# SPACE SHUTTLE ORBITER

## Introduction

The first serious mention of a fully reusable launch vehicle in a widely circulated publication was in 1952. In that year, Collier's Magazine ran a series of articles in which the concept of a fully reusable space launch vehicle was developed to have a vehicle that would transport cargo and people from the ground to an orbiting space station. The principal author of this article was Dr. Wernher von Braun (1).

It took 10 years from the publication of the article in Collier's before the idea of a reusable space ship was seriously considered. During the 1960s, the U.S. Air Force performed detailed studies of a reusable space ship called "Dynasoar," which was intended as a manned reconnaissance vehicle. NASA also conducted studies of reusable space ships. Following a thorough review, a decision was reached in 1969 to assign all manned space operations to NASA. Accordingly, the Air Force's "Dynasoar" was cancelled.

Early in 1969, the Management Council of NASA's Office of Manned Space Flight, chaired by Associate Administrator George Mueller, met several times. Dr. Wernher von Braun, the director of NASA's George C. Marshall Space Flight Center and a member of the Management Council, vigorously advocated adopting the idea of a fully reusable space ship that he had written about in Collier's Magazine 17 years earlier. Eventually, a consensus was reached that a fully reusable space ship should be developed.

Dr. Robert Gilruth, the director of the NASA Manned Spacecraft Center in Houston, Texas (now the NASA-Johnson Space Center), was also a member of the Management Council. When he returned to the Center, he asked Dr. Max Faget, his Director of Engineering and Development (E&D) to study the problem of creating a reusable space ship. The essential problem was that the vehicle had to be able to fly both in the atmosphere as well as in space. Dr. Faget considered the most difficult problem that of returning the vehicle from orbit. He was the key individual in developing the successful Earth atmospheric entry techniques for the Mercury, Gemini, and Apollo spacecraft. Thus, Dr. Faget again looked to the high angle of attack and blunt body as the solution of the problem. The entry heating could be concentrated on the bottom of the vehicle thereby minimizing the weight of the thermal protection required. Using a handmade balsa model he built, Faget demonstrated that such an airplane had a stable, extremely high angle of attack that made the concept feasible. Range could be controlled by rolling around the velocity vector as was done by previous manned spacecraft. Faget believed that a straight wing rather than a delta wing would provide better subsonic landing performance.

While the studies were being performed to see what the Shuttle systems would look like, estimates of the funding were being established that would have a great effect on the design. Economic studies (2) were also being conducted to show the advantage of a reusable launch system. It was determined that the development cost of the fully reusable Shuttle was too high; therefore, the fully reusable booster was eliminated, and the increased operational cost was accepted (3).

## Preliminary Design Considerations

**General Outline.** Technology studies conducted before initiating the Shuttle design indicated that three principal developments would be necessary to achieve the desired performance of the Shuttle. It was determined that if problems occurred, the development risk and possible cost increases were worth the enhanced performance. The three developments were the dual-cycle main rocket engine, the reusable surface insulating (RSI) thermal protection system for the orbiter, and an innovative flight control system. If development problems occurred, it was considered that the budget would allow recovery if only three new systems were designed. Existing technology or only small incremental improvements would be employed for the remaining components of the system.

Phase A studies were conducted to determine basic requirements and their effect on the design. The principal issues were the size and weight of the payload and the cross range requirement for the orbiter. The size and weight of the payload were determined by the requirements of reconnaissance satellites that would be launched using the shuttle. This fixed the payload at 65,000 pounds at takeoff and a 35,000 pound landing capability. The size and shape of the payload bay were set at 60 feet in length and 15 feet in diameter to accommodate the largest national security related payloads. The cross range had to be 1000 miles to provide what is called a "once around" capability for manned reconnaissance missions. This means that the shuttle could execute one polar orbit and return to the original launch site because Earth rotates a distance of about 1000 miles at the equator in the time it takes to execute one orbit.

Specific details of design approaches were studied. Heat-resistant structures were compared to a reusable surface insulating thermal protection system, a hypergolic reaction control system was compared to a more advanced liquid hydrogen–liquid oxygen system, and a fly by-wire flight control system design were the subjects of some of the typical studies. Wind tunnel tests were conducted to determine wing size and configuration. Air breathing jet engines were initially proposed for the flyback capability of both the booster and the orbiter but it was determined that they would be too heavy for the performance gain. Entry technique, cross range requirement, landing speed, and the approach pattern had to be designed. A method to transport the Orbiter needed to be studied to move it from some of the landing sites to the launch pad.

Phase A study contracts were awarded to three competitive teams: Rockwell, North American, and General Dynamics, Convair; Martin Marietta, and Mc Donnell; and Boeing and Lockheed for preliminary designs. Upon completion of Phase A, a competition was held for the Phase B detailed design of the vehicle. The Rockwell, North American-General Dynamics, Convair and the Martin Marietta-Mc Donnell teams were selected to design both a high and low cross range configuration. The Phase A and Phase B studies led to the design of a fully recoverable orbiter, a disposable fuel tank, and parachute-recoverable solid rocket boosters. High performance hydrogen–oxygen engines were placed in the Orbiter to recover these high cost units after each flight.

Slightly later, a study was also awarded to Grumman and Boeing for more innovative designs, and a further study contract was given to Lockheed which had proposed a novel "stage and a half" concept. The studies were extended because budget concerns had not been settled, and a decision between fully reusable system and the development of only one fully reusable vehicle had not been made. More than 144 different configurations were examined; 41 were wind tunnel tested before the final design was accepted. The Air Force cross range requirement dictated the delta wing configuration for the orbiter shown in Fig. 1.

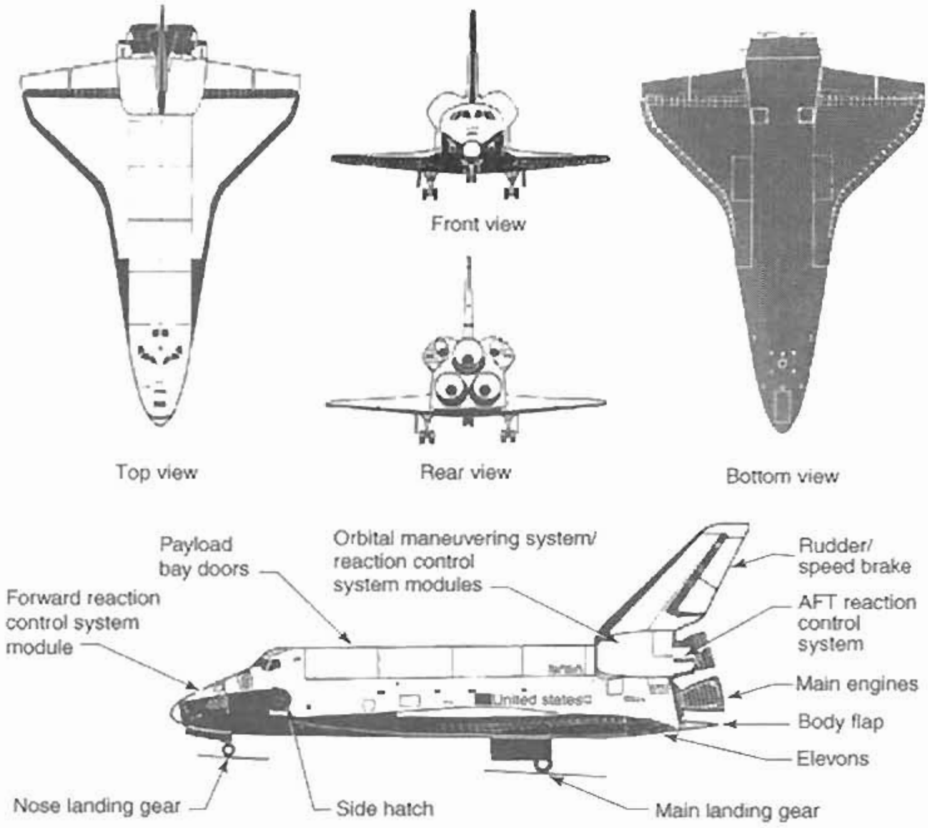
The final configuration consisted of the components shown in Fig. 2, the delta wing orbiter, an externally carried fuel tank for the liquid hydrogen and liquid oxygen that run the Space Shuttle Main Engine (SSME), and two solid rocket boosters attached to the tank. The three Space Shuttle Main Engines and the two solid-fueled boosters are powered up on liftoff, and the solid rocket boosters are jettisoned when they burn out in about 2.5 minutes. The empty rocket cases are parachuted into the ocean where they are recovered and towed back to the launch site. The main engines keep running for six or seven minutes until the fuel is exhausted. The external tank is then jettisoned and is burned up on reentry into the atmosphere. The Orbiter then goes into Earth orbit using the orbital maneuvering engines. As already stated, the Orbiter reenters the atmosphere, when the mission is finished, at a large angle of attack—more than 40°—to dissipate the orbital energy. The parameters of the system are shown in Table 1.

**Engineering Management Considerations.** The Space Shuttle was entirely different from any air/spacecraft that had ever been designed and built. The engineering teams in the NASA Office of Manned Space Flight and the associated institutions had to be organized properly. It was decided to develop in-house engineering design groups. At the NASA Johnson Space Center, key engineers were assigned to a group housed in Building 36 to design a "DC-3" (the first successful passenger airliner) space transportation vehicle. The group soon found the task of designing control systems, propulsion systems, structure, and hydraulic systems more challenging than initially thought, and so more time was required before a complete vehicle design was attempted. This effort, however, was excellent training for the government team that would later lead to a NASA supervised contractor to design and manufacture the actual flight vehicles. Thus, NASA acted as the system integrator for the Space Shuttle.

After a short extension of the Phase B studies, the competition for the Orbiter hardware contract was held, and the contract was awarded to Rockwell, North American in 1972. Later, the external tank hardware contract was awarded to Martin Marietta, and the solid rocket motor boosters to Thiokol, Inc.

## The Space Shuttle Main Engine

The principles of rocket propulsion are described elsewhere in this Encyclopedia (see Liquid-Fueled Rockets). The reusable SSME was a major advance in rocket



### Dimensions and weight

| | | |
|---|---|---|
| Wing span | 23.79 m | (78.06 ft) |
| Length | 37.24 m | (122.17 ft) |
| Height | 17.25 m | (56.58 ft) |
| Tread width | 6.91 m | (22.67 ft) |
| Gross takeoff weight | | Variable |
| Gross landing weight | | Variable |
| Inert weight (approx) | 74 844 kg | (165 000 lb) |

### Minimum ground clearances

| | | |
|---|---|---|
| Body flap (AFT end) | 3.68 m | (12.07 ft) |
| Main gear (door) | 0.87 m | (2.85 ft) |
| Nose gear (door) | 0.90 m | (2.95 ft) |
| Wingtip | 3.63 m | (11.92 ft) |

**Figure 1.** A detailed representation of the reusable Orbiter. The locations of the three Space Shuttle Main Engines (SSME) and the Orbital Maneuvering System (OMS) engines are clearly shown. The control surfaces are also delineated. The figure is taken from NASA website: http://spaceflight.nasa.gov/history/shuttle-ir/multimedia/diagrams/shuttle/shuttle-1.htm.

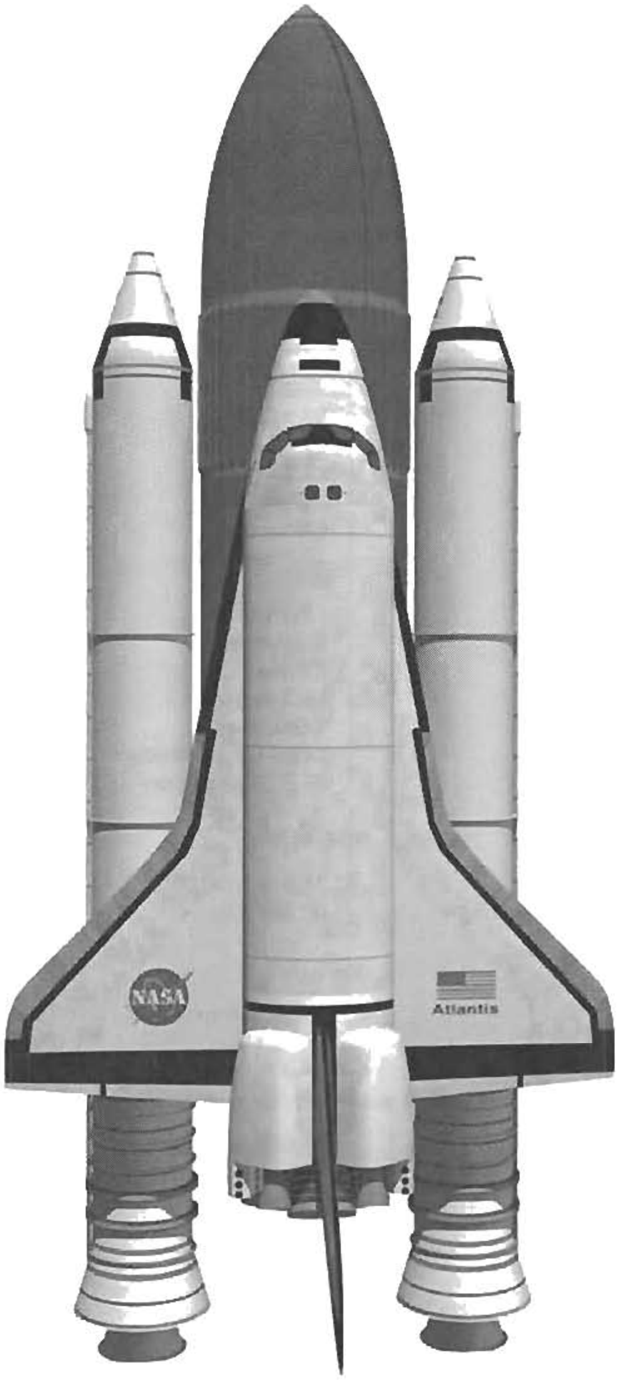


**Figure 2.** A drawing of the final configuration of the Space Shuttle viewed from the top. It shows the relative locations of the orbiter, the fuel tank, and the two solid-fueled boosters. The figure is taken from the following NASA website: http://www.hq.nasa.gov/office/codeq/risk/workshop/bover.doc. This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

engineering. To propel the Space Shuttle into Earth orbit, it had to have a higher thrust-to-weight ratio than any previously high-thrust rocket engine. The higher thrust-to-weight ratio is achieved by operating the SSME at a chamber pressure higher than that of any previous rocket. The high chamber pressure (2960 psi) is achieved by using part of the liquid hydrogen–liquid oxygen supply to operate two high-pressure turbopumps, one for hydrogen and another one for oxygen, that provide the fuel and oxidizer to the combustion chamber at a very high flow rate. The nozzle of the main engine is cooled by liquid hydrogen (regenerative

Table 1. **Orbiter Specifications**

| | | |
|---|---|---|
| | *Dimensions* | |
| Total length | 37.24 meters | 122.17 feet |
| Height | 17.25 meters | 56.58 feet |
| Wingspan | 23.79 meters | 78.06 feet |
| Vertical stabilizer | 8.0 meters | 26.31 feet |
| Tread width | 6.9 meters | 22.67 feet |
| Wing length | 18.3 meters | 60 feet |
| Wing max thickness | 1.5 meters | 5 feet |
| Elevon inboard | 4.2 meters | 13.8 feet |
| Elevon outboard | 3.8 meters | 12.4 feet |
| Payload bay length | 18.3 meters | 60 feet |
| Payload bay diameter | 4.6 meters | 15 feet |
| Payload volume | 148.6 square meters | 1600 square feet |
| Crew cabin | 71.5 cubic meters | 2525 cubic feet |
| | *Weight* | |
| Empty | 74,844 kilo | 165,000 lb |
| Landing with payload | 96,163 kilo | 212,000 lb |
| | *Thrust* | |
| Orbiter, sea level | 1,668,000 newtons | 375,000 lb each engine |
| | *Orbital maneuvering system* | |
| Thrust vacuum | 26,688 newtons | 6000 lb |
| ISP | 313 seconds | |
| Chamber pressure | 125 psi | |
| Mixture ratio | 1.65:1 | |
| Propellant | 10,830 kilo | 23,876 lb |
| | *Reaction control system* | |
| Primary 38, forward 14, aft 2 each pod | | |
| Thrust, vacuum | 3870 newtons | 870 lb |
| Vernier 6, forward 2, aft 4 | | |
| Thrust vacuum | 106 newtons | 24 lb |

Table 1. **(Continued)**

| | | |
|---|---|---|
| | *Electrical power* | |
| Voltage | 28 Volts | |
| Power | 2 kw at 32.5 Vdc, 61.5 amps<br>12 kw at 27.5 Vdc, 436 amps | |
| | *Atmospheric revitalization* | |
| Pressure | 760 mm Hg ± 103 | 14.7 ± 2 psi |
| Ratio | 79% $N_2$, 21% $O_2$ | |
| | *Auxiliary power unit* | |
| Power | 135 hp | |
| Weight | 39 kg | 88 lb |
| Fuel | 158 kg | 350 lb |

cooling) before it is fed to the combustion chamber and burned. The arrangement described here is called a two-stage or dual-combustion system, and the flow diagram for the SSME is shown in Fig. 3. The thrust developed by the SSME, as finally built, is 375,000 lbs.

The concept of the dual-combustion engine was initiated by the Air Force, which had Pratt & Whitney develop and test the high-pressure pumps for the dual-cycle rocket engine. These pumps were built for an XRL-129 engine at the 25,000-pound thrust level.

A competition was held for the contract, and proposals were received from Aerojet, Pratt & Whitney, and Rocketdyne. Rocketdyne was selected to build the engine for 375,000-pound thrust at sea level. The contract, initiated in 1970, preceded the award of the Orbiter contract because it was believed that more time was necessary to develop the engine (4).

The entire space shuttle propulsion system has a thrust of about 7 million pounds, about 375,000 pounds for each of the three SSMEs on the Orbiter, and 2.9 million pounds for each of the solid rocket boosters. The SSMEs can be throttled from 65 to 109% of their rated power level. This thrust is enough to lift the whole space shuttle stack, according to the figures shown in Table 1.

## Orbiter System Descriptions

**Crew Compartment.** The crew compartment has provisions for seven members. Four are on the flight deck, and three are on the mid-deck (Fig. 4). The commander uses the left seat and the pilot the right. Behind the pilot sits the mission specialists, and in the center rear of the flight deck sits the payload specialist. Three additional mission specialists can be seated on the mid-deck. Flight controls and displays are in the usual aircraft positions at the front of the flight deck and a mission or systems panel is located on the right side. The rear of

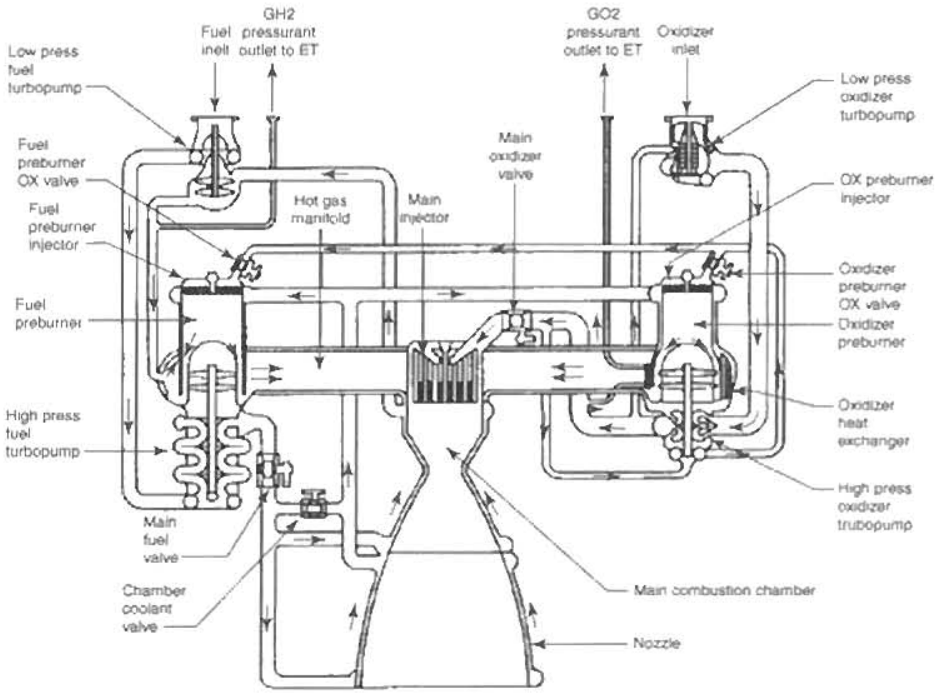


**Figure 3.** The main engine schematic. A drawing of the flow diagram of the fuel and the oxidizer in the Space Shuttle Main Engine. The figure is taken from NASA website: http://www.shuttlepresskit.com/scom/216.pdf.

the flight deck has windows that look out into the payload bay and above. These windows also are used to view the manipulation of the payloads. The mid-deck is used for habitability and contains sleep stations, a galley, and a waste collection system. An air lock is located in the middle of the aft portion for external vehicle access through the cargo bay. The forward portion of the mid-deck is used for storage lockers, and behind the lockers are the flight computers and other avionic equipment.

During a space mission, the crew compartment is operated in a "shirt-sleeve" environment with an atmosphere of oxygen and nitrogen at about 14.7 psi at room temperature (300 K). The air regeneration and waste elimination systems are part of the crew compartment. The flight duration for a given crew size is determined by the power available and the exhaustion of other consumables in the crew compartment. For an "average" mission, the Space Shuttle Orbiter can remain in Earth orbit for about 2 weeks.

**Guidance, Navigation, and Control (GN&C).** The Space Shuttle Orbiter was one of the first operational applications of digital fly-by-wire systems for aircraft flight control. The design expanded on the experimental work conducted by the NASA Dryden Flight Research Center with a modified F-8 aircraft. The GN&C system responds to software commands to provide vehicle control and provides information to the sensors and control data to the flight computers that control the flight. The Orbiter's five computers are arranged into a redundant set

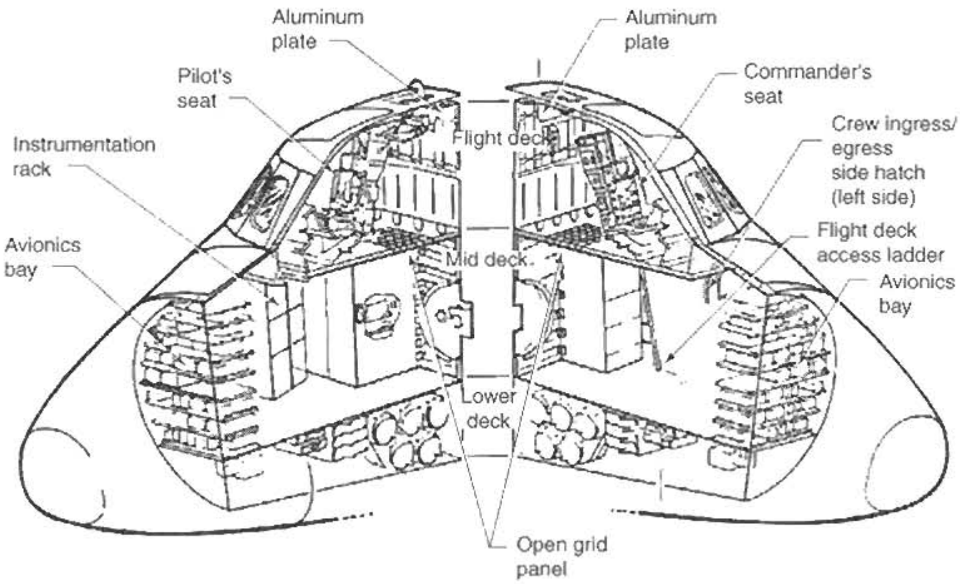


**Figure 4.** A cutaway drawing of the crew compartment as well as some detailed views of the structure. The figure is taken from the NASA website: http://spaceflight.nasa.gov/history/shuttle-ir/multimedia/diagrams/shuttle/shuttle-6.htm.

of four that comprise the primary set; the fifth computer is used as independent, backup, flight control system. Data from vehicle sensors are transmitted through a multiplexer/demultiplexer (MDM) by data bus wire (there are no direct mechanical linkages to the various controls) to the computers, which, using the MDM, send commands to the vehicle control effectors. The system consists of two modes of operation, "auto," where the computers do all the flying, and "control stick" steering, where the pilot can manually introduce commands into the computer system. Multifunctional cathode ray tubes (CRT) display the system's status and flight information to the crew.

The navigational interfaces feed data to the general purpose computer (GPC) to do the navigation and provide the guidance information to the system to drive the control effectors. Air data probes are deployed at subsonic velocity at the end of the flight. A Tacan system was also used to navigate during final flight. Later, the vehicle was modified to accept Global Precision System (GPS) inputs. The backup flight control system has a single-string system that uses some different sensors and was programmed differently from the redundant set. The GPC is also used to operate other vehicle systems.

**Hydraulic System.** Hydraulic power is provided for the aerodynamic flight control system, main engine gimballing and control, nose wheel steering and brakes, and other items. The power source is a hydrazine-fueled auxiliary power unit (APU). Three redundant independent systems can provide full power using only two APUs and reduced rate power using a single system. The systems are active during launch and entry to provide for the engine controls during launch, flight controls during launch, and flight controls during entry and landing approach. The hydraulic pressure supplied is 3000 psi. Deployment of the landing gear is by gravity force only; however, hydraulic actuators are used to stop the free-fall gear because the stopping loads would otherwise be at the design load levels for the entire wing center section.

**Auxiliary Power Unit.** The auxiliary power unit (APU) produces power for the Orbiter's hydraulic system. Three separate systems are used to power hydraulic actuators for flight control during boost and entry. The three APUs are located in the aft fuselage. The APU uses catalytic decomposition of the hydrazine fuel ($N_2H_4$) and creates hot gas to drive a two-stage turbine, which drives a hydraulic pump. The rated power of each APU is 135 horsepower. The APU was built by the Sundstrand Corporation, Rockford, Illinois.

**Orbital Maneuvering System (OMS).** The OMS provides the thrust for orbital insertion, orbital circulation, orbital transfer, rendezvous, and deorbit. Two pods (Fig. 5) on the aft fuselage house the two 6000-pound-thrust OMS engine systems, as well as the aft reaction control system (RCS), which is redundant and can be used if the OMS engine fails. The OMS is pressurized by helium and uses nitrogen tetroxide ($N_2O_4$) and monomethyl hydrazine (MMH), Earth storable, hypergolic propellants. The engine nozzle extension is fabricated from aluminum alloy and is cooled by radiation.The combustion chamber walls are regeneratively cooled by the fuel before it is fed to the engine injector. Two electromechanical gimbal actuators control each engine. The pods are cross-fed, which allows using propellant from either pod. The OMS pod was built by the McDonnell Douglas Astronautics Company of St. Louis, Missouri. The engine was built by the Aerojet Liquid Rocket Company, Sacramento, California.

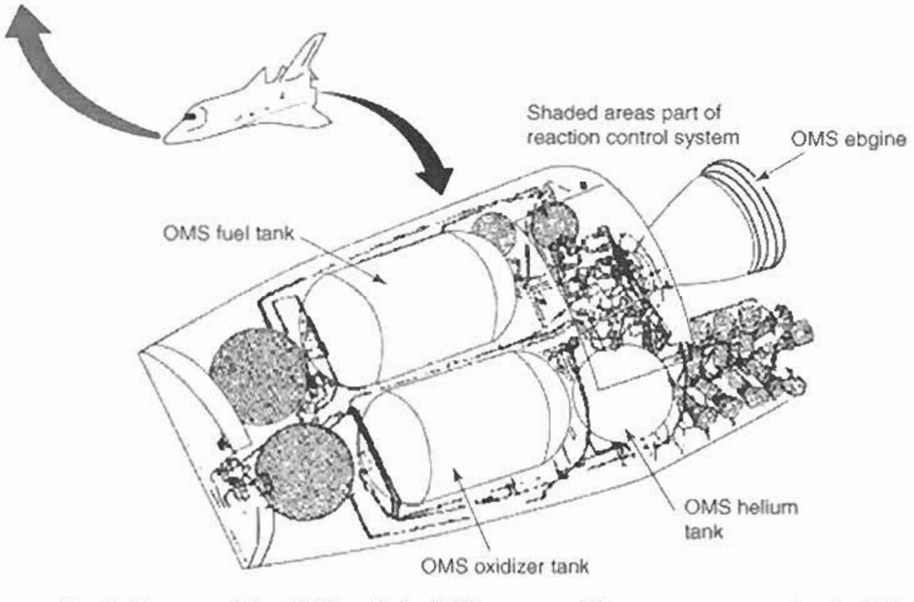


**Figure 5.** A diagram of the OMS and the RCS systems. These systems are closely linked. The figure is taken from the website: http://faculty.erau.edu/ericksol/shuttle/steve'sproject/m1/s1-10aoms.html. This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

**Reaction Control System.** The RCS (Fig. 5) provides attitude control in pitch, roll, and yaw and small velocity changes in translation above 70,000 feet altitude. The RCS thrusters are located in the forward nose area and in both OMS/RCS aft pods. The system is pressure fed and uses the same propellants as the OMS, which can be cross-fed so that the fuel from the OMS tanks can be used. The forward RCS has 14 primary engines of 870 pounds thrust each, and two vernier engines of 24 pounds thrust each. Each aft pod has 12 primary and two vernier engines. The RCS engines were built by the Marquardt Company, Van Nuys, California.

**Communications.** An S-band (2–4 GHz) communication system is the primary means of communicating between the Orbiter, and ground stations during the ascent, orbital, and entry phases of flight (Fig. 6). There is one uplink from the ground which is phase-modulated (PM) and provides commands, voice, and coherent signals to the Orbiter. There are three downlinks; one is phase-modulated and provides voice, telemetry, two-way Doppler, and a coherent ranging signal. The other two are frequency-modulated (FM) for real-time data and video.

In addition to the S band, an ultra-high-frequency (UHF) band is used for air to air and air to ground voice, and the Ku band is used with the Tracking and Data Relay Satellite (TDRS). There are four tracking and data relay satellites in geosynchronous orbit, which provide continuous real-time communications with

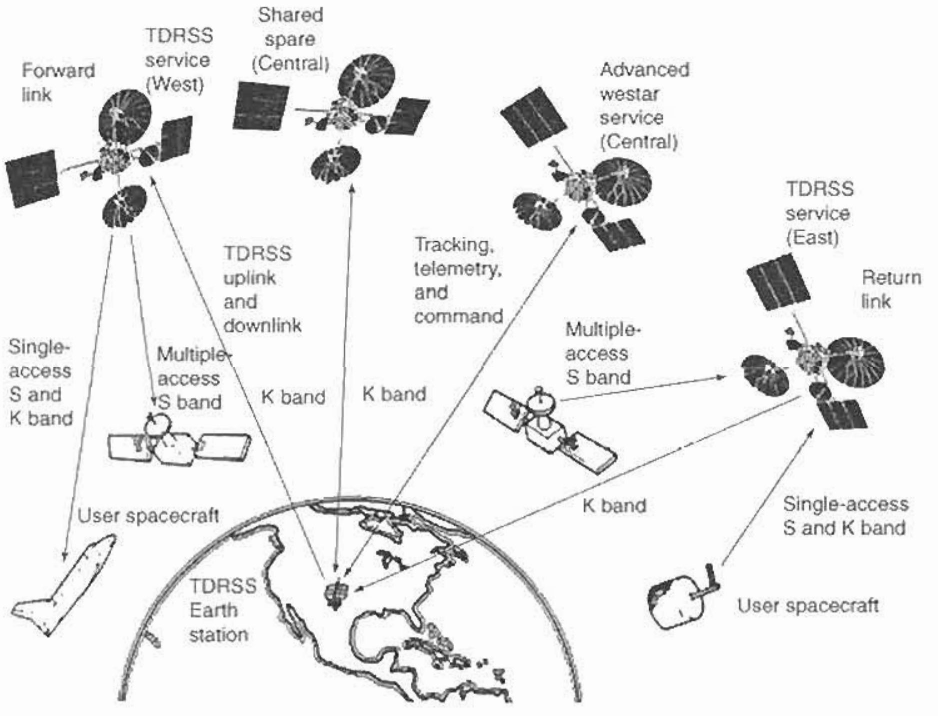


**Figure 6.** Communication System linking four identical and interchangeable satellites with earth station (diagram courtesy of NASA).

the ground control station. UHF is used during landing for aircraft communications and during extravehicular activities (EVA). The Ku band provides a much higher gain signal for higher data rates. The system also includes a rendezvous radar.

**Electrical Power.** Three fuel cells generate 28-volt dc electrical power through a chemical reaction. The fuel cells use hydrogen and oxygen that is stored in a supercritical condition. The dc power is routed to a three-bus system that distributes the power. The fuel cells were built by Pratt & Whitney, East Hartford, Connecticut.

**Environmental Control and Life Support System (ECLSS).** The Atmospheric Revitalization Control System (ARCS) maintains a habitable environment for the crew and passengers and a conditioned environment for avionic equipment inside the crew cabin. The crew cabin is pressurized to 14.7 psia with 79% nitrogen and 21% oxygen. Oxygen is obtained from a supercritical cryogenic storage supply and can also use the oxygen supply system of the fuel cells.

A water coolant loop subsystem (WCLS) is used to condition the crew cabin thermally by collecting heat through air-to-water heat exchangers and transferring heat to the Freon® coolant loop.

**Payload Deployment and Retrieval System.** The Remote Manipulator System (RMS) is the mechanical payload deployment and retrieval system used to release and capture payloads. The basic system consists of a manipulator arm, display and control panel, and interface units, that interface with the Orbiter's computers. The arm is located on the left (port) side longeron of the orbiter's payload bay. It is 50 feet, 3 inches long, 15 inches in diameter and has six degrees of freedom. The booms are made of carbon composite material, and the joints are of aluminum alloy. It can use standard or special purpose end effectors. The RMS has an active and passive thermal control system. A jettison system is available if the RMS cannot be stowed. The system was supplied by Spar Aerospace of Canada.

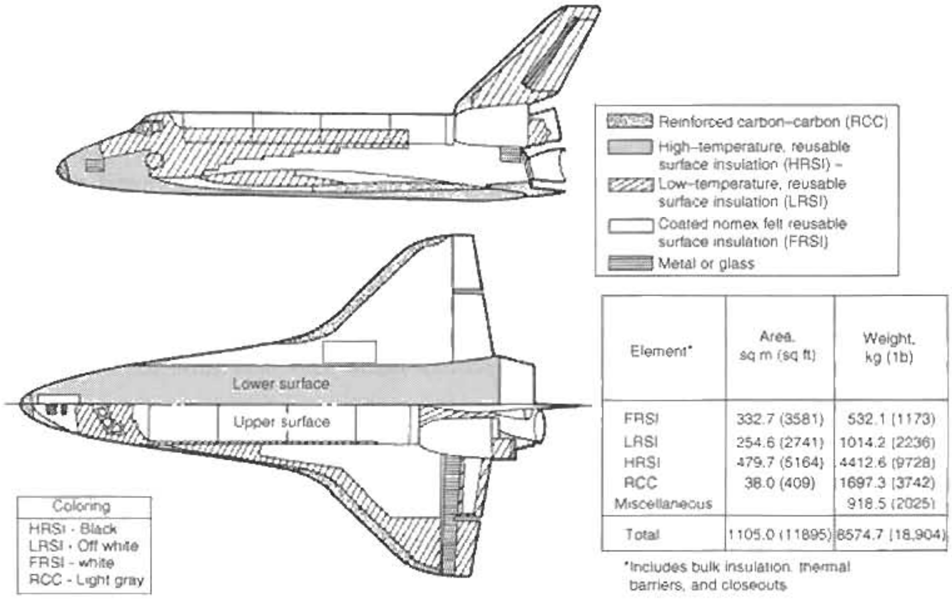
**Thermal Protection System.** Because of its importance in total vehicle weight, one of the most studied systems for the Orbiter was the TPS. The Orbiter was intended as a reusable vehicle, so that the ablative thermal protection used on previous people-carrying spacecraft was considered impractical. It was judged that an ablative system would have to be replaced on nearly every flight. The people at the NASA Research Center had spent much effort for a considerable time on reusable systems, particularly those that featured hot structures. Rene, coated columbium (niobium), and tantalum were some of the metals considered for various areas of the vehicle. Using the high angle of attack technique during the entry phase concentrates the heating on the bottom of the orbiter. The highest heating rates are experienced by the leading edges of the nose and wing. Different heat-resistant metals would be used for different regions of the Orbiter.

A different approach to thermal protection was being studied by people at the NASA Ames Research Center and by some contractors, Lockheed, General Electric, and McDonnell. The reusable surface insulator (RSI) was a new approach that shielded or insulated the heating from the vehicle by being a poor transmitter of the heat generated during atmospheric entry. This approach was considered favorably because the vehicle structure could be made of aluminum, with which the industry has much experience rather than less well understood high temperature metals. The RSI also somewhat uncoupled the TPS from the vehicle structure, which would allow easier adjustment if one or the other needed to be changed as flight experience matured the vehicle. Finally, using an RSI system allowed designing the structure before full understanding of the heating was obtained. Thus, it was possible for the Orbiter to perform the ALT program before the TPS design was complete.

The RSI is comprised of blocks, which were called "bricks" or "tiles" of about 6 × 6 inches. The material is a matrix of microfibers of high-purity silicon whose density is 8 pounds per cubic foot. The low density provides the poor conductivity of the material. Because the material absorbs water easily, a thin borosilicate glass coating is applied to prevent the tile from absorbing water. Absorbed water would add considerable weight to the vehicle and would create other problems. The coefficient of expansion of the tile is much lower than that of the aluminum of the vehicle structure. Thus, the tile is bonded to the vehicle using a felt pad that accommodates the differential motion. A Room Temperature Vulcanizer (RTV) is used as the bonding agent.

Four types of thermal protection materials are used on the Space Shuttle air frame (Fig. 7).

1. High-temperature reusable surface insulation (HRSI) for areas of higher heating is used mostly on the bottom of the vehicle. These tiles are black.
2. Low-temperature reusable surface insulation (LRSI) for areas of lower heating is used mostly on the sides of the vehicle. These tiles are white.



| Element* | Area, sq m (sq ft) | Weight, kg (1b) |
|---|---|---|
| FRSI | 332.7 (3581) | 532.1 (1173) |
| LRSI | 254.6 (2741) | 1014.2 (2236) |
| HRSI | 479.7 (5164) | 4412.6 (9728) |
| RCC | 38.0 (409) | 1697.3 (3742) |
| Miscellaneous | | 918.5 (2025) |
| Total | 1105.0 (11895) | 8574.7 (18,904) |

*Includes bulk insulation, thermal barriers, and closeouts

**Figure 7.** Thermal protection system, Orbiter 102 (diagram courtesy of NASA).

3. Felt (coated nomex) reusable surface insulation (FRSI) for areas of low heating is used mostly on the top of the vehicle. This material is white.
4. Reinforced carbon-carbon (RCC) composite insulation for areas that experience the highest heating. This material is black.

The thickness of the tile is determined so that the bond-line temperature of the aluminum never exceeds 300°F, the temperature at which aluminum begins to lose its mechanical properties. After numerous cycles, the coating for the major heating area was black, whereas a coating for lower heating areas was white because of the different radiative emissivites of the materials. This was also useful for orbit thermal control because of the different reflectivities of the materials when sunlight strikes them.

In areas such as the top of the vehicle, the felt pad used as a strain isolator in bonding the tile is coated with an RTV and is used on top of the wings and fuselage. Lockheed Sunnyvale was the supplier of the RSI.

Because of higher heating, a different approach was needed for the leading edges of the nose and wing. Carbon–carbon material was selected because it has the highest reusable temperature capability of all of the materials considered for the RSI. Of course, RCC is much denser than the other materials employed for the RSI system. Thus, it was necessary to minimize the area on which RCC was used. Great care was taken to perform accurate heating tests in developing the orbiter design to ensure that weight was minimized without endangering the vehicle when it reentered the atmosphere. This system was produced by LTV, Dallas, Texas.

## Structure

The major structural components were made primarily from 2219 aluminum, a material well known to the aircraft industry. Due to the problem of an aft center of gravity, titanium was used in the aft man engine thrust structure because of its high strength to weight. This structure distributed the load from the three main engines into the Orbiter fuselage at the aft bulkhead of the payload bay. The payload bay was designed so that the payload doors did not take any bending loads. This simplified their design. The door material was changed to a graphite carbon composite as a major weight saving after an initial design. The crew cabin consisted of a double shell; the external shell takes the vehicle loads, and the inner shell sustained only cabin-pressure loads. This approach was considered a crew safety issue and was also used on the Apollo spacecraft.

## Space Shuttle Test Flights

**Approach and Landing Test (ALT) Program.** The first Space Shuttle vehicle built was the "Enterprise". The mold lines, the structure, and the weight distribution were essentially identical to the space capable vehicles that would follow. It would be used for flight tests in the atmosphere, "form fit and function" tests at the Kennedy Space Center launch site, and for public relations, such as the trip to the Paris Air Show in 1983 where the "Enterprise" was the centerpiece of the exhibitions.

The Approach and Landing Test Program was conceived as an early demonstration of the glide capability of the Orbiter in the lower atmosphere. It would test flight hardware if the orbital flight program was delayed. The method of selecting a reusable surface insulator (RSI) allowed designing the orbiter, while analysis continued to determine the thermal environment and to develop the parameters (thickness, weight, and composition) of the thermal protection system. The structure of the Orbiter and the thermal protection system were essentially uncoupled.

There was some concern for launching the orbiter from the top of a Boeing 747, which had been selected to ferry the Orbiter between the manufacturing site, a landing site, and the launch pad. Wind tunnel tests of the two vehicles were conducted, and a separation procedure was developed. It was discovered that the procedure used by Mayo, a British designer interested in ultra-long-range air transportation during the 1930s, which had a small seaplane (the "Mercury") carried by a flying boat (the "Mayo"), proved the best. This procedure put the upper aircraft in an attitude with a higher lift-to-drag ratio (L/D) than the carrier aircraft L/D, so that the Orbiter actually dropped the Boeing 747 aircraft when released.

The ALT program allowed demonstration of the innovative fly-by-wire flight control system. Only the Approach and Landing final flight phase software was required, so this also allowed a phased development process. A pilot-induced oscillation (PIO) problem was discovered in the software resulting from a priority limit technique on the hydraulic system. The ALT program offered the operations personnel the opportunity to exercise their systems on a new concept in manned spacecraft. The ALT program was initiated in 1977 and was successfully concluded after five Flights (6).

**Space Flight-Test Program.** "Columbia" was the first space shuttle to be completed. It flew for the first time on 12 April 1981 and returned to Edwards Air Force Base (AFB) on 14 April 1981. Two people were on board, Flight Commander John Young and Pilot Robert Crippen. Earlier first flights for manned spacecraft, Apollo, Gemini, and Mercury, were all performed without a crew. Thus, the risk incurred on previous first flights with a crew aboard was considerably smaller than it was for the Space Shuttle. Thus, special care had to be taken to ensure that nothing went wrong. (Note: The Soviet version of the Space Shuttle, "Buran," copied the American Space Shuttle's platform but did not carry reusable rocket engines. It flew only once without a crew, using an automated landing system. Because "Buran" did not have a redundant flight control system, the risk of putting people on board was deemed to be too high. "Buran" has never flown again (7).

The first four flights of "Columbia" were designated "test flights." During these missions, crews were limited to two people, and no experiments were on board. The purpose of these missions was to explore and to expand the flight envelope of "Columbia." Because of the risks involved, two special measures were taken. The most important was to provide ejection seats on the first flight and three subsequent flights. These seats were used previously on the SR-71 aircraft, and the Approach and Landing Test provided an escape capability for the crew during the first few minutes of flight.

A second concern was the possibility of a software failure of either the primary or the backup computer system. Thus, "manual" override provisions were made so that the crew could select a configuration of the computers that would work. Great care was also taken to select the most experienced and competent crews for the first four flights. The second flight of "Columbia" was executed in November 1981 with Richard Truly as commander and Joseph Engle as the pilot. Commander Jack Lousma and Pilot Gordon Fullerton flew the third flight in March 1982.

The final test flight was conducted in July 1982 with T. K. Mattingly as commander and Henry Hartsfield as pilot. Appropriately, "Columbia" landed at Edwards AFB on 4 July 1982, and President Ronald Reagan was present to welcome the crew. Several hundred thousand people had driven out for the holiday to watch the spectacular landing (8).

## Space Shuttle Operations

Space Shuttles have now flown more than 100 missions during the past 20 years. After the successful test flights by "Columbia" in 1981 and 1982, three other Orbiters were built and launched: "Discovery," "Challenger," and "Endeavor." Each was slightly different from the others, but by any measure, they were sister ships. The Space Shuttles have performed a wide variety of tasks that would never have been possible without them. They have launched a large number of commercial, military, and scientific satellites. They continue to perform these missions successfully, even though the commercial and military satellites have been removed from the Space Shuttle manifests for reasons of policy. The Shuttles have carried Spacelab into Earth orbit in which important scientific experiments have been performed. Finally, a number of Space Shuttle missions have been performed that have involved repairing, replenishing, and retrieving Earth orbiting satellites. The first of these flew in the Spring of 1984; during the flight, the disabled Solar Maximum (Solar Max) satellite was retrieved, repaired, and redeployed. Extravehicular activity (EVA) had to be employed in this mission, and it was considered quite dangerous at the time. Partly, as a result of the Solar Max mission, operations of this kind have become quite routine.

Correction to the Space Telescope Optics was another mission which demonstrated the feasibility of on-orbit repair of satellite repair.

On 28 January 1986, the Orbiter "Challenger" was lost in a tragic accident. It was replaced by the shuttle "Atlantis," and flights of the Space Shuttles resumed in September 1988, a little short of 3 years after the "Challenger" disaster. Because the "Challenger" disaster was not caused by a failure of a system in the Orbiter, the description of exactly what happened will be recounted in another article in this Encyclopedia.

Most recently, the Space Shuttle has been heavily involved in the construction and deployment of the components of the International Space Station. It is interesting that when the reusable space ship was first envisaged, transport back and forth from orbiting space stations was deemed the most important mission

(1). There have been many modifications and changes in the Space Shuttle system since it was first fielded more than 20 years ago, but the basic configuration remains unchanged.

Many studies have been conducted to consider replacements for the Shuttle, but no system has yet shown enough promise to be built. The shuttle never accomplished its goal of substantially reducing the cost of delivering a payload to Earth orbit. There is some question whether the cost goals were ever realistic in the first place. Many reasons, such as flight frequency, operational considerations, and safety, can be put forth to explain why costs have remained high. Nevertheless, the Space Shuttle system has provided a safe method of continuing manned spaceflight. It is quite likely that the Space Shuttle will remain the United States' primary means for reaching Earth orbit in the foreseeable future.

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