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Space Shuttle Launch System 1972–2004

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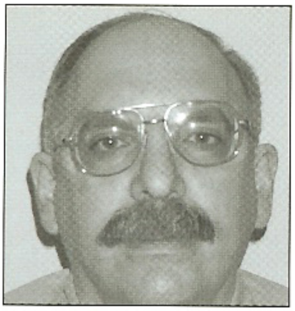
Mark Lardas • Illustrated by Ian Palmer



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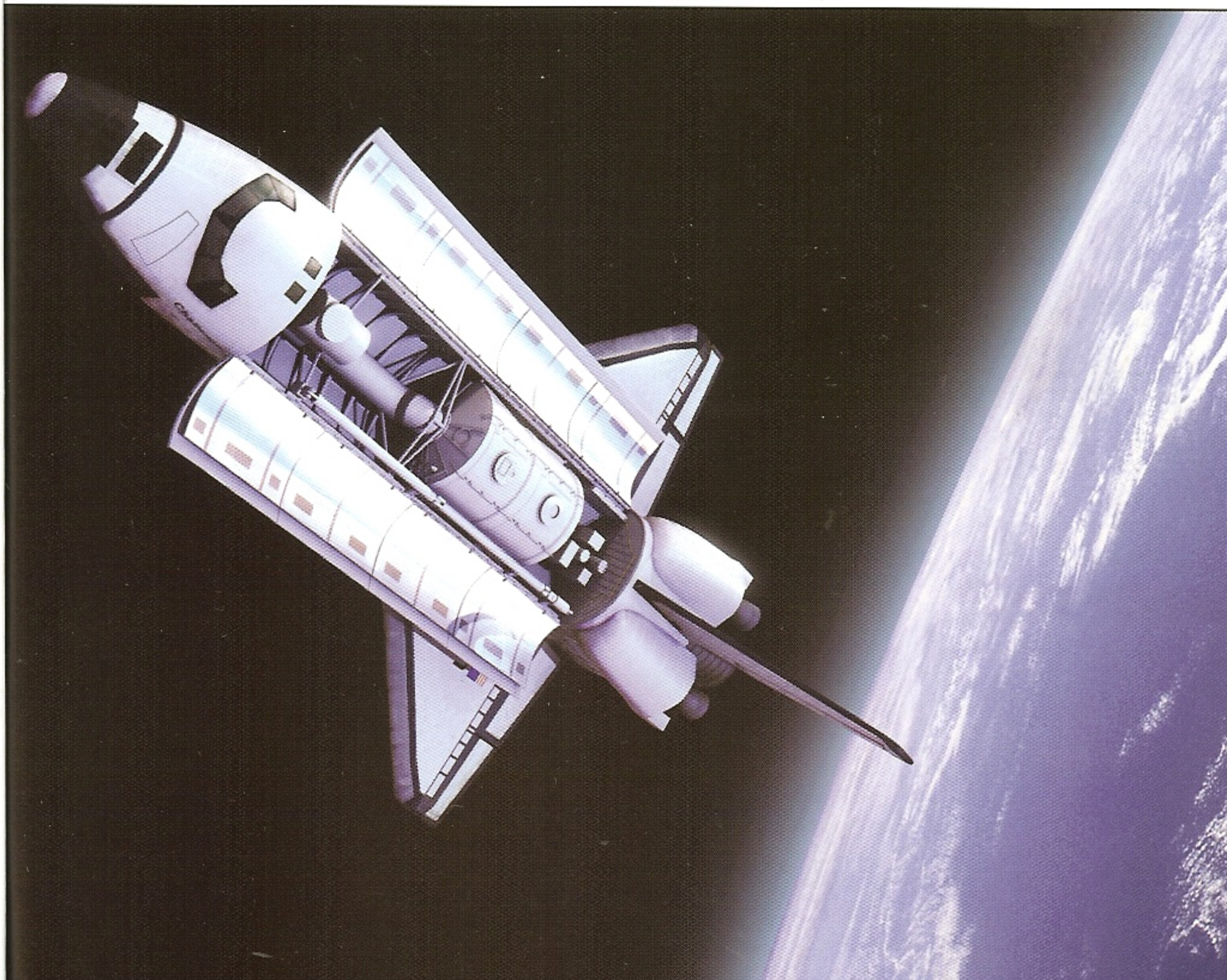

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First published in Great Britain in 2004 by Osprey Publishing, Elms Court, Chapel Way, Botley, Oxford OX2 9LP, United Kingdom.
Email: info@ospreypublishing.com

A CIP catalogue record for this book is available from the British Library.

ISBN 1 84176 691 7

Editor: Simone Drinkwater
Design: Ken Vail Graphic Design, Cambridge, UK
Index by Alison Worthington
Originated by The Electronic Page Company, Cwmbran, UK
Printed in China through World Print Ltd.

04 05 06 07 08 10 9 8 7 6 5 4 3 2 1

For a catalog of all books published by Osprey Military and Aviation please contact:

Osprey Direct USA, c/o MBI Publishing, P.O. Box 1, 729 Prospect Ave, Osceola, WI 54020, USA
E-mail: info@ospreydirectusa.com

Osprey Direct UK, P.O. Box 140, Wellingborough, Northants, NN8 2FA, UK
E-mail: info@ospreydirect.co.uk

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Author's dedication

This book is dedicated to Robert Howarton – model-maker extraordinaire and Shuttle fan.

Author's note

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SPACE SHUTTLE LAUNCH SYSTEM 1972–2004

INTRODUCTION

It was a stock techno-thriller subplot in the 1970s and 1980s: a Space Shuttle launch during a fictional Third World War – an Air Force Shuttle, launched on a military mission to help the United States win the war. Frequently, these stories involved the Shuttle in combat – the first-ever space combat. Sometimes the Orbiter won its fictional encounter. More often, it was destroyed.

Reality followed a different course. Military use of the Shuttle has been tentative, reluctant, and fleeting. Operational shortcomings, rather than military action, have caused Shuttle losses. Rather than being an orbital bomber or daring spy plane, the Shuttle has been a space-age dump truck, a high-tech 18-wheeler.

The Shuttle was conceived when space was seen as the new high ground. It was thought that those who commanded space could keep the rest of the world's nations penned on Earth, much as Nelson's navy kept Revolutionary France trapped on the European continent. Its design shows the influence of a perceived military role: the size of the payload bay, the maximum weight of any payload delivered to orbit it was designed to carry, even its double-delta wing sprang from the military missions it was intended to support.

When the Shuttle finally flew, new realities emerged. The new high ground proved a vulnerable ridgeline, where you could be picked off by invisible enemies hidden in undergrowth. Manned space flight was as public as Times Square on New Year's Day, complicating clandestine operations. Space is an incredibly hostile environment, better fit for electronic robots than human beings, and many uses of space – such as the Global Positioning System – had not been conceived in the late 1960s when the Shuttle design began.

The Space Transportation System – consisting of an orbital space plane, solid booster rockets, and an external fuel tank – was a compromise, with all the limitations that compromises often entail. It has proved less satisfactory than its champions promised. It never delivered a once-a-week launch rate, polar launch capabilities, or even a payload of 65,000lb into low-Earth orbit. It is more expensive than expendable launch vehicles.

Replicas of Christopher Columbus' ships sail past the Orbiter *Endeavour* at Launch Pad 39B as *Endeavour* awaits liftoff on its maiden voyage, STS-49. Photographed during the Columbus quincentennial in June 1992, it illustrates the link between explorers throughout time.

Despite its limitations the Shuttle remains revolutionary. Both it and the spacecraft deployed from it are still the only successful reusable spacecraft. The Shuttle gives humans unprecedented access to low-Earth orbit, allowing ordinary individuals to travel in space. Remarkably flexible, it has made projects like the International Space Station (ISS), the Hubble Space Telescope (HST), and Long Duration Experiment Facility (LDEF) possible.

DESIGN AND DEVELOPMENT

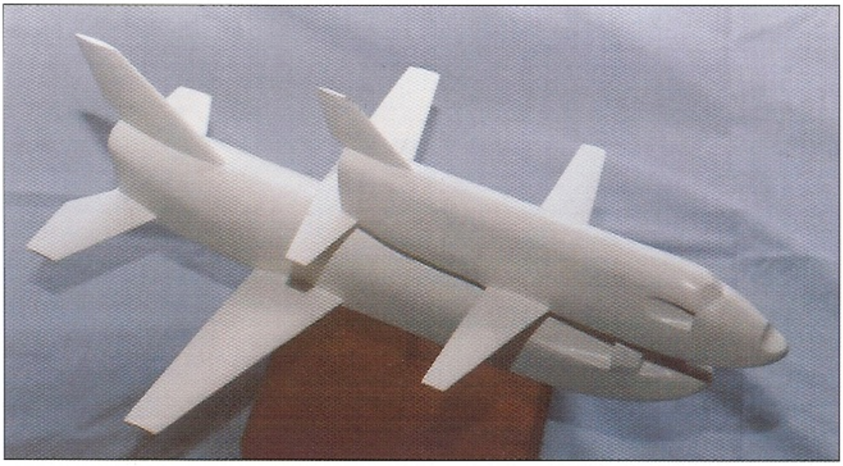
Genesis

In 1969 man reached the Moon and the National Aeronautics and Space Administration (NASA), began to consider its next major endeavor. A manned space station seemed achievable, if transportation costs to low-Earth orbit could be reduced. A reusable launching system – a space shuttle – promised the requisite savings, so NASA proposed a combined station/shuttle initiative.

The initial shuttle design proposed by Maxime Faget, NASA's chief designer, was completely reusable. A manned, fly-back first stage that was the size of a Boeing 747 airliner, but could out-perform an X-15, would launch, carrying an Orbiter. At staging, the Orbiter, which would be larger than a 707 airliner, would launch from the first stage. The first stage would turn around, and fly back to the launch pad. Both first stage and Orbiter had straight wings allowing them to glide to a landing on a conventional runway at airline speeds. Liquid-fueled rockets would power both, and the system could carry a small (20,000–30,000lb) payload.

It was too expensive. NASA could get funding for one of the two projects and about half of the other. Neither project could be justified in isolation: without a space shuttle, a space station could not be maintained. Without a space station, there was insufficient justification for a space shuttle. Seeking extra funds, NASA approached the Air Force.

By 1970 the United States Air Force (USAF) had been striving for a manned military presence for nearly a decade. Two manned programs – Dyna-Soar and the Manned Orbiting Laboratory (MOL) – had been started and then abandoned. Dyna-Soar, a manned orbital spaceplane



This model – currently on display at Johnson Space Center – shows the original Shuttle concept: a manned fly-back first stage, and a straight-winged Orbiter, capable of landing at airliner speeds. (Author's collection)

The Manned Orbital Laboratory (MOL) was the military's second effort to create a manned military presence in space. The program was canceled in 1969, and the seven astronauts assigned to it were transferred to NASA. Ironically, they provided commanders for most of the first Shuttle missions – another program that started as a military effort, but ended being transferred to civilian use.

initially intended as an orbital bomber, evolved into a payload delivery system before cancellation in 1964. MOL, a manned reconnaissance platform, had been abandoned the previous year, in 1969. The seven astronauts were reassigned to NASA. When NASA offered the Air Force a chance to get back into manned space flight, the Air Force was interested.

Air Force–NASA partnerships were common. The X-15 and XB-70 mach-3 bomber were joint Air Force–NASA projects. NASA's launch facilities at Cape Canaveral, Florida, as well as facilities at White Sands (New Mexico) and Edwards Air Force Base (California), were shared with the Air Force, as was the joint research on lifting bodies and hypersonic aircraft performance; the Air Force sometimes provided the funding for these projects. NASA obtained aircraft used to support this research from the Air Force. The Air Force MOL used a militarized version of the NASA's Gemini manned space capsule. A jointly developed shuttle seemed natural.

The Air Force knew that without its support NASA would not get a space shuttle. Reconnaissance was a major space military mission and the United States' principal foe, the Soviet Union, had significant bases in the Arctic. To fly over all of the Soviet Union American military reconnaissance satellites needed high-inclination orbits.

The Earth's rotation assists spacecraft launching due east. Increasing an orbit's inclination reduces this assistance. Launches due north (or south) get no rotational assistance. With launch inclinations in excess of 90° the Earth's rotation reduces the speed of the vehicle. A launch system that puts 30,000lb into orbit launched due east may only carry a 5,000lb payload into the 97° inclination orbit required for observation. The Air Force already planned optical reconnaissance satellites – the Keyhole series – that weighed up to 40,000lb. These required a payload bay that was 15ft across and 60ft in length. Upgraded (by means of adding larger solid rocket boosters) Titan III boosters could place these into a 97° inclination orbit. Faget's design could not.

The Earth's rotation moves the launch site after launch. A rocket launched from the United States crosses roughly 1,100 nautical miles west of its launch site when it has completed one orbit. Due to range safety, satellites requiring inclinations greater than 65° were launched on the Pacific coast, from Vandenberg Air Force Base. This put a spacecraft over the Pacific Ocean after completing one orbit.

To land on American soil – critical for classified military payloads – the Air Force required the ability to fly crossrange (perpendicular to the direction of the orbit) 1,100 nautical miles. The Air Force also planned missions that were to be completed in one orbit. The vehicle would go

By Authority to Proceed, the Orbiter design had evolved to a double-delta wing, but one with twin rudders, raised wing tips, and jet engines for landing. This was a heat transfer model of the design used by Rockwell to refine the craft. (Author's collection)

up, launch or retrieve a payload, then return to Earth at an American military facility. Faget's design had less than 200 miles of crossrange capability, and was thus impractical for the military.

The Shuttle design was altered to accommodate Air Force requirements. The larger payload bay and the increased payload – 65,000lb when launched due east – increased the size of the entire system. A double-delta design was adapted – with a broad triangle forming the wings and a narrow triangle merging the wing to the fuselage. The double delta improved performance at hypersonic speeds – this increased both crossrange capability and vehicle heating during reentry. Additionally, a delta wing has a higher sink rate and stall speed. Faget's straight-winged craft landed at a stately 130 knots. A delta design sizzled down the runway at 190 knots.

Budgetary pressures further complicated these requirements. Previous aerospace craft operating in hypersonic environments, such as the X-15, were made from titanium, using the titanium structure as a heat sink. A "hot-structure" Orbiter would have been the largest titanium airframe ever constructed, and consequently, fantastically expensive.

However, a new insulator was being developed – silica tiles. The insulating silica was light, would not oxidize, and could withstand temperatures up to 2,500°F. This promised a reusable insulation that permitted an aluminum-frame vehicle. It was much less expensive than titanium. Not surprisingly, NASA opted for this thermal tile system.

NASA also reduced costs by substituting strap-on boosters for the fly-back first stage. Initially these were liquid-fueled, but the costs and complexity of liquid-fueled boosters prompted NASA to investigate the use of solid rockets.

Solids were cheap and reliable, burning a mixture of powdered aluminum and ammonium perchloride oxidizer. Their thrust was comparable to that obtainable with liquid oxygen and kerosene, a common rocket fuel. Although the proposed Shuttle would require solids larger than those used before, a solid rocket booster would cost much less than a liquid booster. The solid rocket casings would also be sturdy enough to be retrieved and reused.

Once lit, however, solid rocket boosters (SRBs) burned until they were exhausted. Aborting a launch while they were burning was impossible. All previous manned spacecraft used liquid-fueled engines that could be throttled. NASA chose to accept the risk inherent with SRBs.

NASA contracted for a new motor for the planned Shuttle fueled with liquid oxygen-liquid hydrogen (LO_2-LH_2). Initially they demanded an engine that could generate 415,000lb of thrust, with a motor that was to be reusable and throttleable. After Air Force requirements increased the payload to 65,000lb, NASA changed the engine requirements to 550,000lb of thrust.

The liquid hydrogen and oxygen fuel affected the vehicle design. Liquid hydrogen is bulky and makes up one-seventh of the total fuel weight in a LO_2-LH_2 system, while accounting for three-fourths of the volume. It is light, however, and can be stored in lightweight tanks. Proposals were drafted for storing liquid hydrogen in disposable, external tanks. The proposed Orbiter shrank.

NASA finally put all of the liquid fuel in an external tank, producing the configuration used today. The orbiting spacecraft would be built from aluminum with a silica-tile thermal protection system. Launched with LO_2-LH_2 engines, it would use double-delta wings for reentry and draw fuel from a large external tank. Attached to the external tank, two solid rocket boosters provided the first stage impetus.

The difference between the SRBs and SSMEs can be clearly seen in this view of a Shuttle launch. The solid fuel – a mixture of powdered aluminum and ammonium perchloride – burns with a bright white flame. The liquid-hydrogen and liquid-oxygen of the SSMEs yields an almost-invisible blue flame.

A painful birth

NASA had its design. Success depended upon coordinated completion of several disparate technologies. Both propulsion systems were unprecedented. The Space Shuttle Main Engine (SSME) was larger than any comparable LO_2-LH_2 engine, throttleable and reuseable. The SRBs were so big that, unlike any of their predecessors, they had to be built in sections. While the aluminum structure simplified construction, that gamble was predicated on an untested thermal tile.

NASA's proposal arrived as the United States' economy experienced "stagflation" – economic stagnation combined with inflation. NASA funding came from the discretionary budget – the small fraction of the Congressional spending that could be cut. Always on the budget chopping block, NASA starved its other programs to fund the Shuttle – abandoning the space station, and canceling three Apollo Moon missions.

NASA used extravagant claims to sell the Shuttle: they declared that the Shuttle would make space flight as routine as a bus ride; it could launch once a week; a fleet of four Orbiters would complete 400 missions in ten years; every object placed in orbit would start into space aboard the Shuttle. Based on an economic analysis conducted in 1970, the Shuttle would recoup development costs after 506 launches, and on its next 400 missions NASA would clear a profit.

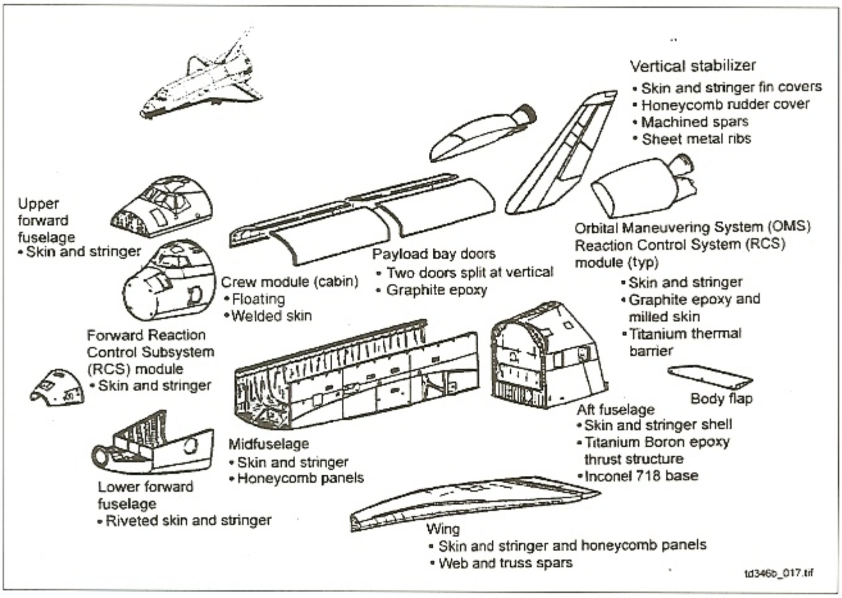
The numbers were based on optimistic assumptions – that the Shuttle would increase demand for space by cutting costs of access, that enough payloads would exist to ensure each Shuttle launch was full, that inflation remained under control. Most importantly, it assumed development would follow schedules. Any slip – whether due to development difficulties or budget cuts – upset the coordination of several mutually dependent and technically challenging development programs. The Shuttle experienced both budget and developmental problems.

The Space Shuttle Main Engine (SSME) proved the first hurdle. Pratt and Whitney, the losing bidder, challenged the contract awarded to Rocketdyne in 1971. Engine development stopped until the challenge was settled, in 1972. The Main Propulsion Test Article (MPTA-098) – used to test the Space Shuttle Main Engines – only began construction in 1974. The SSMEs proved to be the program's laggard child, delaying the first launch by at least six months.

NASA awarded the Orbiter contract to Rockwell International (formerly North American Aviation) in August 1972. Rockwell was also named the system integrator. Martin (later Martin-Marietta) won the External Tank contract, and built it at their New Orleans, LA factory. Marshall Space Flight Center (MSFC), a NASA center, retained responsibility for integration and final assembly of the Solid Rocket Booster, parceling the contracts for the structure to McDonnell Douglas Astronautics in Huntington Beach, CA, and the rocket motors to Thiokol (later Morton-Thiokol) in Wasach, UT.

Rockwell divided the Orbiter contract among major aerospace manufacturers in the United States. Rockwell used Orbiter structural groups – major subassemblies – as the partitions. Grumman (now Northrup-Grumman) in Beth Page, NY, received the subcontract for the wings, General Dynamics in San Diego, CA, built the mid-body, and McDonnell Douglas, in St. Louis, MO, developed the Orbital Maneuvering System and the aft Reaction Control System. The Shuttle was now dispersed throughout the country. If Congress canceled the program the effects would be felt in many Congressional Districts.

The Shuttle required new launch and processing facilities. NASA began converting the two Saturn launch pads and Saturn support buildings, such as the Vehicle Assembly Building (VAB) at the Kennedy



The Orbiter consists of 16 major structural groups. This modular approach allowed NASA to convert a high-fidelity structural test assembly and a collection of operational spares into the Orbiters *Challenger* and *Endeavour*.

Space Center (KSC) for Shuttle use. The Air Force agreed to convert their never-completed MOL launch pad at Vandenberg AFB – Space Launch Complex 6 (SLC-6) – for polar Shuttle launches.

Other facilities were needed. To reduce costs, the SRBs would parachute to a soft landing, then be recovered and refurbished. NASA let contracts for two recovery ships – *Liberty* and *Freedom* – as well as SRB refurbishment facilities.

Transporting the Orbiter was a problem. Unless it always landed at KSC or Vandenberg – which was unlikely given uncooperative weather or an emergency landing situation – a means of transporting the Orbiter was required. It was too large to travel by road, and moving it by water was too slow – and you could not guarantee all contingency landings would be made close to waterways.

The solution came from the test program. Drop tests, simulating an entry were necessary, and it became clear that the Orbiter could be carried atop a 747 aircraft. A 747 was leased and modified for the drop tests. NASA realized they had their transporter. The 747 was retained, and a second was purchased in the 1980s.

NASA contracted for permanent mate-demate facilities (to separate or join the Orbiter to the 747 transporter) at KSC, Vandenberg, and Dryden-Edwards, as well as an air-portable mate-demate mechanism for contingencies.

From prototype to flight

In 1972 Rockwell had contractual authority to produce two Shuttle Orbiter Vehicles, a Main Propulsion Test Article (MPTA-098), and a Structural Test Article (STA-099). The Orbiter Vehicles, then unnamed, were OV-101 (*Enterprise*) and OV-102 (*Columbia*). Both were intended as operational Orbiters.

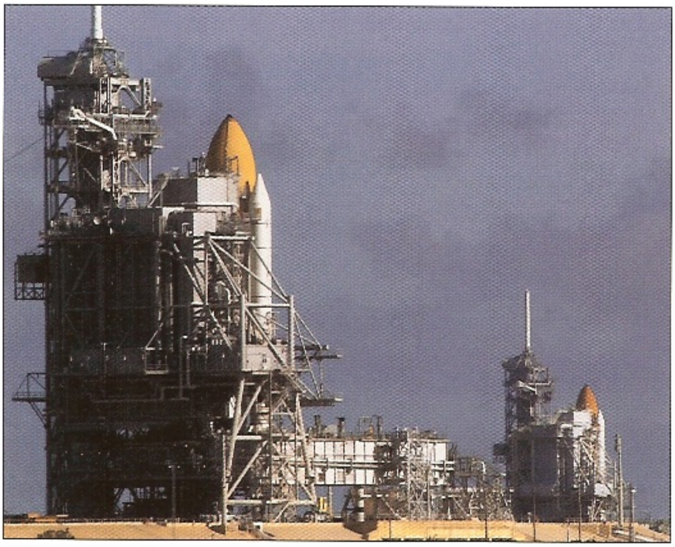
MPTA-098 replicated the structure of the main propulsion system and was to be used to prove the Space Shuttle Main Engine (SSME).

STA-099 was a high-fidelity structural replica of the Orbiter vehicle. It contained a boilerplate crew compartment, but would be otherwise identical to the flying vehicles. It would be used for structural, vibration, and pressure testing.

The conventional aluminum structure allowed construction of the first Orbiters to progress rapidly. The airframe of OV-101, started in June 1974, was essentially completed by September 1976 – well before the rest of the system required for flight, and before the infrastructure needed for basic operations was ready. Systems required for space flight, such as the SSMEs and OMS/RCS pods, were incomplete at *Enterprise*'s rollout to Dryden. Aerodynamic dummies were installed to make *Enterprise* available for necessary pre-launch testing in advance of space flight.

Development of the SRBs – despite their unprecedented size – also came together swiftly. Thiokol, the motor developer, had beaten Aerojet, a Florida-based company, to win the competition for the SRBs. Aerojet lost despite proposing a monolithic motor – one solid piece of fuel. Thiokol's design used a segmented SRB. Three sections of propellant would be stacked, then mated together at a launch site processing building.

Building the engines in segments simplified transportation – which was significant when SRBs had to be shipped to two launch sites separated by a continent. Aerojet's monolithic motor would have to be barged, simple



ABOVE **One of the few times that two Orbiters were on launch pads simultaneously awaiting launch occurred in July 2001.**

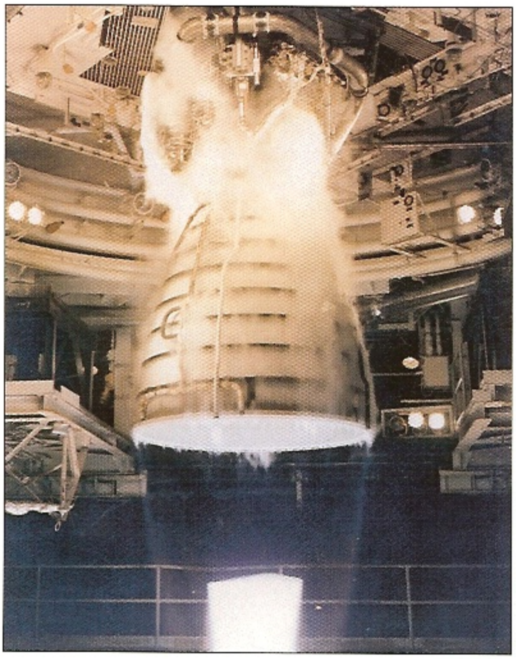
enough when shipping to KSC at Cape Canaveral, but more problematic when sending motors to Vandenberg, California. Thiokol held the first test firing of an SRB on July 18, 1977 followed by two more the next year.

The conversion of KSC facilities progressed satisfactorily. While still supporting Saturn launches in 1975, new construction and facility conversion proceeded swiftly enough to support Shuttle activities at the end of 1978. The Vehicle Assembly Building was ready by the summer of 1978, launch pad 39-A had been converted by December 1978, and Mission Control in January 1979. Pad 39-B would not be finished until late 1985. NASA was ready for launch operations on schedule.

Other parts faired more poorly. The Air Force began converting SLC-6 (or "Slick Six") in 1979, late for launches planned in the early 1980s. At Kennedy NASA converted facilities built for the Saturn, a rocket larger than the Shuttle. SLC-6 was originally intended as a launch site for a smaller vehicle, the Titan III, and the conversion spiraled into a succession of modifications and alterations in an ultimately unsuccessful attempt to match SLC-6 to the Shuttle. The facility was unfinished in 1986, when the *Challenger* accident halted Shuttle launches.

SSME development, which started late, continued to run late. The first test firing of an SSME occurred in December 1976. MPTA-098 was installed at the National Space Technology Laboratory, in Bay St. Louis, Mississippi, by autumn 1977, with a first test firing in April 1978. Frustrating test failures followed – shutdowns, turbopump failures, a fractured valve that caused structural damage. It was not until January 1981 – two years after the planned 1979 first lift-off date – that the SSMEs successfully completed a full flight demonstration.

BELOW **A test firing of the SSME in May 1981 at the National Space Technology Laboratories in Mississippi. Developing reliable SSMEs delayed the Shuttle program more than any other single factor.**



Thermal tile system production also lagged. The tiles used for *Columbia*'s first flight were not completely delivered and installed until a few weeks before the first launch.

Originally *Enterprise* was to be returned to Downey for conversion to flight status, after integrated ground vibration tests held at MSFC in 1978. However, after design evolution while *Enterprise* was undergoing testing, the flight vehicle was considerably different to the Orbiter that had emerged from Downey in 1975. *Enterprise*'s conversion was deemed uneconomical, and canceled, which would have left NASA without a second Orbiter until 1984, when follow-on Orbiters were planned. NASA instead converted STA-099 to flight status, replacing the boilerplate crew compartment with a flight article. Conversion began in 1979. STA-099 became OV-099, *Challenger*.

Evolution in the flight era

Even after the Shuttle's first flight in April 1981, it remained an experimental vehicle, under development. NASA awarded Rockwell a contract for two additional vehicles, OV-102 (*Discovery*) and OV-103 (*Atlantis*) in 1979, along with *Challenger*. The two new vehicles saw significant improvements over the first Orbiters. They were structurally lighter, and substituted thermal blankets for tiles over the low heat areas. *Discovery* and *Atlantis* were nearly 8,000lb lighter than *Columbia*, the equivalent of a standard commercial satellite.

NASA also continued development of the External Tanks. Initially, the ETs weighed 77,000lb. A new lightweight ET was introduced in 1983, which weighed 66,000lb, increasing available payload by 10,000lb. In 1998, a super-lightweight tank was introduced. Made from aluminum-lithium alloy, it reduced tank weight, increased cargo weight by an additional 7,500lb, and is 30% stronger than the lightweight tanks.

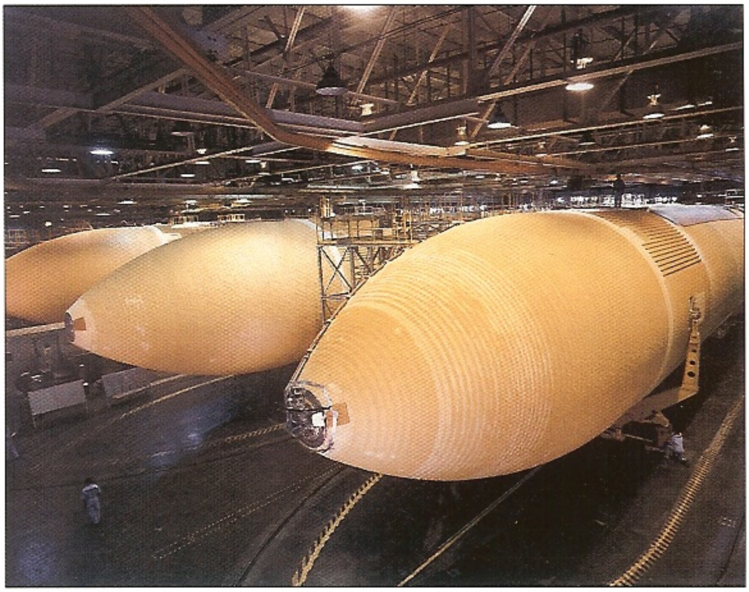
NASA developed three new upper stages for use with the Orbiter. The Payload Assist Module (PAM) and Inertial Upper Stage (IUS) were solid-fueled transfer stages intended to put payloads into higher orbit. A PAM could hoist a 500–1,400lb payload into geostationary orbit (an orbit with a 24-hr period, that remained in the same spot over the Earth as the earth rotates). The IUS could place a 5,000lb satellite into geostationary orbit. Both were used successfully after initially experiencing embarrassing failures.

The Centaur upper stage was a high-energy, liquid-fueled (LO_2-LH_2) booster developed to allow the Orbiter to launch interplanetary probes, but it was never used aboard the Orbiter. Development fell behind. Its first operational use was scheduled for spring 1986, when launch windows opened for a Jupiter and Saturn mission. The Centaur was already controversial because its cryogenic fuel had to be dumped prior to landing in a launch abort. Engineers were uneasy as to the effect of venting flammable fuel while the engines were thrusting the Shuttle to a landing site. Additionally, the Orbiter lacked the plumbing to dump all of the Centaur's fuel by the time the Orbiter landed when performing the shortest aborts. After the 1986 *Challenger* accident, the Shuttle-Centaur was canceled.

Following *Challenger*, NASA made a number of changes to the Shuttle. The most significant was the redesign of the SRB field joints, where the SRB segments mated together. Hot gasses escaping from a joint destroyed the Shuttle, so a more robust joint was added, with a stronger tang and clevis structure, and longer pins to preclude gas leakage.

Other nagging problems were also resolved. Improved Auxiliary Power Units (APUs) were developed. These lasted three times longer than the old units. Improved disconnects

Three completed lightweight ETs at the Michoud assembly plant awaiting delivery to KSC in 1981.



Deployment of a TDRSS satellite from the Orbiter. A spring-loaded platform in the harness holding the satellite in the cargo bay pushes the satellite out of the Orbiter. An IUS upper stage (white portion on bottom) then boosts the satellite (gold and black upper portion) to a geostationary orbit.

for the Space Shuttle Main Engine (SSME) fuel lines were added. With the previous disconnects, inadvertent closure of the valve connecting the Orbiter to the ET (external tank) could have caused a catastrophic failure.

Other changes included the addition of a drag parachute, to shorten the Oribiter's roll-out following landing, a steerable nose wheel, to increase control on landing, upgraded brakes, and a crew escape system. The crew escape system allows the crew hatch to be opened in flight, and the crew to bail out once the Orbiter vehicle is in subsonic flight. It is useful only when a problem precludes an intact Orbiter landing, but allows the Orbiter to survive through most of reentry.

After the *Challenger* accident, NASA ordered a replacement Orbiter. Built from structural spares ordered in 1983, it became the Orbiter *Endeavour*, and incorporated the post-*Challenger* changes.

Alterations in the 1990s included an Extended Duration package that allowed 30-day missions, a "glass cockpit" that upgrades the flight avionics from a 1970s standard to current state-of-the-art, and a relocated airlock, allowing the Orbiters to dock with the International Space Station.

Rivals and replacements

The Shuttle remains the world's only reusable launch system, although the Soviet Union came closest to duplicating it. They did not believe a rival would spend billions developing the Shuttle unless national security was involved and thought that the economic analysis used to justify the Shuttle was completely phony. They regarded the involvement of the United States Air Force with suspicion, and believed that NASA provided cover stories for previous Air Force military activities: the U-2 spy plane, for example, was once passed off as a NASA research aircraft.

The Soviets knew the Shuttle must have a military purpose beyond satellite delivery – they just could not determine what it was. Their best guess was that it was a hypersonic bomber, intended to strike high value targets in the Soviet Union. To learn what the Shuttle was for, they felt they had to build one.

In 1976 Brezhnev authorized a Soviet space plane. The Soviets poured over $10 billion into its development and construction, and came up with a system that used the *Buran* ("blizzard") space plane and the *Energia* ("energy") launcher.

Buran had four turbojets on the space plane, used both for vertical takeoff and landing. *Energia* used four LO_2-kerosene strap-on boosters, and a central core fueled with liquid hydrogen and liquid oxygen.

Five *Buran* Orbiters were planned, but only one was completed which launched once. This *Buran* was a test item with no life support system or computer displays installed. When it flew for the first time on

November 15, 1988, it was launched, unmanned, with no payload, and successfully landed with automated robotics.

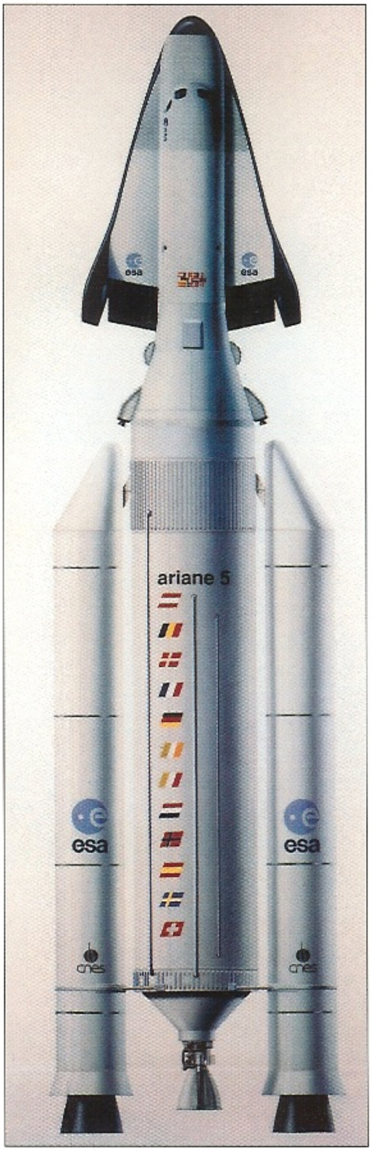
The second *Buran* was scheduled for a manned mission in 1993. It was nearing completion when the Soviet Union collapsed in 1991. By then it was obvious that the American Shuttle was not a military system. Lacking a purpose, the Russian program was suspended, then canceled.

The European Space Agency (ESA) also planned a space plane. *Hermes* started as a French initiative. They planned a space plane carrying four to six astronauts and a payload of 4,500kg (around 10,000lb) to low-Earth orbit, atop an Ariane 5 booster. Its first flight was scheduled for 1995.

The French space agency, CNES, initiated *Hermes* in 1984. In 1987 *Hermes* was transferred to the ESA, and as the design progressed, the weight and cost of the vehicle grew dramatically. Development was initially priced in 1984 at $2 billion US dollars. By 1991, *Hermes* had consumed $2 billion, and was expected to eat another $11 billion before its first launch – which was scheduled for 2002. A downsized *Hermes* was considered, but ESA canceled the project in 1992.

American attempts to replace or significantly upgrade the Shuttle were similarly barren. The first attempt came during shuttle development. The Shuttle-C was a heavy-lift variant. Using the same SRBs and ET, the Shuttle-C substituted a wingless, unmanned "can" for the Orbiter. In some versions the SSME section, OMS/RCS pods, and flight control systems were detachable modules retrievable by the Orbiter for reuse. Although the Shuttle-C would have proved a valuable supplement to the Orbiter, it never got beyond the planning phase.

Two other space planes were proposed following *Challenger*. The X-30 National Aerospace Plane (NASP) was a possible Shuttle replacement. A single-stage-to-orbit space plane, which used scramjets that converted to rockets for propulsion, the program was started in 1990. It was canceled while in the design phase. The X-38 (Crew Emergency Reentry Vehicle) was intended as a space-going lifeboat. Carried aboard the Orbiter, it would be docked on the International Space Station (ISS), where it could return the crew to Earth in an emergency. CERV progressed to the prototype stage, with drop tests conducted from a B-52, before cancellation in 1998.



ABOVE **Hermes was the ESA's attempt to design a manned orbital space plane. The only thing that took off in this project was cost – which led to its cancellation. (Courtesy ESA)**

LEFT **The X-38, Crew Emergency Reentry Vehicle, was one of the proposed Shuttle successors. This captures the CERV during a drop test prior to cancellation of the program in 1998.**

OPERATIONAL HISTORY

Approach and landing tests

NASA prefers unmanned testing of manned systems before flying a crew, but the Shuttle lacked an unmanned capability. For safety, some systems require human intervention. The crew aboard the Orbiter pulls a lever to lower the landing gear, for example, and the Orbiter lacked a crew escape system. There were two ejection seats installed on *Enterprise* and *Columbia*, but these were to be removed once the Shuttle was declared operational.

NASA planned an unprecedented level of testing prior to the first manned flight, including the Approach and Landing Tests (ALT). Five drop flights were planned. Before flying the drop missions, NASA conducted background testing. Initially, *Enterprise* was mounted atop the 747 and several taxi tests were made to check the structural and dynamic integrity of the odd coupling. A tail cone was added to *Enterprise* to reduce aerodynamic turbulence.

The Orbiter first flew on February 18, 1977. The vehicle was unmanned as it was a captive flight atop a 747 carrier aircraft and was the first of eight such flights. Five captive flights used an unmanned Orbiter. A two-man crew rode in *Enterprise* during the final three captive flights, which were dress rehearsals for the drop tests. The Orbiter's control system were tested, as well as low- and high-speed flutter tests checking the interaction between the 747 and Orbiter. The final captive test flew a separation trajectory.

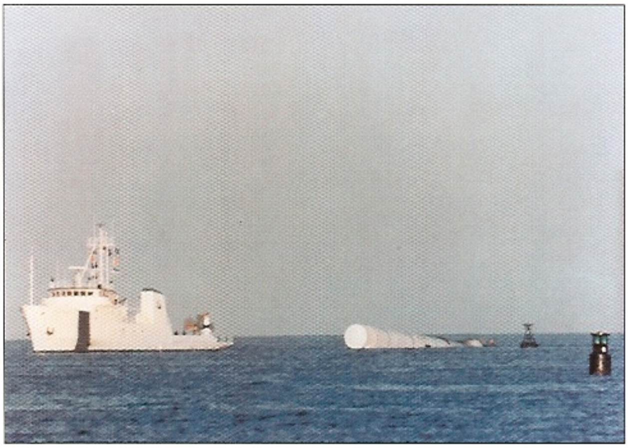
On August 12, 1977, *Enterprise* was released from the 747, gliding to the dry lakebed runway at Edwards AFB. Four drop flights followed. The boat tail fairing used on the first three flights was removed on the fourth flight. On the fifth flight, November 26, 1977, *Enterprise* landed on a concrete runway, simulating a return from space.

Following ALT, NASA began planning a flight program. Initially, the Shuttle was scheduled to fly in 1979. The planned flight research and development missions belatedly started in 1981, but one early operational Shuttle mission was canceled.

Skylab, America's first space station, was launched in 1973. It lacked an engine, and NASA planned a reboost mission using the Shuttle to carry a

Enterprise separates from the 747 carrier aircraft on the fifth and final ALT flight. This was one of two ALT flights made without the aerodynamic boat tail fairing on the Orbiter, and the only free-flight to land on a concrete runway.

propulsion module to Skylab. This mission was abandoned when Skylab reentered the Earth's atmosphere in July 1979 – four years earlier than expected, and two years before the first Shuttle flight.



A SRB recovered at sea following the STS-1 launch is towed back to KSC by the recovery ship *Liberty*. NASA has two SRB recovery ships, *Liberty* and *Freedom*.

Research and development flights

On April 12, 1981, the Space Shuttle, with Orbiter *Columbia*, entered space. John Young, an astronaut who first flew in Gemini and one of 12 men to have walked on the Moon, commanded the flight. His pilot was Robert Crippen, one of seven former "blue," or military, astronauts transferred to NASA in 1969 when MOL was canceled.

Three other "Research and Development" flights followed STS-1. All had two-man crews, as *Columbia* had only two ejection seats. The commanders were veterans of space – typically having last flown on Apollo missions. The exception, Joe Engle, who commanded STS-2, was an X-15 veteran and flew several ALT missions. The pilots were all former MOL (Manned Orbiting Laboratory) astronauts. Until the *Challenger* accident halted flights, the MOL astronauts proved the backbone of the Shuttle program. They provided the pilots for the first six flights and commanded ten of the next 19 missions.

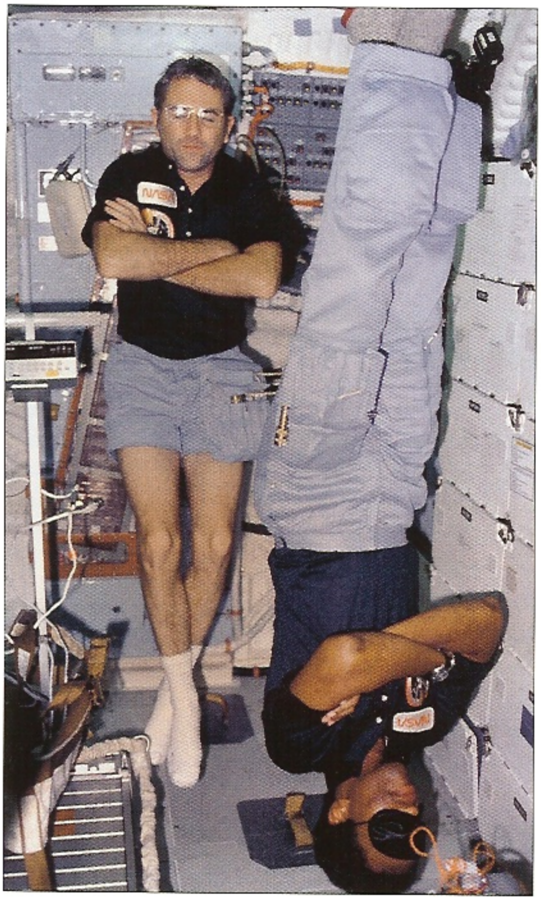
The focus for the R&D phase was testing the Shuttle. All flights carried instruments to measure Orbiter performance in space. The last three R&D flights tested the Shuttle's Remote Manipulator System (RMS), the "robot arm" that was a fixture on future Shuttle missions. These flights also carried attached payloads on pallets, although none required significant crew attention. On STS-4, one of the pallets was a secret Department of Defense payload, carried along with the otherwise unclassified mix of experiments.

Even as Shuttle carried its first military payload, the Air Force was having second thoughts. The program was late and early predictions about its reusability were wildly optimistic. Flying a virtually empty Orbiter, with minimal payload processing, the Shuttle flew only three times in its first year of flights. Congress mandated that the Shuttle would be the United States' only launch vehicle. A backlog of satellites intended for Shuttle launch had accumulated – and worse, the Defense Department would have to compete for Shuttle launch slots.

The military hedged its Shuttle bet, placing orders for expendable launchers long after the time that they initially agreed to stop using them. National security and slips in the Shuttle program justified this supposedly stopgap action.

STS-4 underscored the difficulty of maintaining security within an essentially civilian program. Operational security requires non-sensitive activities to be kept secret, lest those details allow an analyst to determine secrets. (Payloads described in "Military Missions" were determined in that manner.)

Johnson Space Center (JSC), where the missions were planned and developed, was then an open facility visited by hundreds of tourists daily. The secure facility for Shuttle software was in Building 30, the site of JSC's Mission Control Center, one of the Center's most popular tourist



Life aboard the Orbiter. Dick Truly (back) and Guion Bluford (forward) sleeping in the Shuttle middeck. In a weightless environment, up and down are relative concepts.

OPPOSITE, TOP ***Challenger*, captured in orbit by a camera aboard the SPAS free-flyer during STS-7. SPAS, deployed with the RMS (forming a "7" in the front of the payload bay), became the first free-flyer successfully flown from the Orbiter. The two white structures in the aft of the payload bay are cradles for PAM satellites which were also deployed during the mission.**

OPPOSITE, BOTTOM **A standard Shuttle mission in the operational era saw the Orbiter deploy a satellite to a transfer orbit, where a solid fuel upper stage would loft it to its final orbit. Most military Shuttle missions followed this profile.**

attractions. Yet the Air Force could not afford to build a parallel facility in a secure location because their Shuttle budget was being consumed by the construction of SLC-6.

Following STS-4 the Shuttle was declared "operational." The Shuttle remained a developmental and experimental vehicle, but NASA had sold the system as a space "airliner," so despite those realities the operational era began.

The operational era

With STS-5, the Shuttle opened for business. In practice this meant that crew size was increased, the ejection seats were disabled, and the Orbiters began deploying satellites.

The first two operational flights demonstrated the program's immaturity. For the first time the PAM (Payload Assist Module) or IUS (Inertial Upper Stage) were used to send satellites to geostationary orbit. Two communications satellites deployed on STS-5 and a critical Tracking and Data Relay System Satellite (TDRSS) deployed on STS-6 went astray following upper stage failures. Additionally, the first Shuttle-era spacewalk, scheduled for STS-5, was canceled when the spacesuit malfunctioned. It was instead conducted on STS-6.

These problems were typical of those seen in the initial phases of every program pushing technological limits. All were quickly fixed, and not repeated. NASA recovered and refurbished the two communications satellites lost on STS-5, and circularized TDRSS in a usable orbit. In retrospect, the surprise was that there were so few failures, and those that occurred were relatively minor.

For 19 missions, from STS-7 to the final flight of *Challenger* on Mission 51-L, the Shuttle seemed about to deliver on the extravagant promise made for it. It served as a platform to rescue and repair satellites – starting with the Solar Max on 41-C. It provided a "shirtsleeve" environment for space travelers. It transported the ESA Spacelab module – a manned laboratory that fit in the cargo bay – on two missions. It carried as many as eight people into space in one mission.

Columbia was joined by *Challenger*, then *Discovery* and *Atlantis*. Lightweight ETs became available, and lightweight filament-wound SRBs were on track for a first Vandenberg launch in July 1986. The second crawler came on-line in 1983. The second launch pad – allowing two launches in one month – was ready in January 1986.

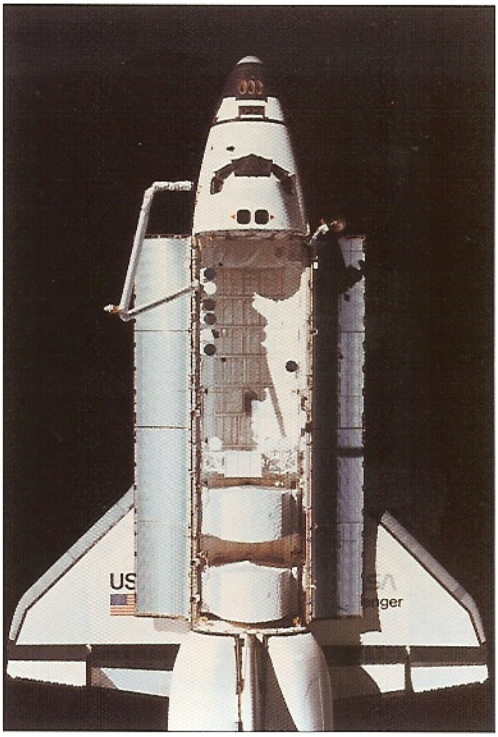
The "operational" era was illusory. There were nine launches in 1985, but only through massive effort. Personnel worked overtime. Equipment was shuffled from one Shuttle to another. Margins were shaved. Missions slipped, were canceled, or reshuffled.

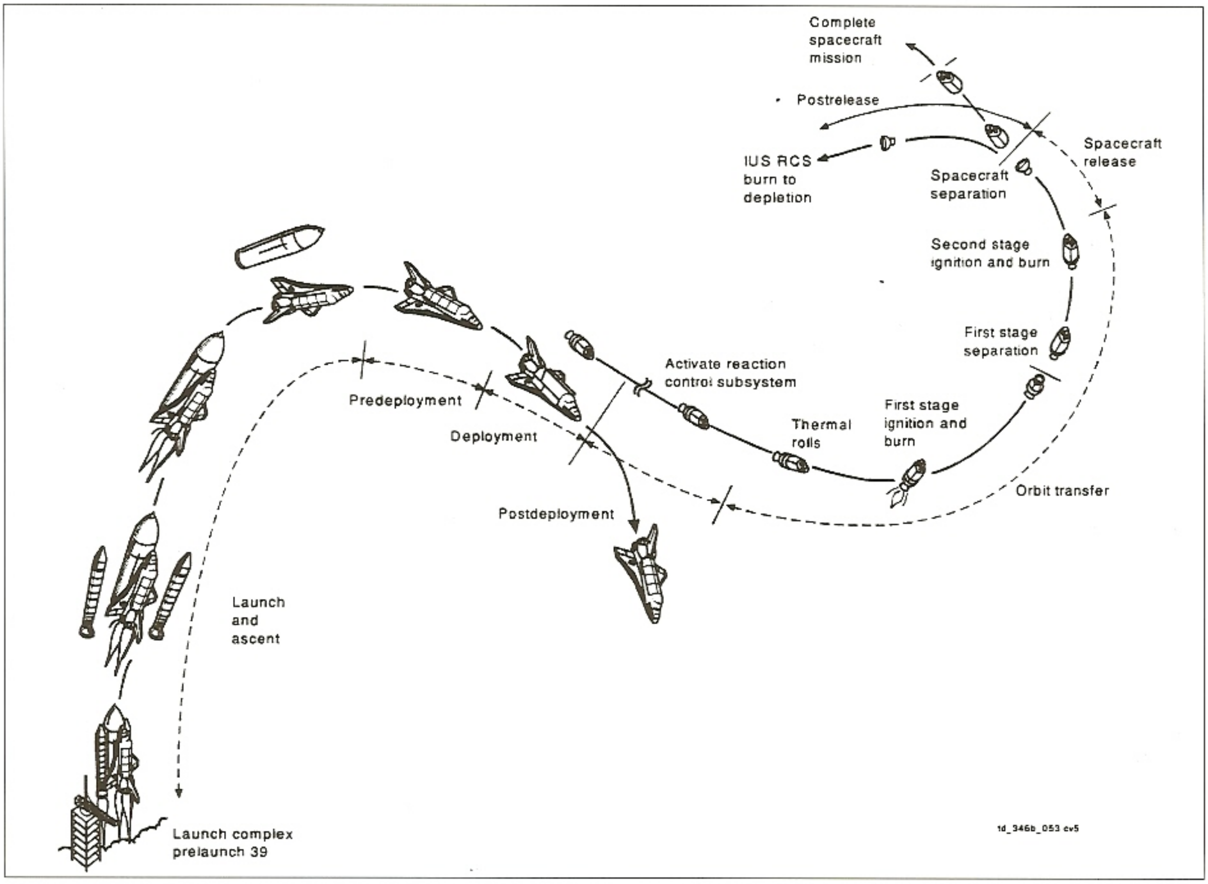
The techno-thriller era of military space never occurred. By 1980, military space was the province of robots. Both the US and USSR orbited unmanned satellites to watch and monitor the activities of their foes, or relay the information captured by other satellites.

The Air Force was using the Shuttle as a simple delivery system. For routine satellite launches Shuttle was less capable, flexible, and reliable than expendables and more expensive. Additionally, launching military satellites to geostationary orbits was routine and unremarkable when launched from expendable boosters. The Air Force saw that a manned launch vehicle turned every military mission into a media circus, with the press speculating wildly about the mission. The press "knew" the Air Force would not use the Shuttle for routine satellite launches – although this is exactly what the Air Force did use it for.

NASA abandoned the "STS" numbering system in 1983 replacing the sequential numbering with a coded collection of numbers and letters. Officially the change was done to identify the launch site – Vandenberg or Kennedy. Unofficially, many believed that the new system was to disguise launch manifest changes caused when problems occurred.

1986 was to have been the year that the Shuttle proved itself. Fifteen missions were planned, including the two Vandenberg launches, and two missions, 61-F and 61-G, scheduled to launch interplanetary probes that used Centaur upper stages.





Challenger **was lost following liftoff of the 25th Shuttle mission. Here, one of the SRBs can be seen flying out of the cloud shrouding the disintegration of the External Tank. Range safety destroyed the SRB shortly after a tracking camera captured this image.**

All four missions were at the edge of the Shuttle's performance ability. All required the SSME to run at 109% of rated power – a jump from the 104% used on standard missions. All had virtually no abort to orbit capability – the ability to put the Orbiter into a lower orbit than planned, so that Mission Control could evaluate options. Instead, if the engines faltered, the Orbiter had to conduct a riskier Abort Once Around (AOA) landing after one revolution, in some cases with a liquid-fueled payload still aboard.

Many flight controllers expected problems on those flights. Instead, trouble came unexpectedly in January, 1986. 51-L began as a routine TDRSS deployment with a schoolteacher as part of *Challenger*'s flight crew. The Shuttle disintegrated 71 seconds after launch.

Return to flight and beyond

The *Challenger* accident forced reevaluation of the Shuttle. Investigations revealed a design flaw – an SRB field joint linking two SRB segments allowed hot gasses to escape the SRB during cold weather. These leaks occurred on several other flights. On the fatal *Challenger* mission, the leak was on the inboard side of the SRB. It cut the strut separating the SRB from the External Tank (ET), allowing the SRB to swing and rupture the ET.

The investigation also revealed serious management problems in NASA. Rather than demonstrating that the Shuttle was safe to fly before proceeding with the launch, on 51-L engineers had to prove that the Shuttle was unsafe to fly to stop the launch. This violated flight rules, but the pressure to keep the Shuttle "operational" had shifted NASA's priorities. The main cause of launch schedule pressure was less the mission scheduled for 51-L (even with the high-visibility "Teacher in Space" aboard). Rather, 51-L had to launch in January so *Challenger* could be prepared for an inflexible interplanetary launch in May 1986.

The physical problems were fixed. The joint was redesigned, and the SRBs are now probably the safest part of the system. Several other minor changes were made to the Shuttle. There was no similar overhaul of NASA's management.

Challenger did force a realistic reappraisal of the Shuttle's capabilities. NASA finally admitted that the Shuttle was uneconomical as a launch system for commercial satellites. Only TDRSS and Orbiter-tended satellites, such as the Hubble Space Telescope (an orbiting optical telescope), would be launched using the Shuttle. The Centaur was deleted as a Shuttle upper stage, as it was too dangerous. Satellites already manifested for the Orbiter would be launched from the Shuttle. New satellites would be launched on expendables. The Shuttle would now focus on science missions.

The Air Force pulled the plug on their involvement with the Shuttle following *Challenger*. The *Challenger* hiatus delayed deployment of several critical satellites, making it difficult to monitor the Soviet Union during a critical phase of what proved to be the first steps of its disintegration. SLC-6 was incomplete in early 1986 and these deficiencies required expensive rework. Post-*Challenger* modifications reduced the Shuttle's payload, rendering it incapable of lofting critical military payloads into a polar orbit from SLC-6. The Shuttle lacked operational flexibility – the Air Force could not quickly schedule a Shuttle mission to respond to a national crisis.

The military decided to use the Shuttle to launch any already-completed satellites originally manifested for the Shuttle. Others would be converted so they could be launched on expendables. Between 1988 and 1992 eight military flights were conducted. Six flights launched satellites. Two others used free-flyers deployed from and retrieved by the Orbiter in military research missions. The last DOD missions, overtaken by the collapse of the Soviet Union, carried unclassified payloads in addition to their military cargo.

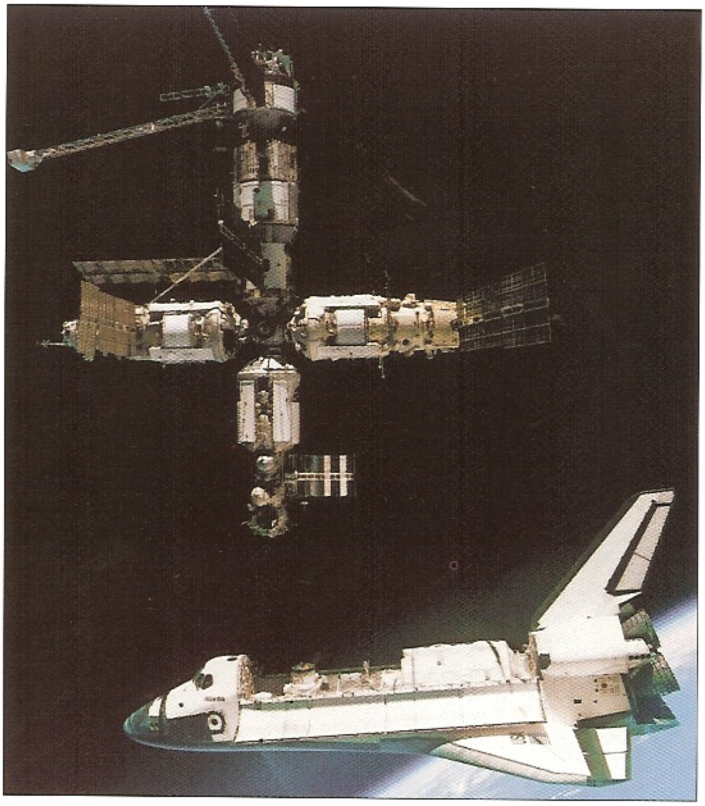
An artist's concept of the Tether Satellite System deployment. An ambitious project, TSS was flown twice on the Orbiter. Neither mission was successful. In the first mission the TSS jammed after reeling out a few hundred feet. In the second mission, the tether broke when the TSS was fully deployed, 20km (12.5 miles) from the Orbiter.

The first flight after *Challenger*, STS-26, returned to the old numbering system, as if announcing the end of the operational era. It carried a replacement for the TDRSS lost on 51-L. Interplanetary probes scheduled for Centaur missions were launched with an IUS upper stage. STS-30 carried the *Magellan* probe which was sent to Venus, and STS-34 launched *Galileo* to Jupiter. Since the IUS had less thrust than the Centaur, *Galileo* used gravitational assists from Venus, then Earth, to reach Jupiter. STS-32, in January 1990, retrieved the Long Duration Exposure Facility – placed in orbit by *Challenger*, but stranded by the launch hiatus – literally months before it would have reentered the atmosphere.

This period also saw several other pioneering missions, including the deployment of the Hubble Space Telescope and Compton (Infrared telescope) observatories, and two tethered satellite missions, where the Orbiter reeled a subsatellite out on a 20km(12.5 mile) tether.

International Space Station

Beginning in the early 1990s the Shuttle gained a new mission, building an orbital space station, and thus returned to NASA's original intention for the vehicle. As with the development of the Shuttle, the development of the space station was neither straightforward, nor untroubled. Announced as an objective by President Reagan after *Challenger*, in its original incarnation, the space station was solely a United States affair, Space Station *Freedom*. Eventually, *Freedom* included participation from ESA, NASDA (the Japanese space agency), and the Soviets.



ABOVE ***Atlantis*** **departure from *Mir* in 1996. This photo, taken from a Soyuz TM, as it approached *Mir*, is a rare side view of the Orbiter in space. Normally the Orbiter approaches other orbital vehicles with the payload bay facing the target.**

In 1992 *Freedom* was suspended in favor of a new design. The primary feature of the new plan was greater Russian participation. Following the collapse of the Soviet Union in 1991, the Russian space agency lost most of its funding. A partnership with the United States was one way to maintain a Russian space capability. While the USA had backed away from orbital space stations following *Skylab* in 1973, Russia launched a series of *Salyut* and *Mir* space stations throughout a 30-year period. Long-duration on-orbit experience was one area where the Russians outperformed the United States in space, and both gained from the partnership.

Initially, starting in the middle 1990s, Shuttle participation in the space station program consisted of trips to the Russian *Mir* space station. These were advertised as a way of familiarizing both nations with the processes of the other. In reality, the first elements of the new space station – called the International Space Station (ISS) – would not be ready until 1998. Both nations wanted a mission for their manned space programs until ISS was ready for assembly. While some benefits were gained by the nine Shuttle visits to *Mir*, these flights preserved *Mir* past its service life.

Finally, in February 1998, STS-88 delivered the first of nearly 50 packages that would constitute the ISS. Of the 19 Shuttle missions since STS-88, 14 have been devoted to the ISS. The most recent flew in November 2002. Virtually all of the scheduled future Shuttle missions,

RIGHT **All that remains. Recovered debris from *Columbia* in a hangar at KSC. Following the loss of *Columbia* in February 2003, NASA scoured the Texas countryside for pieces of the Orbiter as part of the effort to determine what caused the breakup.**

with the exception of the final Hubble Space Telescope servicing mission, go to ISS.

The loss of *Columbia* in 2002 during STS-107 – a stand-alone Spacelab mission – may accelerate the exclusive use of the Shuttle for ISS missions. The Orbiter was lost after the Thermal Protection System (TPS) was damaged during liftoff. A tile inspection system will fly on all future missions, but on ISS missions ISS can serve as a "lifeboat" for the Orbiter's crew until either the TPS is repaired or a rescue mission can be launched.

Regardless of the future, the Shuttle has a remarkable record. Conceived during the Cold War as an Apollo follow-on, it may be remembered more for what it failed to accomplish rather than for its real achievements. If it failed as a space bus and an orbital warplane, it has carried more humans into space than any other launch system. It remains the world's only reusable space system.

Military missions

Ten military missions were flown on the Space Shuttle. Four other military missions planned for Kennedy launch were canceled, either due to payload problems or following the *Challenger* disaster. Seven polar missions were planned using the Vandenberg launch site. All were scheduled after January 1986, and canceled after *Challenger*, only two were under active development before cancellation.

Flown Military Missions

51-C
Vehicle: *Discovery*
Orbit: 28.5° inclination, 220nmi altitude
Crew: 5
Launch: January 24, 1985, Pad 39-A
Landing: January 27, 1985, KSC Runway 15

Mission patches for the ten Department of Defense Shuttle flights. From left to right: Top row: 51-C, 51-J, STS-27. Middle row: STS-28, STS-33, STS-36, STS-38. Bottom row: STS-39, STS-44, STS-53.

The first dedicated military mission, 51-C carried a classified cargo: a Magnum model geostationary electronic intelligence satellite. The mission – a routine delivery of a satellite to orbit using an IUS upper stage – highlighted the problem of military use of the Orbiter. A satellite that could have been quietly launched on an expendable was launched with the publicity that attended every NASA manned launch.

51-J
Vehicle: *Atlantis*
Orbit: 28.5° inclination, 319nmi altitude
Crew: 5
Launch: October 3, 1985, Pad 39-A
Landing: October 7, 1985, Edwards AFB Runway 23
The first launch of the Orbiter *Atlantis*, this second Defense Department mission deployed two DSCS-III military communications satellites for the United States Air Force, using a single IUS to boost both to geostationary orbits.

STS-27
Vehicle: *Atlantis*
Orbit: 57° inclination, 220nmi altitude
Crew: 5
Launch: December 2, 1988, Pad 39-B
Landing: December 6, 1988, Edwards AFB Runway 17
The first military mission following *Challenger*, STS-27 deployed a Lacrosse reconnaissance satellite. Lacrosse uses side-looking radar for an all-weather capability. It does not have a booster stage. This Lacrosse placed into orbit by *Atlantis* was the lowest of four Lacrosse satellites.

STS-28
Vehicle: *Columbia*
Orbit: 57° inclination, 166nmi altitude
Crew: 5
Launch: August 8, 1989, Pad 39-B
Landing: August 13, 1989, Edwards AFB Runway 17
STS-28 deployed a subsatellite ferret (SSF) and SDS-2 communications satellite. The SSF is believed to be a one-off design, produced to test the COBRA BRASS imaging system currently used for optical reconnaissance. SDS-2 is a high-inclination communications satellite in a highly elliptical "Molniya" orbit used to relay secure communications from other military satellites to prevent interception.

STS-33
Vehicle: *Discovery*
Orbit: 28.5° inclination, 302nmi altitude
Crew: 5
Launch: November 22, 1989, Pad 39-B
Landing: November 27, 1989, Edwards AFB Runway 4
STS-33 deployed the second Magnum model geostationary electronic intelligence satellite. Once deployed, it was boosted into a geostationary orbit by an IUS upper stage. This mission was a night launch, the first DoD night launch and the third program night launch.

A night launch of the Shuttle, as seen from the Shuttle Training Aircraft as it flew near the pad. This image captures the launch of STS-33, one of the ten military Shuttle missions.

STS-36
Vehicle: *Atlantis*
Orbit: 62° inclination, 132nmi altitude
Crew: 5
Launch: February 28, 1990, Pad 39-A
Landing: March 4, 1990, Edwards AFB Runway 23
The mission for which the Shuttle had been designed: STS-36 deployed the KH-12 reconnaissance satellite. This payload had defined the size of the cargo bay, and the maximum capacity of the Orbiter. The satellite was intended for a sun-synchronous orbit (97.7° inclination), possible only when launched from Vandenberg. Subsequent KH-12s were redesigned for launch from Titan-4s, although the first KH-12 was nearly complete when this decision was made. Combined with the age of then-available KH-11 satellites, this KH-12 was deployed at a sub-optimal inclination. Even with a 62°-inclination launch, the Orbiter was at the edge of its performance limits in placing this 43,130lb (19,600kg) payload in orbit.

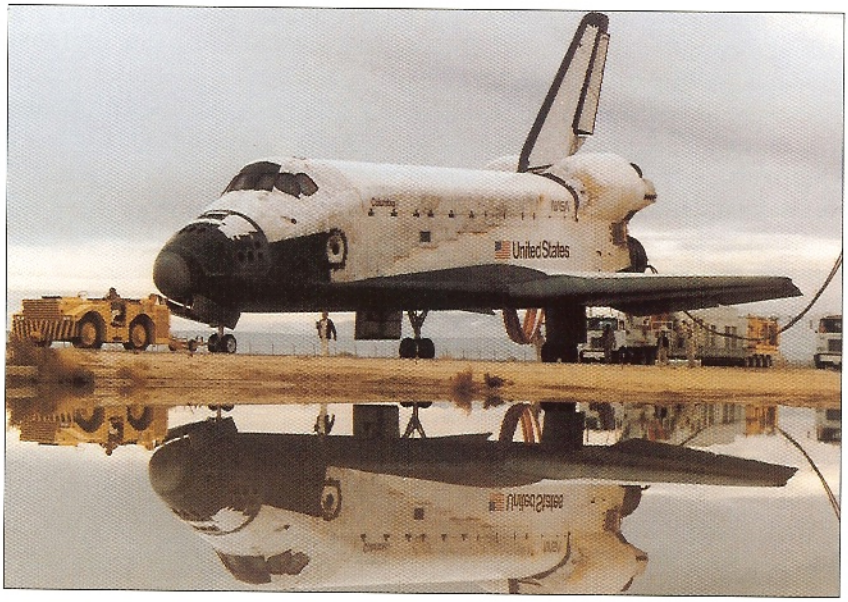
STS-38
Vehicle: *Atlantis*
Orbit: 28.5° inclination, 142nmi altitude
Crew: 5
Launch November 15, 1990, Pad 39-A
Landing: November 20, 1990, KSC Runway 33
The third launch of a Magnum model geostationary electronic intelligence satellite.

STS-39
Vehicle: *Discovery*
Orbit: 57° inclination, 140nmi altitude
Crew: 5
Launch April 28, 1991, Pad 39-A
Landing: May 6, 1991, KSC Runway 15

A dedicated Department of Defense mission, STS-39 contained mostly unclassified payloads. These included Air Force Program-675 (AFP675); Infrared Background Signature Survey (IBSS) with Critical Ionization Velocity (CIV), Chemical Release Observation (CRO) and Shuttle Pallet Satellite-II (SPAS-II) experiments; and Space Test Payload-1 (STP-1). Classified payloads consisted of Multi-Purpose Release Canister (MPEC). Also aboard was Radiation Monitoring Equipment III (RME III) and Cloud Logic to Optimize Use of Defense Systems-IA (CLOUDS-I).

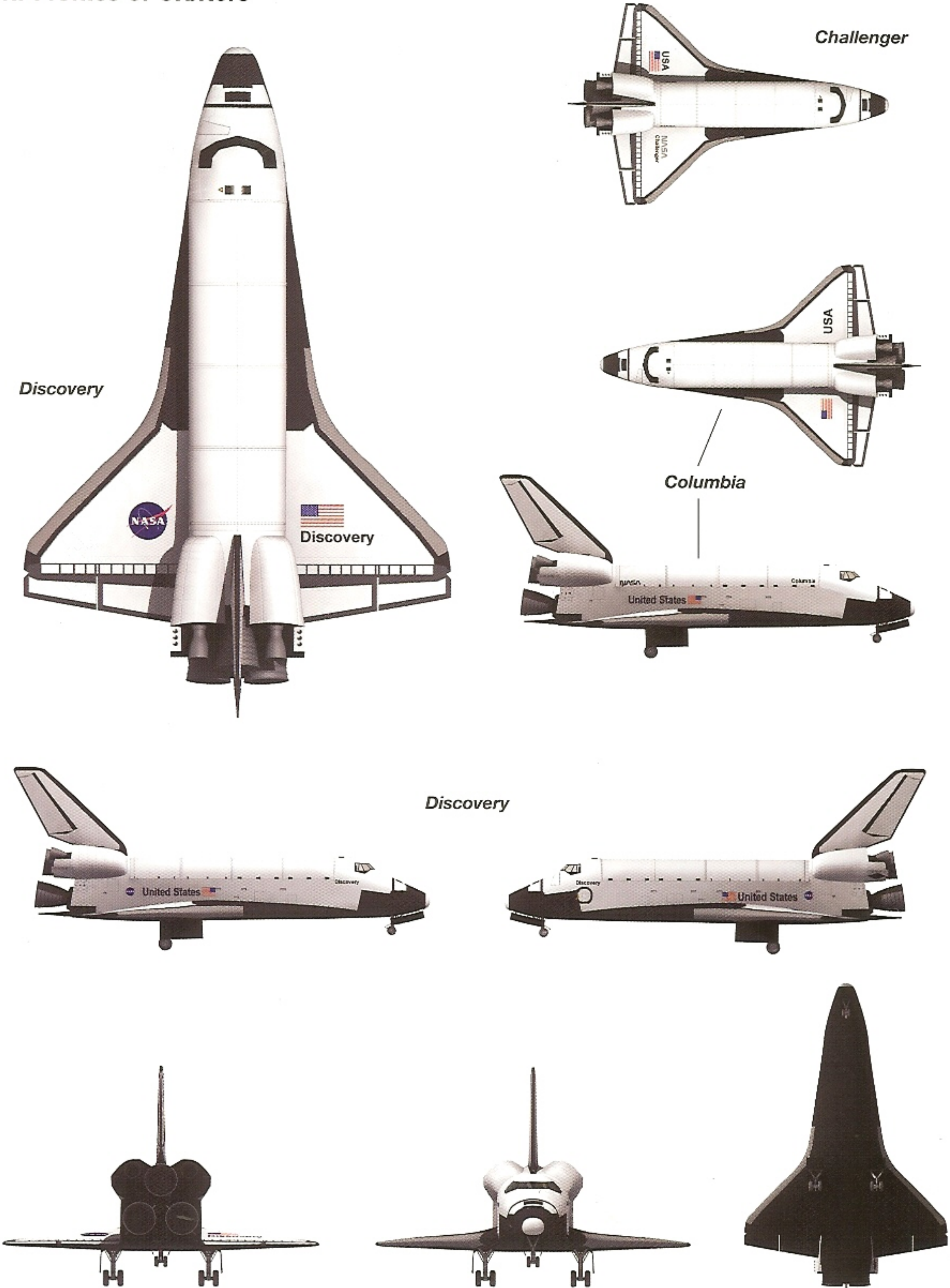
STS-44
Vehicle: *Discovery*
Orbit: 28.5° inclination, 197nmi altitude
Crew: 5
Launch: November 24, 1991, Pad 39-A
Landing: December 1, 1991, Edwards AFB Runway 5
Another dedicated Department of Defense mission with unclassified payloads. The Orbiter deployed a Defense Support Program (DSP) satellite, an early-warning satellite. It was boosted into a geosynchronous orbit with an IUS. It also carried numerous cargo bay and middeck payloads.

STS-53
Vehicle: *Discovery*
Orbit: 57° inclination, 174nmi altitude
Crew: 5
Launch: December 2, 1992, Pad 39-A
Landing: December 9, 1992, Edwards AFB Runway 22
The final military mission deployed another SDS-2 satellite, USA 89. Secondary payloads in the cargo bay included the Orbital Debris Radar Calibration Spheres (ODERACS) and the combined Shuttle Glow Experiment/Cryogenic Heat Pipe Experiment (GCP).



Columbia at Edwards AFB being towed to the Shuttle Processing Area at NASA's Dryden Flight Research Center following landing on STS-5. Orbiter landing servicing vehicles can be seen behind the Orbiter, while a tug pulls the Orbiter.

A: Profiles of Orbiters

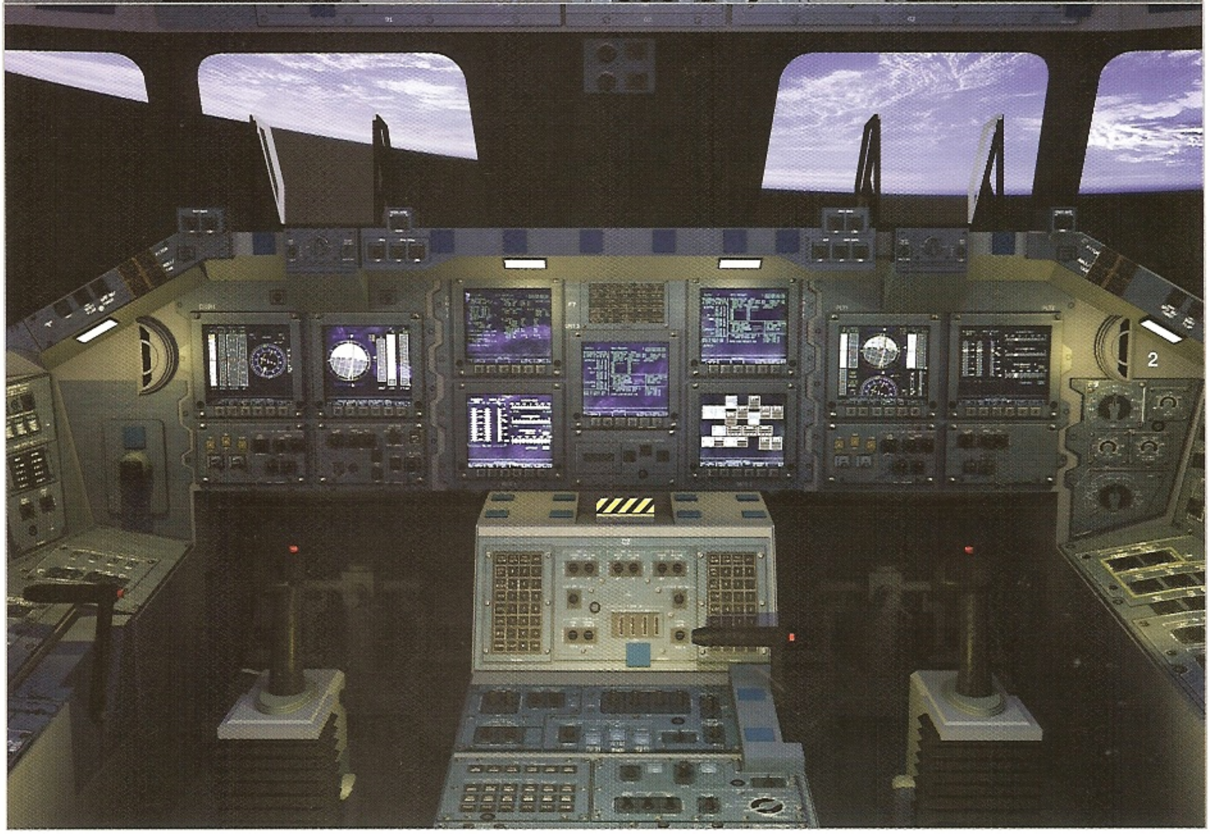


A

B: STS-1 launch

C: Flight deck/cockpit

1



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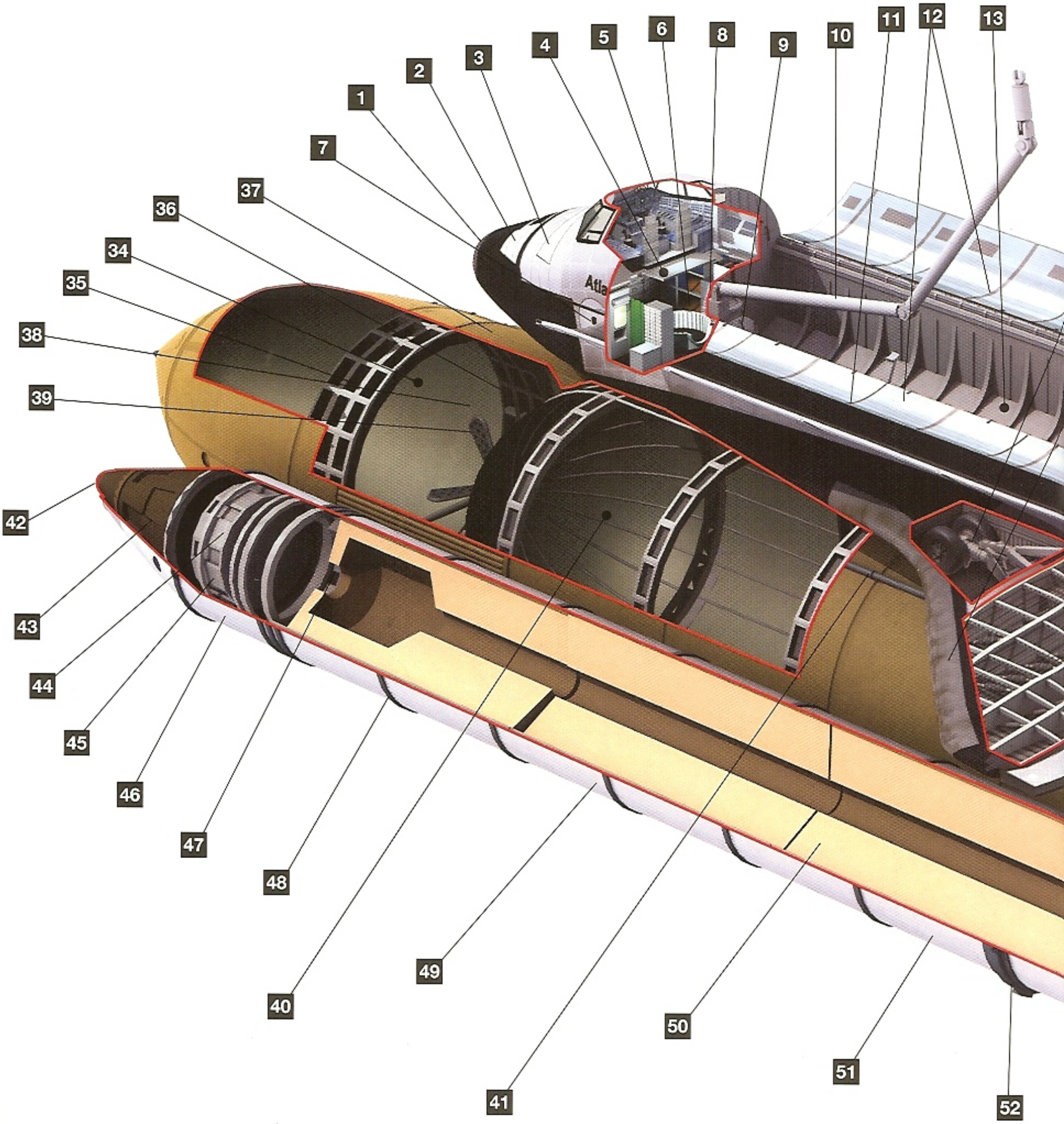
C

D: CUTAWAY OF SHUTTLE STACK



KEY

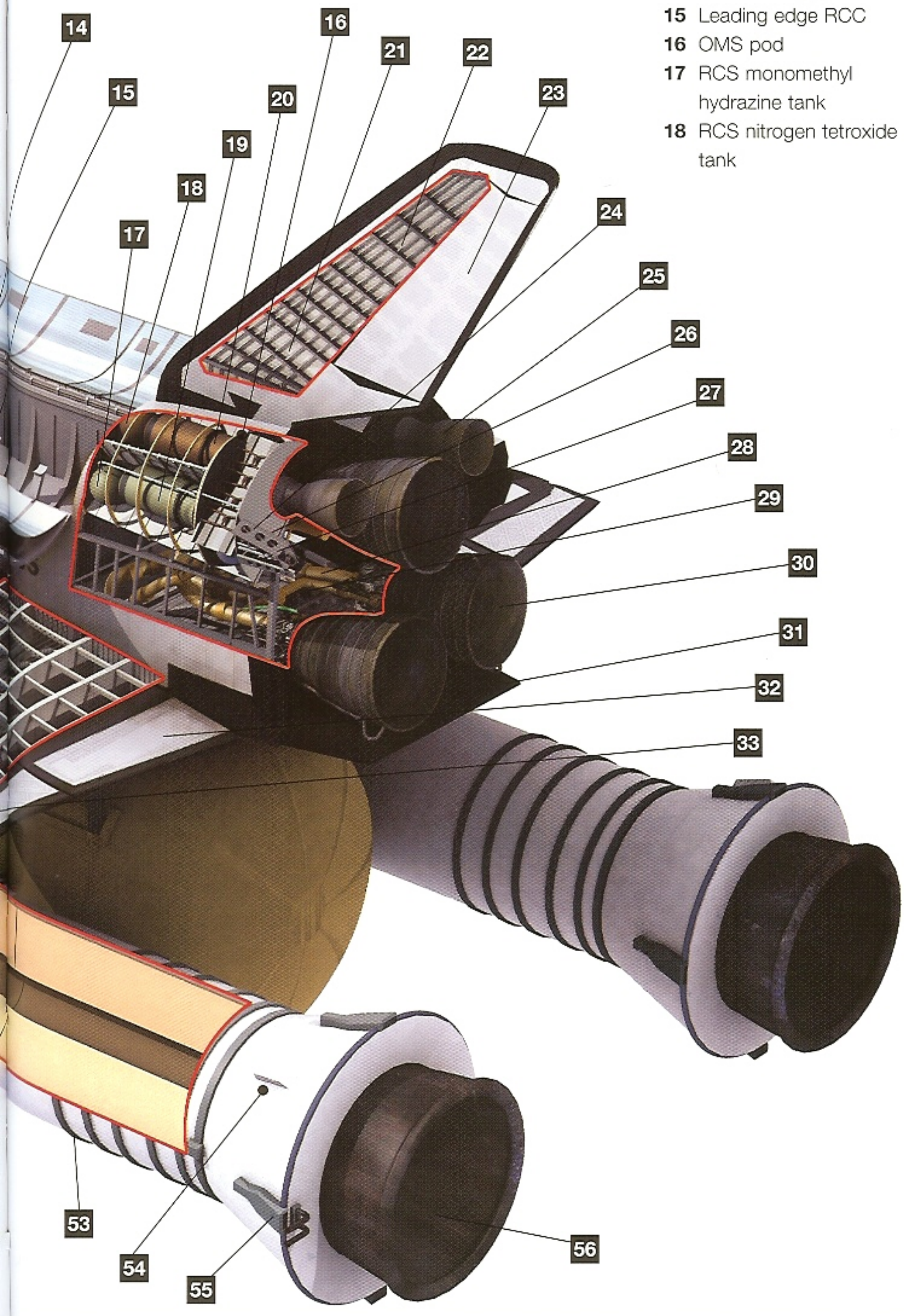
1 Reinforced Carbon-Carbon (RCC) nose
2 Forward Reaction Control System
3 Star tracker
4 Crew module
5 Flight deck
6 Mid-deck
7 Hatch
8 Mid-deck lockers
9 Airlock
10 RMS
11 Payload bay doors
12 Radiators
13 Payload bay
14 Main landing gear
15 Leading edge RCC
16 OMS pod
17 RCS monomethyl hydrazine tank
18 RCS nitrogen tetroxide tank
19 OMS monomethyl hydrazine tank
20 OMS nitrogen tetroxide tank
21 Auxiliary power unit
22 Rudder
23 Speed brake
24 Aft RCS unit
25 OMS engine
26 Primary RCS thruster
27 Vernier RCS thruster
28 Liquid oxygen fuel line
29 Liquid hydrogen fuel line
30 Main engine bell
31 Outer elevon
32 Inner elevon
33 Body flap

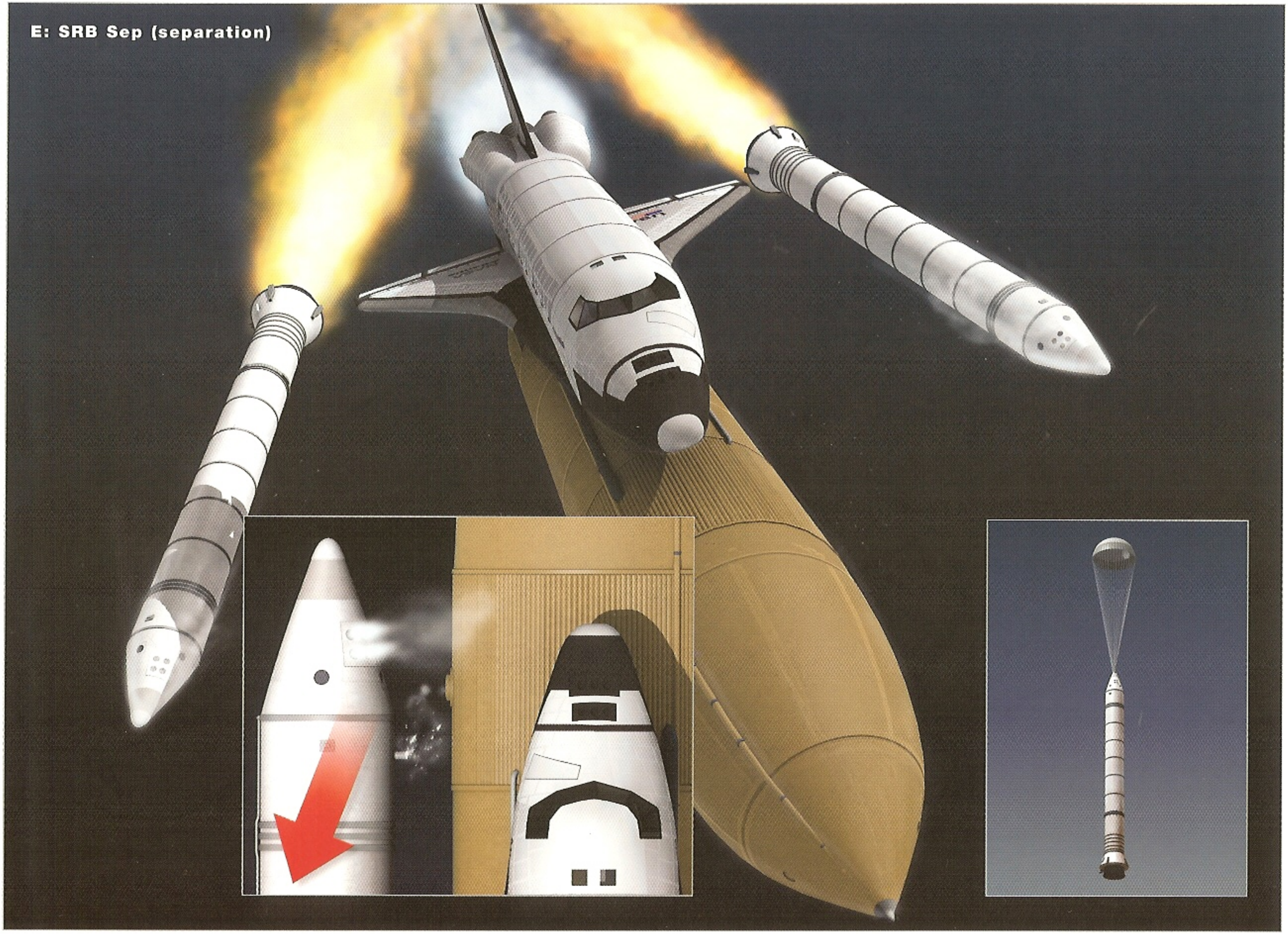
External tank

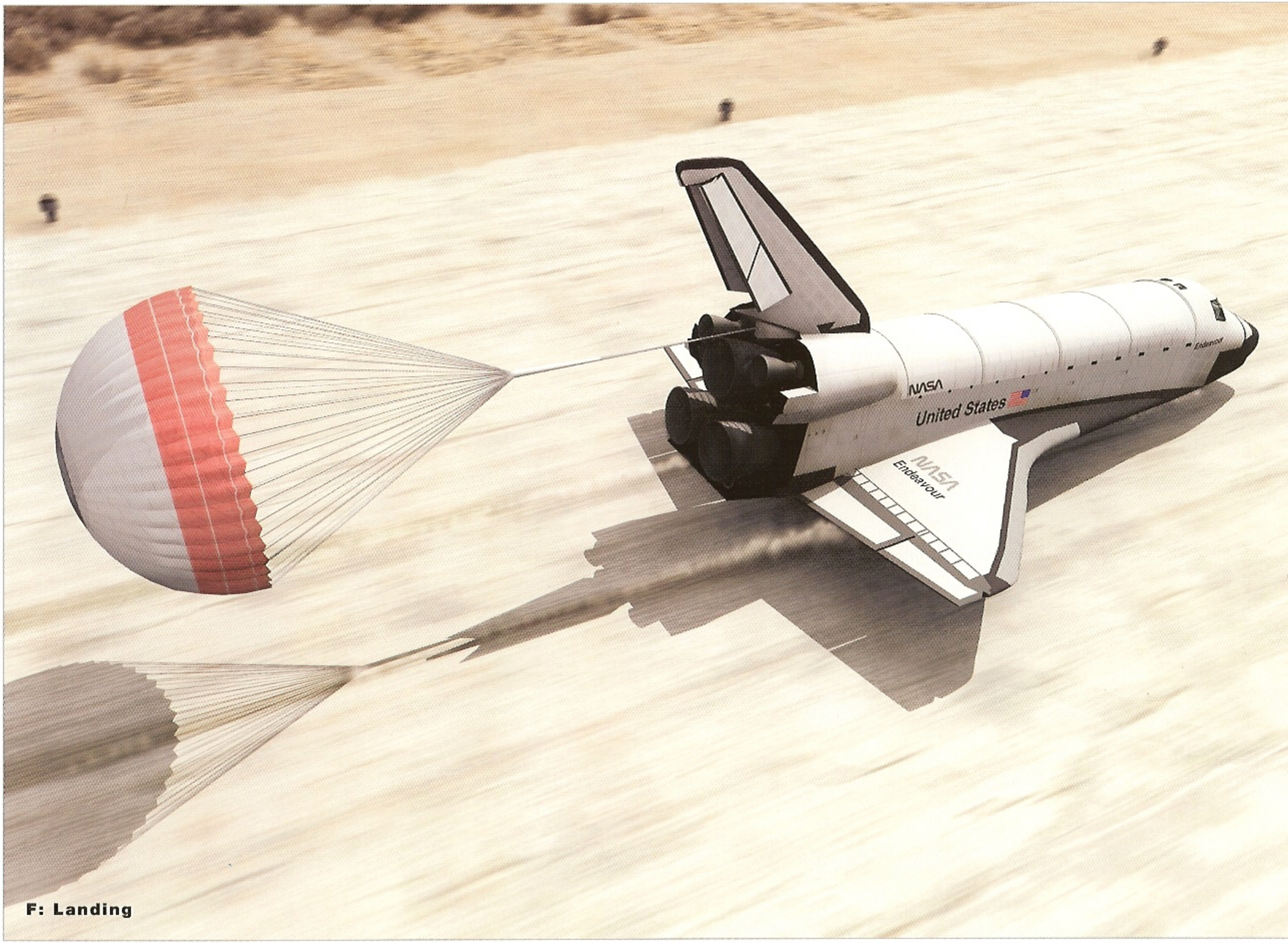
34 Liquid oxygen tank
35 Forward slosh baffle
36 Intertank
37 Thrust panel
38 SRB beam
39 Anti-vortex baffles
40 Liquid hydrogen tank
41 Fuel lines

Solid rocket boosters

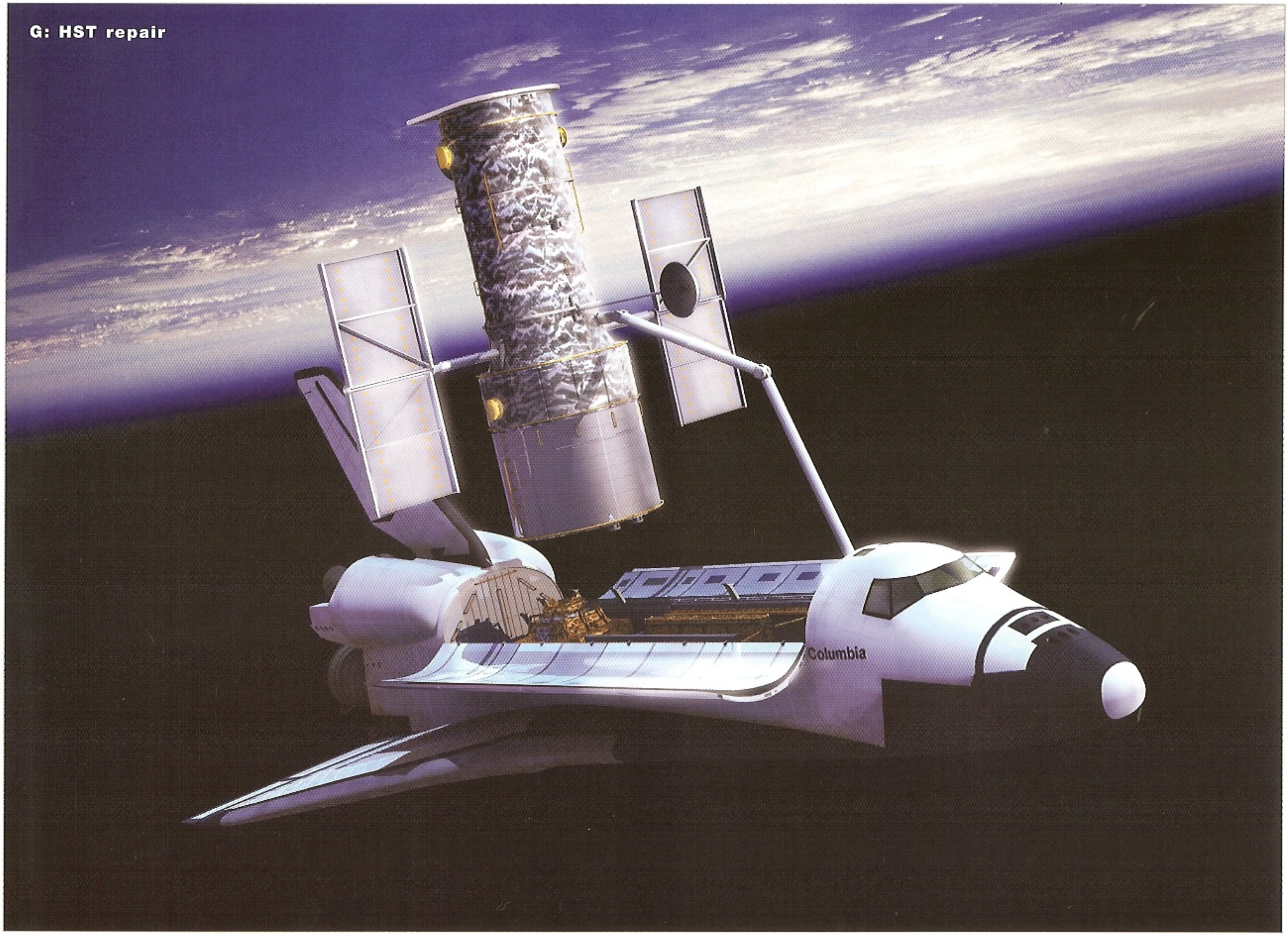
42 Nose cap with drogue chute
43 Frustrum with three main parachutes
44 Camera pod
45 Avionics
46 Forward skirt
47 Igniter
48 Forward segment
49 Forward mid segment
50 Solid propellant
51 Aft mid segment
52 Attach ring
53 Aft segment (with nozzle)
54 Aft skirt
55 Booster holddown posts (4)
56 Nozzle extension




E: SRB Sep (separation)



F: Landing



G: HST repair

The mission that never was. The crew of 62-A, the first planned Vandenberg flight, poses for its official mission photo. In the background, the never-used SLC-6 launch complex can be seen. The Orbiter is probably *Enterprise*, used for SLC-6 fit tests.

Mid-deck experiments included Microcapsules in Space (MIS-l); Space Tissue Loss (STL); Visual Function Tester (VFT-2); Cosmic Radiation Effects and Activation Monitor (CREAM); Radiation Monitoring Equipment (RME-III); Fluid Acquisition and Resupply Experiment (FARE); Hand-held, Earth-oriented, Real-time, Cooperative, User-friendly, Location-targeting and Environmental System (HERCULES); Battlefield Laser Acquisition Sensor Test (BLAST); and the Cloud Logic to Optimize Use of Defense Systems (CLOUDS).

Cancelled Military Missions

STS-10 and 41-E, and 41-H

These were military flights originally scheduled for 1984 and 1985, which were canceled due to IUS development problems and left the Air Force with no means of launching scheduled payloads in orbit. It is likely that the payloads flown in the first four Defense Department missions were originally intended for these flights.

62-A, 62-B

These were the first of nearly a dozen launches scheduled from Vandenberg Air Force Base, using the SLC-6 complex. They may be the only two that reached the planning stage. 62-A was scheduled for July 1986, and 62-B for late September. 62-A had a crew of six commanded by Robert Crippen (the pilot on STS-1). The mission would probably have launched a TEAL RUBY sensor test satellite, with the first KH-12 being lofted in 62-B in September. Problems with SLC-6 probably caused both of these missions to slip and they were abandoned completely following *Challenger* when SLC-6 was abandoned, and all Vandenberg flights scrubbed.

61-N

A KSC DOD mission scheduled for September 1986, it was canceled following *Challenger*. It would probably have carried one of the cargoes launched in STS-27 or STS-28.

ORBITER VEHICLES

OV-101 *Enterprise*

The first Shuttle Orbiter, OV-101 was originally to have been named *Constitution*, to celebrate the American bicentennial and to honor "Old Ironside," the sailing frigate *Constitution*. The name was changed when fans of the science fiction show *Star Trek* petitioned to change the name to *Enterprise*, the starship in the TV show. President Gerald Ford had served in the US Navy in the Pacific during World War II, and it is likely that he viewed the name change as honoring another notable *Enterprise*, the aircraft carrier CV-6, which fought through the war.

Enterprise was rolled out on September 17, 1976, at Rockwell International's Palmdale assembly plant. On January 31, 1977, it was towed overland 36 miles to the Dryden Flight Research Center in California, where it was used in the Approach and Landing Tests.

Enterprise flew 17 times during the nine-month ALT program. It initially flew five unmanned captive flights atop a 747 carrier aircraft, testing structural integrity and handling characteristics. This was followed by three manned captive flights with a two-man crew in the Orbiter to test the flight control system before the drop tests. This included a dress rehearsal for the drop tests.

Five more flights ensued when *Enterprise* was released from the 747 and glided to a landing at Edwards Air Force Base, adjacent to Dryden. These tests verified that the Orbiter would perform as expected during reentry. On the final two free-flight tests, the tail cone (known as a boat tail), normally used when the Orbiter was carried by the 747 to reduce turbulence, was removed. The Orbiter was dropped with three simulated SSME engine bells and two simulated OMS engine bells to test its performance when these were aerodynamically exposed. The final drop test simulated a return from space, as closely as possible, with *Enterprise* landing on the concrete runway, instead of the dry lake bed as had been done for the other tests. The final four ALT flights tested ferrying the Orbiter with the 747.

Following the ALT flights, *Enterprise* was flown to Marshall Space Flight Center in Alabama, arriving on March 13, 1978. Mated with an External Tank and two Solid Rocket Boosters, it spent the next year in vertical vibration tests.

On April 10, 1979, *Enterprise* was ferried to the Kennedy Space Center, mated with an ET and two SRBs, and used in a series of fit tests involving the refurbished Pad 39-A. This also enabled ground crews to practice launch preparation procedures.

Transferred back to Dryden on August 16, 1979, *Enterprise* was returned to Palmdale. Initial plans had called for *Enterprise* to be converted to space flight status, and follow *Columbia* into space. Partly as a result of *Enterprise*'s tests, the design of the Orbiter had evolved, and while similar in appearance, *Columbia* and its sisters incorporated significant structural and internal improvements. Due to the cost of retrofitting *Enterprise* to flight status, NASA decided to convert a test article into a flying Orbiter, and retire *Enterprise*.

Enterprise about to enter the Heading Alignment Circle (HAC) preparatory to landing at Edwards AFB on the third Approach and Landing Test free flight.

Between 1981 and 1984 *Enterprise* was ferried to various fairs and air shows in Europe and North America for publicity purposes. In November 1984 *Enterprise* was taken to Vandenberg AFB, where it was used for fit tests at SLC-6, the intended polar mission launch site. On Nov. 18, 1985, *Enterprise* was flown to Dulles Airport, Washington, D.C., and sent to the Smithsonian Institution for display in the Air and Space Museum. Following the *Columbia* accident, components from *Enterprise* were removed and used in the accident investigation.

OV-102 *Columbia*

The first Orbiter in space, *Columbia* was named after a sloop, *Columbia*, which discovered the Columbia River in 1792. That *Columbia* was also the first ship from the United States to complete a circumnavigation of the world.

Columbia rolled out of the Palmdale Assembly plant on March 8, 1979, and was ferried to KSC later that month. While originally intended to first fly in 1979, lagging development of key systems such as the main engines and thermal protection system kept *Columbia* grounded for the next two years. *Columbia* was used for integrated testing in 1980 and 1981, culminating in a flight readiness firing that certified the SSMEs on March 20, 1981.

Following the first launch, on April 12, 1981 (STS-1), *Columbia* flew the next four missions before being joined by *Challenger*. This included STS-3, the only Shuttle mission to land at White Sands in New Mexico, and STS-5, the first "operational" Shuttle mission, and the first with a crew greater than two, carrying five astronauts, then a record.

Following STS-5, in November 1982, *Columbia* was sent to Palmdale, where the ejection seats for the commander and pilot – used during the flight test missions (STS-1 through 4) – were removed, and the vehicle modified to carry laboratory modules.

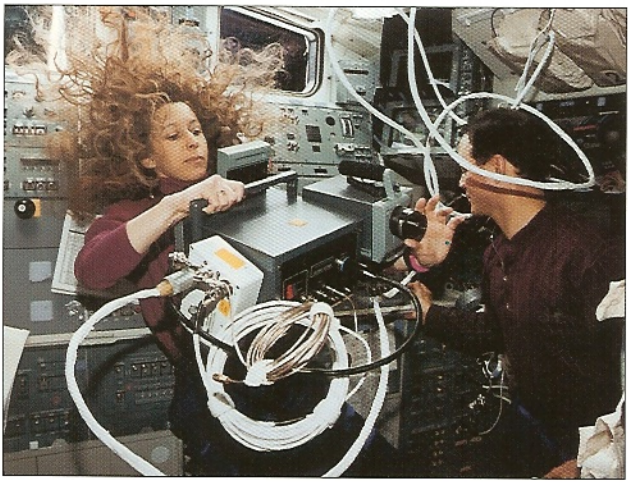
Columbia flew two more missions before the *Challenger* hiatus: STS-9, the first Spacelab mission; and 61-C, an extended-duration mission combining satellite deployments with space science research.

Following return to flight, *Columbia* flew another 21 missions. While some were satellite deployments, *Columbia* flew the bulk of the Spacelab and Spacehab missions, missions with a habitable laboratory in the cargo bay. Of the 17 missions using a laboratory module, *Columbia* flew 12, and 11 of the 13 following the *Challenger* hiatus.

One reason for this was, as the heaviest Orbiter, *Columbia* was ill-suited for missions which stretched Shuttle's performance abilities. It could not have been launched from Vandenberg, nor was it ever assigned a payload involving a Centaur or IUS upper stage, and only flew one military mission.

Columbia was initially incapable of reaching the International Space Station (ISS), although a refit in 1999 rectified this, and it was scheduled for a Space Station resupply flight in 2003. Alone of the active Orbiter fleet, *Columbia* was never sent to the ISS. Since the launch of the first ISS element in December 1998, *Columbia* was used for non-ISS missions, including a Hubble Space Telescope servicing mission.

Columbia had three major refits following the 1983 overhaul. In 1991 it went through an overhaul at Palmdale. Fifty changes were made to *Columbia*, including many recommended in the wake of the loss of *Challenger*. These included the addition of a drag chute, carbon brakes,



In space, no one has a good hair day. Astronaut Marsha Ivins wrestles with a thermal imaging camera during the 14-day STS-62 mission. She is near the aft station on the flight deck. The puffy appearance of her face is characteristic of someone in zero gravity over a long period.

enhanced nose-wheel steering, and enhancements to the Thermal Protection System.

In 1994 *Columbia* entered its first Orbiter Maintenance Down Period (OMDP) – a major overhaul and maintenance process. Over 90 modifications and upgrades were made during this process, including improvements to the landing gear thermal barrier and tire pressure monitoring.

In 1999 *Columbia* underwent a second OMDP. The structure was lightened, allowing it to carry a payload to the ISS. *Columbia* became the second Orbiter, after *Atlantis*, to get the new "glass-cockpit" crew displays (see Plate C for a fuller discussion of the glass cockpit).

Columbia was lost on February 1, 2003. The wing leading-edge of the Thermal Protection System (TPS) was damaged during liftoff. On reentry, heating caused the aluminum structure to fail and *Columbia* broke up. The crew of seven, including two women and a guest astronaut from Israel, died.

OV-099 *Challenger*

Challenger was named after HMS *Challenger*, a Royal Navy research vessel that circumnavigated the globe on a scientific expedition during the 1870s. When construction began on what would become *Challenger* in 1975, it was intended as a high-fidelity Structural Test Assembly (STA-099), to be used for stress and vibration testing. Rockwell delivered the completed airframe to Lockheed in February 1978. For 11 months STA-099 underwent testing simulating the stresses and vibrations associated with all mission phases, from liftoff to landing.

As STA-099 was completing testing, NASA realized converting *Enterprise* (OV-101) to flight status would be cost-prohibitive and contracts for follow-on Orbiters had not yet been awarded. Without *Enterprise, Columbia* would be the sole Orbiter until 1983. Since STA-099 was built from flight components, NASA decided to convert it to flight status. A supplemental contract for the conversion was awarded to Rockwell International on January 5, 1979, and Rockwell began construction of the crew cabin – an item originally boilerplated when STA-099 was a test article.

NASA skipped a final round of structural testing that would have damaged the airframe, and STA-099 was returned to Palmdale in November 1979 for conversion to a flight article. Retaining its item number – 099 – it then became Orbital Vehicle 099 or OV-099. The forward fuselage was split and the dummy crew compartment replaced with a new, operational compartment. The wing structure was modified – reinforced and lightened, using the results from the structural testing done on it when it was a test article. The Orbiter that emerged from Palmdale in June 1982 was stronger and 2,900lb lighter than *Columbia*.

Challenger was modified at KSC in 1983. It was one of two Orbiters scheduled to deploy the liquid-fueled Centaur upper stage in spring 1986. Plumbing was added to allow the fuel to be dumped in an abort situation, and controls and instrumentation were added to the aft station to allow the stage to be monitored and controlled.

Challenger's career was brief but spectacular. It achieved several notable program firsts, including:

- The first space walk during the Shuttle program (STS-6)
- Carrying the first American woman in space (STS-7)
- The first free-flying satellite deployed and retrieved during the Shuttle program (SPAS-1, during STS-7),
- First use of the Remote Manipulator System (RMS, during STS-7)
- First night launch and landing (STS-8)
- First untethered spacewalk using the Manned Maneuvering Unit (41-B)
- First KSC landing (41-B)
- Deploying the first satellite to return to orbit (the SPAS pallet flown during STS-7, again flew on 41-B)
- First on-orbit satellite repair (Solar Max, during 41-C)
- Carrying the first woman to walk in space (Katheryn Sullivan, in 41-G)
- First eight-person crew (61-A).

Challenger achieved two less notable firsts. It was the first Orbiter to use an abort launch: 51-F did an abort-to-orbit when one of its SSMEs shut down during the ascent, after a faulty sensor reading. When a second engine was erroneously flagged as running hot *Challenger* nearly became the first Orbiter to do an abort-once-around. The flight controller correctly assessed the problem as a bad sensor, not a bad engine, and overrode the shut-down command. *Challenger* completed the mission from a lower orbit than planned.

Challenger was also the first Orbiter lost. Hot gasses leaking from the SRB melted the strut holding the SRB to the ET. The SRB struck the ET, rupturing the liquid hydrogen tank. Thrown off the stack as the ET collapsed, *Challenger* disintegrated, torn apart by the airflow. All seven crew members aboard died.

OV-103 *Discovery*

The third orbital Orbiter, *Discovery* was named after one of two ships that accompanied the explorer Captain James Cook on his 1776–79 voyage when he discovered the Hawaiian Islands and explored Alaska. The name also honors several other famous ships named *Discovery*, including one sailed by Henry Hudson, and two used by the Royal Geographic Society used to explore the Polar Regions.

Construction began on *Discovery* in 1979, at Rockwell's Palmdale plant. Final assembly was completed on February 25, 1983. Rollout to Dryden following checkout and acceptance testing occurred on October 16, 1983.

Using lessons learned from experience in flying *Columbia* and *Challenger*, *Discovery* and its later sisters were both lighter and stronger than the earlier Orbiters. Many variations are internal, but one visible change involved the Thermal Protection System. Thermal blankets – lighter and easier to maintain than tiles – were substituted on the upper surfaces of the outer wings and forward body. As a result, *Discovery* could carry 6,870lb more payload into orbit than *Columbia*.

Discovery arrived at KSC on November 9, 1983, where it was immediately modified to carry a Centaur liquid-fuel upper stage. *Discovery* went through a nine-month OMDP in 1995–96. A fifth set of cryogenics tanks was added, extending the time it could remain in orbit,

One of the highlights of the Shuttle program occurred in November 1984, when 51-A recovered two stranded communications satellites. After recovering the second satellite, Dale Gardner celebrates in the payload bay by holding a sign reading "For Sale." The two satellites are in the bottom right corner of the picture.

and an external airlock was added, so that it could dock with the ISS when that was launched.

Discovery was removed from flight status in January 2002 to undergo Orbiter Maintenance and Modification (OMM) at KSC. The OMM began September 3, 2002, and was continuing through July 2003, when these words were written. The *Columbia* accident appears to have delayed completion of the OMM, as *Discovery* is not manifested for another flight through the end of 2004.

Despite this stand-down, *Discovery* has been in space more than any other Orbiter. *Discovery* flew 30 missions through 2003. It first flew on August 30, 1984, and completed five flights before the *Challenger* hiatus, including a military mission, 51-C. During that period it was used on four missions in one year, the only Orbiter to have reached that flight rate. *Discovery* was the Orbiter that flew the first post-*Challenger* mission, STS-26, in September 1988.

Discovery comes closest to becoming the "blue" or military Orbiter. It flew half the ten military missions flown by the Space Shuttle, and had been the Orbiter scheduled to fly the first two Vandenberg launches. It was also scheduled for the 61-N military flight, canceled after *Challenger.*

Discovery was manifested for two missions in September 1986 – both military: 62-B and 61-N. Whether this reflected a lack in confidence in SLC-6 being completed as scheduled or a preference for *Discovery* on military missions is hard to say. *Discovery* would have been used for the first two Vandenberg flights, and was one of two Orbiters capable of deploying the Centaur upper stage. Had the Shuttle program gone as planned, *Discovery* may have remained at Vandenberg, exclusively military in use.

Instead, along with *Atlantis, Discovery* remained at KSC to close out the Shuttle military program, and became one of the pillars of the space station program, making two trips to the Russian *Mir* and four trips to the ISS.

Early in its career, *Discovery* was used for one of the Shuttle program's greatest triumphs. Two communications satellites were stranded in useless orbits when their Payload Assist Module upper stages failed in February 1984. NASA devised a retrieval mission. Nine months later, in November 1984, *Discovery* was launched on mission 51-A, deployed two additional communications satellites, then rendezvoused with each stranded satellite, captured them, and returned them to Earth. Both were successfully relaunched. The mission was a showpiece for manned space travel. The capture device failed, so the crew improvised a capture method in real time.

Discovery also deployed the Hubble Space Telescope, the *Ulysses* interplanetary probe, and conducted three Spacelab/Spacehab missions, as well as conducting one HST (Hubble) servicing mission.

OV-104 *Atlantis*

Atlantis, the fourth Orbiter completed, and the last intended for the fleet, was named after a two-masted sailing ketch used by the Woods Hole Oceanographic Institute in Massachusetts. This 460-ton vessel was used for oceanographic research from 1930 to 1966, the first American ship used for that purpose.

Atlantis was contracted in 1979 along with *Discovery.* Structural assembly began in March 1980, and was completed in April 1984. Although it took two months longer to complete than either *Columbia* or *Discovery,* the construction of *Atlantis* used 50 percent fewer man-hours, partly because the engineers applied lessons learned in the construction of the earlier vehicles. Like *Discovery,* *Atlantis* was completed with thermal blankets instead of silica tiles on much of the upper surfaces. Combined with other weight savings and structural improvements, *Atlantis* weighed 6,974lb less than *Columbia,*

A camera on the launch pad support structure captures *Atlantis* as it lifts off for its first voyage to space, mission 51-J. *Atlantis* carried five crewmembers and two military satellites on the Shuttle's second Department of Defense mission.

Atlantis had its first OMDP between 1992 and 1994. During that 20-month refit, a drag chute was installed, the plumbing was altered so that it could fly extended missions, the airframe was modified, additional thermal protection was installed, and landing-gear door insulation was improved.

A second 10-month OMDP followed in 1998. An external airlock was installed in the payload bay so that *Atlantis* could dock with the ISS, the communications and cooling systems were improved, weight reduction measures were implemented, and the crew cabin floor strengthened. Additionally, *Atlantis* was the first Orbiter to receive the new "glass cockpit." Over 100 modifications were incorporated during this refit.

Atlantis first flew for 51-J, the second military mission, in October 1985. It flew only one other mission before the *Challenger* hiatus. *Atlantis* returned to space in December 1988 on STS-27, the second flight after the loss of *Challenger,* and another military mission. *Atlantis* flew two further military missions for a total of four.

Orbiter **_Atlantis_ being mated to the 747 for transportation to KSC at the mate-demate device at Dryden Flight Research Center in 1991.**

Atlantis had flown 26 missions by the end of 2002, which included deployment of three significant planetary and space science satellites. In May 1989 it deployed the *Magellan Venus* probe on STS-30. Five months later, in October, it deployed *Galileo*, a planetary probe sent to Jupiter. Originally these were to have been launched using a Centaur upper stage, but the missions and satellites were modified to allow a solid fuel Inertial Upper Stage to be used. On April 7, 1992, *Atlantis* deployed the 34,000lb Compton Gamma Ray Observatory.

During STS-46, which launched July 31, 1992, *Atlantis* carried the Tethered Satellite System 1 (TSS-1), an ambitious joint US–Italian tethered satellite project. Unfortunately a problem with the reel prevented the satellite from deploying more than half a mile (860m) from *Atlantis*, and after three days of effort, the subsatellite was reeled in.

Atlantis also flew one stand-alone Spacelab flight in 1992, and seven missions where it rendezvoused and docked with the Russian *Mir* Space Station between 1995 and 1997. On those missions it used a Spacehab module to facilitate docking, and to provide additional working space.

During this program, *Atlantis* conducted the first astronaut shuttles of the Space Shuttle program, where a crew person was left at *Mir* on one mission to be retrieved and exchanged for a replacement on a later mission. This flight finally validated the concept of using the Space Shuttle as a space station resupply vehicle, an ambition which had been part of NASA's initial motivation to build a space shuttle in the late 1960s.

Since completing its 1998 overhaul, *Atlantis* has been used exclusively for the construction and supply of the ISS. As of December 2002, *Atlantis* made six flights to the ISS, carrying supplies and structural elements to assemble the ISS.

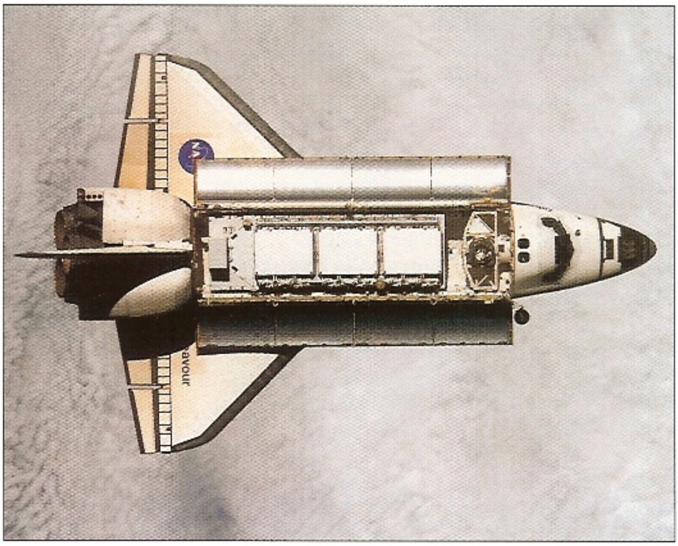
OV-105 *Endeavour*

Endeavour, the fifth and final Orbiter to fly in space, is named for the ship HMS *Endeavour* (formerly a collier) commanded by Captain James Cook on his first voyage of exploration, 1768–71. The name was chosen from those submitted in a national competition open to United States students in primary and secondary schools.

Like its namesake, the Orbiter *Endeavour* is a conversion. With the closure of the Orbiter production line after the completion of *Atlantis*, NASA needed spares to provide replacement parts for damaged elements. NASA issued a supplementary contract to Rockwell International in April 1983 for an aft-fuselage, crew compartment, mid-fuselage, forward fuselage halves, vertical tail and rudder, wings, elevons, forward RCS, one set of OMS/RCS pods, and a body flap.

At the time of the *Challenger* accident, the mid-fuselage and the body flap had been completed and were in storage. Construction of several other parts was also well advanced (work on the crew module had begun in 1982 – before the structural spares contract had been signed). On July 31, 1987 NASA awarded Rockwell International a contract to build a replacement Orbiter – OV-105 – using the structural spares. Rockwell reactivated the assembly floor at their Palmdale facility on August 3, and fabrication of OV-105 began in September.

Endeavour was completed on July 6, 1990, and delivered to NASA on April 25, 1991. The completed Orbiter was a prototype for improvements the other Orbiters would receive in subsequent out-of-service overhauls. It had a drag parachute, plumbing and electrical connections that would permit 28-day missions, upgraded avionics, nose-wheel steering, and improved APUs (Auxiliary Power Units).



ABOVE ***Endeavour* approaches ISS with a truss package. The new, external airlock is visible immediately behind the crew cabin. The dish immediately to the right of the crew cabin is the rendezvous radar.**

Endeavour underwent an eight-month OMDP in 1996 and 1997, where an external airlock was added so it could support the ISS program.

Endeavour flew its first mission, STS-49, on May 7, 1992, demonstrating the post-*Challenger* capabilities for the first time. The mission included a dramatic satellite rescue. Ironically, the satellite they captured, INTELSAT VI, had been stranded by a failure of a Titan expendable launch vehicle, to which many such satellites had been shifted after the *Challenger* hiatus.

Endeavour flew 19 missions prior to the *Columbia* accident in February 2003. Unique among the Orbiters, it never flew, or was scheduled for a military mission. By the time it joined the fleet, the Defense Department had abandoned the Shuttle for military purposes.

It also only deployed one payload with an upper stage intended to take it to a higher orbit, a TDRSS on STS-54 in 1993. This reflects the change in use of the Shuttle following *Challenger,* with less emphasis on its use as a satellite delivery system. Instead, *Endeavour* has carried a number of Spacelab/Spacehab payloads, as well as deploying then retrieving a number of free-flying research satellites, such as Spartan, EURICA, and the Wake Shield Unit. Additionally, *Endeavour* conducted the first commercial Spacehab mission, on STS-77 in 1996.

BELOW **The External Tank photographed drifting back to Earth after a successful ascent in 2002.**

Endeavour also carried out the Hubble Space Telescope (HST) repair mission in 1993. This involved several long space walks to correct serious problems with the HST imaging system. *Endeavour* docked with *Mir* on one mission, and since 1999 has supported construction of the ISS, carrying elements or supplies to the ISS on six missions.

ACRONYMS

ADI Attitude Director Indicator
ADS Air Data System
AFB Air Force Base
ALT Approach and Landing Test
AOA Abort Once Around (Shuttle abort mode)
APU Auxiliary Power Unit
ATCS Active Thermal Control System
ATO Abort To Orbit (Shuttle abort mode)
BFS Backup Flight System (Shuttle backup computer)
C&T Communications and Tracking
C/W Caution and Warning
c.g. Center of gravity
COAS Crewman Optical Alignment Sight
CPU Central Processor Unit
CRT Cathode Ray Tube
DAP Digital Autopilot
DOD, DoD Department of Defense
EAFB Edwards Air Force Base
ECLSS Environmental control and life support system
ELV Expendable Launch Vehicle
EMU Extravehicular mobility unit
EPS Electrical Power System
ESA European Space Agency
ET External Tank
EVA Extravehicular Activity
FM Frequency Modulation, Frequency Modulated
fps Feet per second
GN&C Guidance, Navigation and Control
GMT Greenwich Mean Time
GPC General-Purpose Computer (Shuttle onboard computer)
GPS Global Positioning System (constellation of satellites in a 12-hr orbit used for navigation)
HAC Heading Alignment Cylinder
HSI Horizontal Situation Indicator
HST Hubble Space Telescope
HUD Heads-Up Display
IMU Inertial Measurement Unit
ISS International Space Station
ITA Integrated Test Article
IUS Inertial Upper Stage
JPL Jet Propulsion Laboratory
JSC Johnson Space Center
KSC Kennedy Space Center
LDEF Long Duration Exposure Facility (satellite carrying small payloads to examine effects of space environment, left in orbit to be retrieved on a future flight)
LH2 Liquid Hydrogen
LO2 Liquid Oxygen
LRU Line-Replaceable Unit
MDD Mate/Demate Device
MDM Multiplexer/demultiplexer
MECO Main engine cutoff
MET Mission Elapsed Time
MMH Monomethyl Hydrazine
MMU Manned Maneuvering Unit
MOL Manned Orbiting Laboratory (DOD reconnaissance station)
MPS Main Propulsion System (Shuttle main engines)
MPTA Main Propulsion Test Article
MSBLS Microwave Scan Beam Landing System
MSFC Marshall Space Flight Center
NASA National Aeronautics and Space Administration
NSTL National Space Technology Laboratory
nmi Nautical mile
N_2O_4 Nitrogen Tetroxide
OMS Orbital Maneuvering System (Shuttle secondary engines)
OV Orbiter Vehicle
PAM Payload Assist Module
PASS Primary Avionics Software System (Shuttle onboard computer software)
PBI Push Button Indicator
PEAP Personal Egress Air Pack (emergency oxygen)
PLB Payload Bay (the major mission payloads were stored here)
PLBD Payload Bay Doors
psi Pounds per square inch
RA Radar Altimeter
RCC Reinforced Carbon-Carbon (thermal protection on leading edge and other high-heat areas)
RCS Reaction Control System (Orbiter maneuvering jets)
RGA Rate Gyro Assembly
RHC Rotational Hand Controller (pilot's controller used on Orbiter for attitude control)
RMS Remote Manipulator System (Orbiter robot arm)
RTLS Return To Launch Site (Shuttle abort mode)
SAIL Shuttle Avionics Integration Laboratory (JSC)
SCA Shuttle Carrier Aircraft (747 that ferries the Orbiter)
Scramjet Supersonic Combustion RAMJET (a hypersonic ramjet engine that burns its fuel externally, in the supersonic airstream produced by an aircraft)
SLC-6 Space Launch Complex 6
SRB Solid Rocket Booster
SRM Solid Rocket Motor (motors on SRBs)
SSME Space Shuttle Main Engine (Shuttle primary engines)
ST Star Tracker
STA Structural Test Article
STDN Spaceflight Tracking and Data Network (communications & tracking system)
STS Space Transportation System
T/W Thrust-to-weight
TACAN Tactical air navigation
TAEM Terminal Area Energy Management (Landing regime)
TDRS Tracking and Data Relay Satellite (communications and tracking satellite used with Shuttle)
TDRSS Tracking and Data Relay Satellite system (the system, including ground tracking stations used with the TDRS satellites)
THC Translational hand controller (pilot's controller used on Orbiter for translation)
TIO Target insertion orbit
TPS Thermal protection system (system used to keep Orbiter from melting during reentry)
TVC Thrust vector control
UHF Ultrahigh frequency
VAB Vehicle Assembly Building
VAFB Vandenberg Air Force Base
WSTF White Sands Test Facility

SHUTTLE MISSION NUMBERING SYSTEM

Shuttle missions used one of two numbering systems.

STS-n: STS stands for Space Transportation System. The number that follows (eg: STS-105) is the order in which the mission was manifested for flight. NASA used this system for the first nine Shuttle flights and all Shuttle flights after the *Challenger* hiatus. Since numbering is assigned as flights are manifested, sometimes missions fly out of sequence. STS-107, the flight on which *Columbia* was lost, was delayed. As a result, this flight, the 113th Shuttle mission, flew after STS-111, STS-112, and STS-113. While the next flight after the *Columbia* hiatus will be STS-114 (and will be the 114th Shuttle flight), the flight manifested to fly after that is STS-121, which was manifested during the *Columbia* hiatus, and after STS-115 through 120 were planned.

41-G: The first number represents the fiscal year in which the mission was manifested to fly. A flight starting with a "4" was originally scheduled to fly sometime in Fiscal Year 1984. (A fiscal year for the United States Federal Government starts on October 1 of the previous year, and ends on September 30 of the year. FY1984 started on October 1, 1983, and ended September 30, 1984.) The second number represents the launch site: 1 is the Kennedy Space Center; 2 is Vandenberg AFB. The letter represents the order in which the flight was manifested in the fiscal year. "A" was the first flight, "L" was the 12th. Occasionally you will see missions referenced as STS-41G instead of 41-G, even at NASA. This is anachronistic, a practice occasionally seen after NASA went back to the STS numbering system with STS-26.

So 51-L (when *Challenger* was destroyed) was originally manifested to fly in FY1985 (between Oct 1984 and Sept 1985) from KSC (the 1), and was the 12th flight scheduled for FY1985. Schedule problems often shifted the order in which flights were made. Flight 51-B flew after 51-C and 51-D. Missions 51-E and 51-H were never flown. Flight 51-L was launched in January 1986, well after the end of FY1985, and after missions 61-A, 61-B, and 61-C.

CORPORATE IDENTITIES

Over the 30-plus years of the Shuttle program many of the manufacturers involved have changed names or been purchased by other companies. This list is not exhaustive, but does attempt to list the major changes.

North American Aviation (built the Apollo capsule and X-15) was purchased by **Rockwell**, and became **North American Rockwell**. In the late 1970s **Rockwell** abandoned the North American name becoming **Rockwell International**. In the 1990s **Boeing** purchased **Rockwell**, and the company is now known as **Boeing**. **Boeing** (built the Saturn V first stage) has remained Boeing throughout, even after absorbing **McDonnell Douglas** and **Rockwell**.

Douglas Aircraft and **Aerospace** (built Skylab) was purchased by **McDonnell Aircraft** (Mercury and Gemini capsules) in the late 1960s, becoming **McDonnell-Douglas**. In the late 1990s, **McDonnell Douglas** merged with **Boeing**, and the resulting company was known as **Boeing**.

Lockheed (manufactured many unmanned satellites) purchased **General Dynamics** in the early 1990s, using the **Lockheed** name. Then **Lockheed** and **Martin-Marietta** (manufactured the Titian booster) merged in 1995 as **Lockheed-Martin**.

Grumman (built the Lunar Module) merged with **Northrop** (B-2 bomber) to form **Northrop-Grumman**.

Spacelab was set of ESA science modules built for and flown on the Shuttle. **Spacehab** was a US company that licensed **Spacelab** technology from the ESA and built a commercial science module that has also flown on the Shuttle. **Spacehab** has since build modules for the ISS.

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COLOR PLATE COMMENTARY

A: PROFILES OF ORBITERS

Each Orbiter is unique, and most differences are internal. The major external difference is in the tile patterns: *Columbia* and *Challenger* had tiles on the outer upper wings and upper forward fuselage, whereas *Atlantis*, *Discovery*, and *Endeavour* substituted thermal blankets. *Enterprise* (not shown in the plate) lacked thermal tiles, had a different nose shape, and an air-data probe in the nose.

NASA adopted the main color scheme shown by *Discovery* on this plate in 1998. The four surviving Orbiters were repainted to match this scheme during either OMDPs or OMM periods that year. Prior to that, Orbiters' markings varied. All had the United State Flag, with the words "United States" on the sides, and the NASA 'worm" logo on the payload bay doors just forward of the OMS pods. (NASA replaced its blue and red "meatball," in 1976. A stylized set of initials substituted as a logo until 1993, when the "meatball" was restored.)

Enterprise and *Columbia* (as shown by *Columbia* on this plate), initially had a US flag on the upper left wing, and "USA" in block black initials on the right wing, with the name of the Orbiter, printed in black, on the payload bay doors, immediately aft of the front. While receiving maintenance during the *Challenger* hiatus, *Colombia* had the name moved to the forebody, under the side window, but markings were otherwise unchanged.

Between 1981 and 1998 the rest of the Orbiter fleet used the following markings. The Orbiter's name was on the forebody, beneath the side window. As shown by *Challenger*, the rest of the Orbiters were painted so that the left upper wing had the letters "USA" in black, with the United States flag immediately below it. The right upper wing had the NASA crawl logo, in dark gray, with the vehicle name immediately below. At some point prior to the SLC-6 fit tests in 1986, *Enterprise*'s wing markings were altered to match the rest of the fleet.

B: STS-1 LAUNCH

The first Shuttle mission launched into space on April 12, 1981, after many frustrating delays. In January 1981 a gag calendar circulated around Johnson Space Center repeating the Center Director's proclamation: "We *Will* Launch in March!" Every month between February and December was labeled March. Some veterans of that era joke that *Columbia* was launched on March 43rd.

This Orbiter is *Columbia*, although its unique wing markings cannot be seen from this bird's eye view. The white External Tank marks an early launch and identifies the Orbiter as *Columbia*. The tank's insulation is brown, although initially it was painted white, for thermal control. The paint weighed nearly 500lb and as the ET is carried most of the way to orbit, an unpainted tank increased payload by almost the weight of the tank. NASA soon decided that the thermal qualities of a white tank were less important than payload. After STS-2 the tanks were left unpainted in the brown that has become a signature of the Shuttle program.

The Shuttle has cleared the launch tower in the plate. The Shuttle's thrust-to-weight ratio is 1.5:1, compared to 1.2:1 for the earlier Saturn V. Those that watched both lift off often comment on the speed at which the Shuttle departs, compared to the more stately progress of a Saturn V. STS-1 marked the first launch from Launch Complex 39 since the last Saturn launch on July 17, 1975. The Apollo launch crawlers were used, and the pad was extensively modified for the Shuttle program.

C: FLIGHT DECK/COCKPIT

Anyone who flies aircraft would recognize the instrument layout in the Shuttle forward cockpit. It was the first spacecraft to use an instrument panel laid out like an aircraft's. In front of both the commander and pilot is a panel with the familiar "T" of flight control instruments – or rather the spacefaring equivalents.

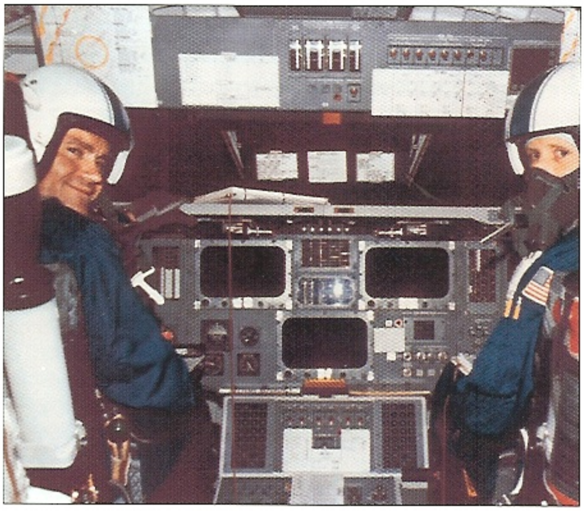
Instead of an airspeed indicator in the top left is an Alpha/Mach Indicator that indicates angle of attack, acceleration and Mach number. In the center-top, the artificial horizon is replaced by an Attitude Direction Indicator, or "eight-ball." Instead of an altimeter on the upper left, the Orbiter has an altitude/Vertical Velocity Indicator. Where the compass sits on an airplane, the Orbiter uses a Horizontal Situation Indicator.

During landing, when the Orbiter reenters like an airplane, these controls behave like their aircraft analogs. On orbit they measure acceleration, attitude and attitude rates.

The Orbiter originally had three CRT displays positioned between the commander and pilot, used for displaying information. The top half of the plate illustrates the original configuration – as modified with the Heads-Up Display (HUD) used during entry. The CRTs display a wide range of data formats to present information critical to the mission activities being undertaken.

In 1998, NASA began replacing this design with a "glass cockpit" shown in the lower half of the plate, whereby flat panels display the flight instruments digitally. The displays in the center of the panel were increased from three green-screen CRTs to five full-color flat panel displays. In addition to increasing the flexibility with which data could be displayed, the new cockpit requires less electrical power and weighs 75lb less than the original instrument panel. *Atlantis* was the first Orbiter to receive the modified panel, followed by *Columbia*. *Discovery* is being modified in 2003, but *Endeavour* may not receive these upgrades until 2006.

In the Vehicle Assembly Building, *Discovery* is being lifted in preparation to being mated with the External Tank for STS-95.



The cockpit of *Enterprise* immediately prior to the fifth and final ALT free flight. Fred Haise, an Apollo-13 veteran, commanded the flight in the left seat. Gordon Fullerton, a former MOL astronaut was the pilot.

D: CUTAWAY OF SHUTTLE STACK

The Space Shuttle has three major parts – an Orbiter, one External Tank and two Solid Rocket Boosters.

The winged Orbiter carries the crew and payload. It glides to a dead-stick landing to conclude a successful mission. It contains the most expensive parts of the systems – life support systems, the main engines that put the Shuttle in orbit, the Remote Manipulator System (the Shuttle's robot arm), avionics, and computers.

The Space Shuttle main engines exhaust 8hrs 30mins after launch. Limited orbital changes are then done with the Orbital Maneuvering System (OMS), two engines with 6,000lb thrust mounted in pods on the back of the Orbiter. Orbiter attitude is maintained with the Reaction Control System (RCS). The RCS has two aft modules on each OMS pod and a forward RCS module. Six RCS jets are vernier thrusters generating 24lb of thrust. The rest, 38 Primary jets, each produce 870lb of thrust. OMS and RCS use storable propellants, liquid at room temperature, that spontaneously combust when the oxydizer mixes with the fuel. The OMS engines and the aft RCS are interconnected. The Orbiter could deorbit with just the RCS jets, if necessary.

The External Tank, the largest element of the stack, contains tanks for liquid hydrogen and liquid oxygen, and an intertank section that connects the oxygen tank in the nose of the ET with the hydrogen tank in the main body of the ET. The intertank also contains a structural beam that holds the SRBs during ascent. The ET is the only disposable part of the Shuttle and normally crashes in the Indian Ocean after launch.

Two Solid Rocket Boosters provide the first-stage thrust for the Shuttle. When the SRBs exhaust, they fall away from the Shuttle and parachute back to earth, where they are recovered.

E: SRB SEP (SEPARATION)

Watch the crowd in a film of a Shuttle launch. If they cheer when the Shuttle clears the launch tower, the launch was filmed before the *Challenger* accident. If they cheer at SRB separation, 126 seconds after launch, it was filmed after *Challenger*.

SRB separation represents a milestone. Once the solid rocket motors ignite, the Shuttle is committed to flight until the SRBs burn out. If all three SSMEs failed at SRB ignition, the SRBs alone will lift the Shuttle off the pad.

When combustion chamber pressure in both SRBs drop below 50psi, the flight software initiates the SRB separation. The pressure limit ensures that both SRBs have burned out prior to separation, and that they will not swing in, striking the ET.

The forward ET attachment is a ball and socket; the SRB has the ball, and a pin with an explosive bolt connects the ball to the SRB. The aft SRB attachment is composed of three struts with an explosive bolt at each end. When SRB Sep is initiated, the bolts are detonated (see inset), freeing the SRBs from the External Tank.

There are four booster separation motors on each end of each SRB. After the bolts have blown, the motors are ignited, pushing the SRBs away from the ET and Orbiter. The nose, pushed by the airstream, falls away more quickly, and the Shuttle's onboard computers switch control to the Orbiter's rate gyro assemblies.

As the SRBs fall, the nose cone pops off at 15,700ft, as sensed by a barometric altimeter. A ribbon parachute first slows the SRB, then three main parachutes deploy, slowing the fall so the SRB can be recovered at sea.

F: LANDING

One of the most visible changes adopted after *Challenger* was the addition of a drag parachute to slow the Orbiter without additional braking. The parachute is stored in a compartment at the base of the tail. It is deployed after the Orbiter has landed on the runway, normally after the nose wheel has touched down. The drag chute is then dropped before the Orbiter stops to prevent it from interfering with the vehicles that service the Orbiter after landing.

The drag chute has the potential to reduce the post-landing rollout by 1,000–2,000ft, significantly reducing the runway length requirements. However, the drag chute does not necessarily reduce the Orbiter's rollout distance – the distance between the point at which the Orbiter's main wheel touches the ground and the point at which it stops. Rather, it eases loads on the brakes. In turn, this reduces

The Orbiter is controlled in space with using a 44-jet Reaction Control System. Here, two aft primary RCS jets can be seen firing.

An External Tank under assembly in what was then the *Martin Marietta Aerospace* factory in Michoud, LA. Today, this plant is run by Lockheed-Martin.

brake friction heating which reduces the chances of a tire bursting during landing.

The plate illustrates the first use of the drag parachute, at the end of Shuttle mission STS-49, in 1992, *Endeavour*'s maiden voyage. The drag chute was retrofitted on the existing Orbiters during 1992. On STS-49, *Endeavour* landed at Edwards Air Force Base in California, touching down on Runway 22, the paved runway used for Shuttle landings. Rollout was 9,490ft. While longer than the shortest rollout (6,364ft on STS-37 in 1991), it is shorter than the 13,732-ft rollout concluding STS-3, the only Shuttle flight that landed at White Sands, New Mexico.

G: HST REPAIR

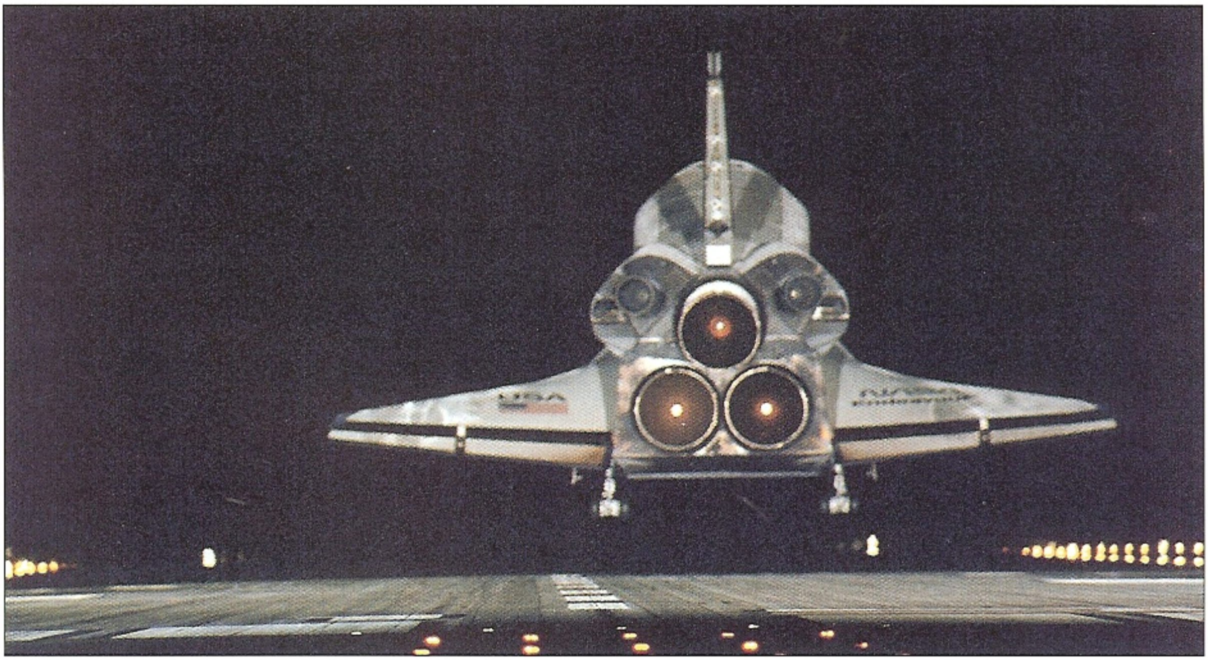
The Hubble Space Telescope, launched from the Shuttle in April, 1990, was one of the first satellites designed with the intention of using the Space Shuttle for servicing. It included items not carried on earlier research satellites, such as trunnions to allow the HST to be grasped by the Shuttle RMS, handholds and footholds for astronauts to ease servicing activities, and modular components that could be extracted and replaced in space.

The servicing capability prevented the Hubble from becoming the world's most expensive opera glasses. A manufacturing error, undiscovered until it was in orbit, prevented the telescope from focusing properly. This precluded its use for many optical purposes. The problem was repaired on a subsequent Shuttle mission, and the HST has since given humans glimpses into the cosmos impossible to see from Earth.

NASA has flown a total of four repair and servicing missions through January 2003. A final visit is tentatively scheduled for 2005, but might be canceled given safety concerns that have emerged since the loss of *Columbia*.

The most recent HST servicing mission, STS-109, was flown in March 2002. During that mission, a power unit and HST's solar panels were replaced, and a reaction wheel assembly (for attitude control) and a new camera were installed.

The plate shows the HST being released after the end of the servicing it received during that mission. The Hubble now sports smaller, yet more efficient solar panels, which replaced the gold-colored panels with which the HST was launched. Additionally, two members of the STS-109 crew, payload commander John M. Grunsfeld and mission specialist Richard M. Linnehan installed a new Power Control Unit on the satellite.



A Shuttle night landing on KSC Runway 15 concludes STS-72 on January 20, 1996. The lights in the centers of the SSME and OMS engine bells are from light reflecting off the ignition chambers.

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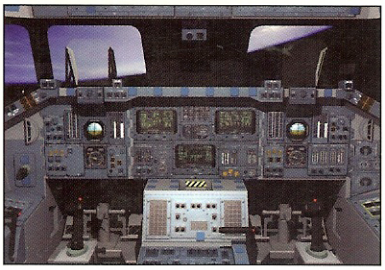
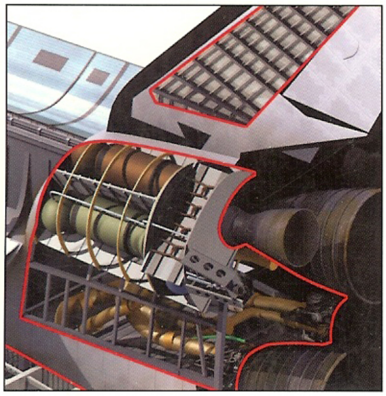
The design, development, operation and history of the machinery of warfare through the ages

Full color artwork



Unrivaled detail



Cutaway artwork

Photographs

Space Shuttle Launch System 1972–2004

The Space Shuttle is one of the oldest and most famous manned launch systems. The only launch vehicle that has been used for a longer period of time is the Soviet (now Russian) R-7 booster. By the start of the third millennium, the Space Shuttle had carried crews into space over 85 times. Although it is not a military structure, the Shuttle had been sold as an all-purpose launch system to be used jointly for military and civilian purposes. Featuring full-color photos throughout, this book covers the design, development and operational history of a unique vehicle.

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ISBN 1-84176-691-7

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