% by 1980. In contrast, the rate between 1990 and 2000 was only 34% in total. This magnified the development costs of the Shuttle. The original process by which contractors bid for Shuttle work has also inflated overall project costs as there were political and industrial pressures to spread Shuttle work around. For instance, the need for a single-piece SRB design was dismissed as only one company, Aerojet, was located close enough to the launch site to make this viable. The company that secured the SRB contract, Morton Thiokol, is based in Utah, necessitating the modular design that contributed to the Challenger loss. Ironically, the U.S. aerospace mergers of the 1990s mean that the vast majority of the STS contracts are now held by a single company (Boeing).

However, this does not explain the high costs of the continued operations of the Shuttle. Even accounting for inflation, the launch costs on the original estimates should be about $100 million today. The remaining $400 million arises from the operational details of maintaining and servicing the Shuttle fleet, which have turned out to be tremendously more expensive than anticipated. Some of this can be attributed to operating beyond the 10-year anticipated lifespan of each Shuttle.

The main reasons for higher costs can be ascribed to:

- the reentry tiles turned out to be very expensive (averaging about 1 person week to replace a tile, with hundreds damaged with each launch)
- engines were highly complex and marginal necessitating removal and maintenance after each flight
- launch rate is much lower than ideal (studies showed that launching 50 times per year would have dramatically cut costs- the current shuttle launches about 4 times per year- the written record shows that NASA never installed any infrastructure to launch more than 12 times per year)
- original costs of $118/lb were marginal costs, not total costs

Shuttle operations

When originally conceived, the Shuttle was to operate similarly to an airliner. After landing, the Orbiter would be checked out and start "mating" to the rest of the system (the ET and SRBs), and be ready for launch in as little as two weeks. Instead, this turnaround process takes months. Decisions to cut short-term development costs have resulted in a continued high-cost maintenance schedule. The documentation requirements have become extremely thorough. Dramatically increasing the number of support personnel needed to launch also caused a significant increase in costs. This was exacerbated in the aftermath of the *Challenger* disaster. Even simple changes require significant amounts of documentation. This paperwork results from the fact that, unlike current expendable launch vehicles, the Space Shuttle is manned and has no escape systems mode for most of the flight regime, and therefore any accident which would result in the loss of a booster would also result in the loss of the crew. Because loss of crew is unacceptable, the primary focus of the Shuttle program is to return the crew to Earth safely, which can conflict with other goals, namely to launch payloads cheaply. Furthermore, because there are cases where there are no abort modes — no potential way to prevent failure from becoming critical — many pieces of hardware simply must function perfectly and so must be carefully inspected before each flight. The result is a massively inflated labor cost, with around 25,000 workers in Shuttle operations and labor costs of about $1 billon per year.

Initially NASA hoped the Shuttle's manned capacity would be justified as a "space taxi" to a revived Skylab or a Saturn V-launched "Skylab 2". With the go-ahead for the large, modular "Freedom" Space Station proposal the Shuttle appeared to have a continued justification with the prospect of a 6- to 10-crew outpost only being serviceable by the Shuttle. The scale back of the Space Station concept in the 1990s ultimately made the utility of the Shuttle as a manned ferry obsolete.

NASA's justification of the STS for its own unmanned science missions has also declined. Following the Challenger disaster, use of the powerful Centaur upper stages required for interplanetary probes was ruled out. The Shuttle's history of unexpected delays also makes it liable to miss the narrow launch windows. Advances in technology over the last decade have made probes smaller and lighter, and as a result it is possible to reach Mars using a relatively cheap and reliable Delta launcher.

Another possible impediment to the Shuttle system was the politically required participation of the United States Air Force. To receive the funding required, Congress mandated that the Shuttle replace all other launch vehicles in the national inventory as a cost-cutting measure. This requirement dramatically altered the size and scope of the program as the Air Force needed significant capabilities to allow it to meet national defense objectives. Ironically, neither NASA nor the Air Force got the system they wanted or needed, and the Air Force eventually returned to their older launch systems and abandoned their Vandenberg shuttle launch plans; many of the Air Force-imposed capabilities that most seriously hobbled the Shuttle system have never been used.

Opinions differ on the lessons of the Shuttle. In general, however, future designers look to systems with only one stage, automated checkout and, in some cases, overdesigned (more durable) low-tech systems. Another consideration for future manned space flight is to pursue the construction and operation of "space planes", which could fly up to the edge of the atmosphere and then rocket out into Earth orbit, thereby being more efficient and versatile than such vehicles as the space shuttle.

Shuttle Trivia

- When watching a launch, look for the "nod" ("Twang" in "NASAese"). After main engine start, but whilst the solid rocket boosters are still clamped to the pad, the offset thrust from the Shuttle's three main engines causes the entire launch stack (boosters, tank and shuttle) to flex forwards about 2 metres at the cockpit level. As the 'O'rings in the boosters flex back into shape, the launch stack springs slowly back upright. At the point when it's perfectly vertical, the boosters ignite and the launch commences.

- The subject of missing or damaged thermal tiles on the Shuttle fleet only became an issue following the loss of Columbia in 2003 as it broke up on re-entry. In fact Shuttles have been flying since their inauguration and coming back missing as many as 20 tiles without any problem. STS-1, STS-16 and STS-41 have all flown with missing thermal tiles from the orbital maneuvering system pods (visible to all the crew). This image from the NASA archives shows many missing tiles on the STS-1 OMS pods : Media:http://images.jsc.nasa.gov/lores/STS001-12-332.jpg The problem on Columbia was that the damage was sustained to the carbon-carbon leading edge panel of the wing, not the heat tiles. On the same subject, a little-publicised factoid about the first Shuttle mission, STS-1, was that they had a protruding gapfiller which ducted hot gas into the right wheel well on re-entry. They buckled the right main gear on landing as a result. (source : John Young's April 2003 After Dinner Speech)

CNN erroneously states Columbia was doing 18 times the speed of light

- When CNN reported on the breakup of the Columbia over Texas, they erroneously reported it was doing 18 times the speed of *light*, instead of 18 times the speed of *sound*.

Terrestrial transportation vehicles

- The Crawler-Transporter moves the Space Shuttle from the Vehicle Assembly Building to Launch Complex 39
- The Shuttle Carrier Aircraft is a modified Boeing 747 that flies the Space Shuttle from alternative landing sites back to Cape Canaveral.

See also

- NASA Space Shuttle Decision
- Space Exploration
- Shuttle Derived Launch Vehicle
- Reusable launch system
- HOPE-X the Japanese (cancelled) shuttle program.
- Kliper Reuseabe Russian lifting body spacecraft that is likely to replace the Soyuz system in 2011
- EADS Phoenix the European Shuttle successor to the cancelled Hermes.
- Shuttle *Buran* the Soviet Union's (cancelled) shuttle program.
- Shuttle SERV
- Manned space mission
- List of space shuttle missions
- List of human spaceflights
- List of human spaceflights chronologically
- List of space disasters
- Atmospheric reentry
- Lifting body
- Military space shuttle
- Space Shuttles in fiction