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Proving the Space Transportation System
The Orbital Flight Test Program

by Tony Reichhardt

The Induced Environment Contamination Monitor tested the Shuttle environs on STS-4.

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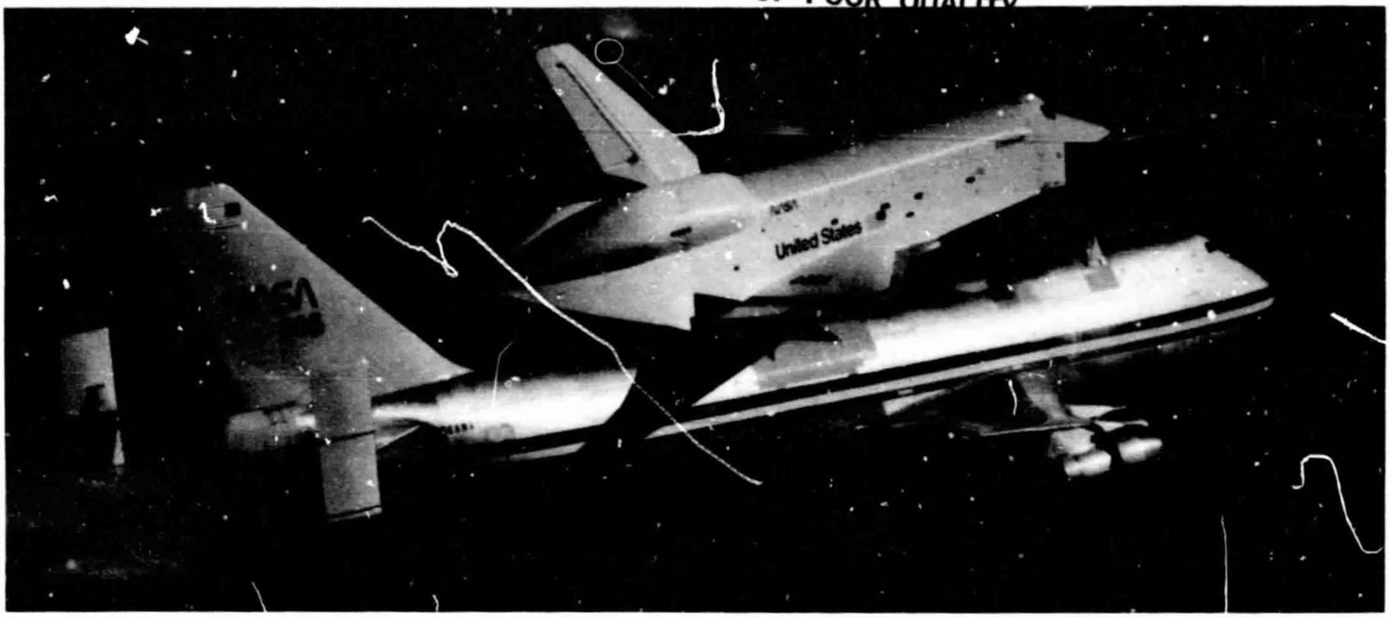

The first orbiter *Enterprise* never rocketed into space, but it was tested aerodynamically during Approach and Landing Tests in 1977.

Long before John Young and Robert Crippen stepped aboard Space Shuttle *Columbia* for its first trip into space on April 12, 1981, their new vehicle had been tested, and tested thoroughly. In wind tunnel experiments in the mid-1970's, engineers had verified the vehicle's basic aerodynamic design with scale models. Later, in 1977, the first Orbiter *Enterprise* had been dropped from a carrier aircraft for five manned Approach and Landing Tests to prove its ability to glide through the atmosphere and land like an airplane.

One by one, the Space Shuttle's components were tested and declared ready: the main engines at NASA's National Space Technology Laboratories in Mississippi; the solid rocket motors at a test range in Utah; computer software and insulating tiles at several NASA centers and contractor plants. The entire mated assembly of Orbiter, solid rockets and external fuel tank was checked out in ground vibration tests completed in February, 1979 at the Marshall Space Flight Center in Alabama. Finally, in February, 1981 came the Flight Readiness Firing of *Columbia*'s main propulsion engines on the launch pad at Kennedy Space Center in Florida.

But until April, 1981 there was no proof of the Shuttle as an integrated Space Transportation System capable of reaching Earth orbit, performing useful work there, and returning safely to the ground. This was the purpose of the Orbital Flight Test (OFT) program—to verify the Shuttle's performance under real spaceflight conditions, and to establish its readiness for operational duty. During four manned flights of *Columbia* conducted from April, 1981 to July, 1982 the Shuttle was tested in its many capacities as a launch vehicle, living quarters, freight handler, instrument platform and aircraft. Ground operations before, during and after each launch were also evaluated.

Following the landing of STS-4 on July 4, 1982 the Space Transportation System was declared operational—payload requirements would, from that point on, take precedence over spacecraft testing. With nearly 95% of its objectives accomplished, the Orbital Flight Test (OFT) program was also declared a success, even though further testing and expansion of the Shuttle's capabilities were planned on operational flights.

The OFT program consisted of more than 1100 carefully outlined tests and data collections. Many components were tested by functioning as planned—if an engine valve or an insulating tile worked normally, then its design was verified. Still others, like the Remote Manipulator System arm, were put through rigorous validation runs to check out different capabilities. Final documentation of Shuttle performance during OFT took into account the reports from astronaut crews, ground observations and measurements, and data from Orbiter instruments and special Developmental Flight Instrumentation (DFI) that collected and recorded temperatures and accelerations at various points around the vehicle and motion from points around the Shuttle. The DFI instruments were removed from *Columbia* after STS-5, while the solid rocket boosters were scheduled to carry them through STS-10.

The guiding philosophy of the test program was to expand the Shuttle's performance "envelope," or range of operation, toward the limits of its design in careful increments. Each flight increased the various structural and thermal stresses on the vehicle, both in space and in the atmosphere, by a planned amount.

The primary goal of *Columbia*'s first flight was to "get up and down safely" and verify the Shuttle's most basic task of reaching orbit and returning to Earth. Mission Commander John Young and Pilot Robert Crippen were launched from Kennedy Space Center on April 12,

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Mission	Crew	Launch/Landing	Orbital Altitude/ Inclination	Total Weight in Payload Bay	Payloads and Onboard Experiments
STS-1	Commander John W. Young Pilot Robert L. Crippen	4/12/81 Kennedy Space Center 4/14/81 Dry lakebed, Edwards AFB	237 kilometers 148 nautical miles (n.mi.) 40°	4870 kilograms (10,823 lbs.)	Data Flight Instrumentation (DFI); Passive Optical Sample Assembly; Aerodynamic Coefficient Identification Package (ACIP)
STS-2	Commander Joe H. Engle Pilot Richard H. Truly	11/12/81 Kennedy Space Center 11/14/81 Dry lakebed, Edwards AFB	222 x 230 km. (139 x 144 n.mi.) 38°	8900 kg. (19,778 lbs.)	DFI; ACIP; Induced Environment Contamination Monitor (IECM) Tile Gap Heating Experiment; (Tile) Catalytic Surface Experiment; Dynamic, Acoustic and Thermal Experiment (DATE); *OSTA-1 Payload* (for Office of Space & Terrestrial Applications) • Shuttle Imaging Radar-A • Shuttle Multispectral Infrared Radiometer • Feature Identification & Location Experiment • Measurement of Air Pollution From Satellites • Ocean Color Experiment • Night/Day Optical Survey of Lightning • Heflex Bioengineering Test
STS-3	Commander Jack R. Lousma Pilot C. Gordon Fullerton	3/22/82 Kennedy Space Center 3/30/82 Northrup Strip White Sands, New Mexico	208 km. (1[illegible]0 n.mi.) 38°	10,220 kg. (22,710 lbs.)	DFI; ACIP; IECM; Tile Gap Heating; Catalytic Surface; DATE; Getaway Special Canister; Monodisperse Latex Reactor; Electrophoresis Test; Heflex Bioengineering Test; Shuttle Student Involvement Project (Insects in Flight); *OSS-1 Payload* (for Office of Space Science) • Contamination Monitor • Microabrasion Foil Experiment • Vehicle Charging & Potential Experiment • Shuttle-Spacelab Induced Atmosphere • Solar Flare X-Ray Polarimeter • Solar Ultraviolet Spectral Irradiance Monitor • Plant Growth Unit • Thermal Canister Experiment • Plasma Diagnostics Package
STS-4	Commander Thomas K. Mattingly Pilot Henry W. Hartsfield, Jr.	6/27/82 Kennedy Space Center 7/4/82 Runway 22, Edwards AFB	258 km. (161 n.mi.) 28.5°	11,021 kg. (24,492 lbs.)	DFI; ACIP; IECM; Tile Gap Heating Experiment; Catalytic Surface Experiment; DATE; Getaway Special (9 experiments); Shuttle Student Involvement Project (2 experiments); Monodisperse Latex Reactor; Continuous Flow Electrophoresis System; Night/Day Optical Survey of Lightning; Department of Defense Payload DOD-82-1

1981 and landed on a dry lakebed at Edwards Air Force Base in California on April 14. Stresses on the vehicle were kept to a minimum for this first flight, and the only cargo weights were the Data Flight Instrumentation (DFI) and the Aerodynamic Coefficient Identification Package (ACIP). ACIP was a group of accelerometers and gyros included on all test flights to gather aerodynamic data during the Shuttle's atmospheric flight. STS-1 successfully demonstrated two vital spacecraft systems: the payload bay doors with their attached heat radiators and the Reaction Control System thrusters used for attitude control in orbit.

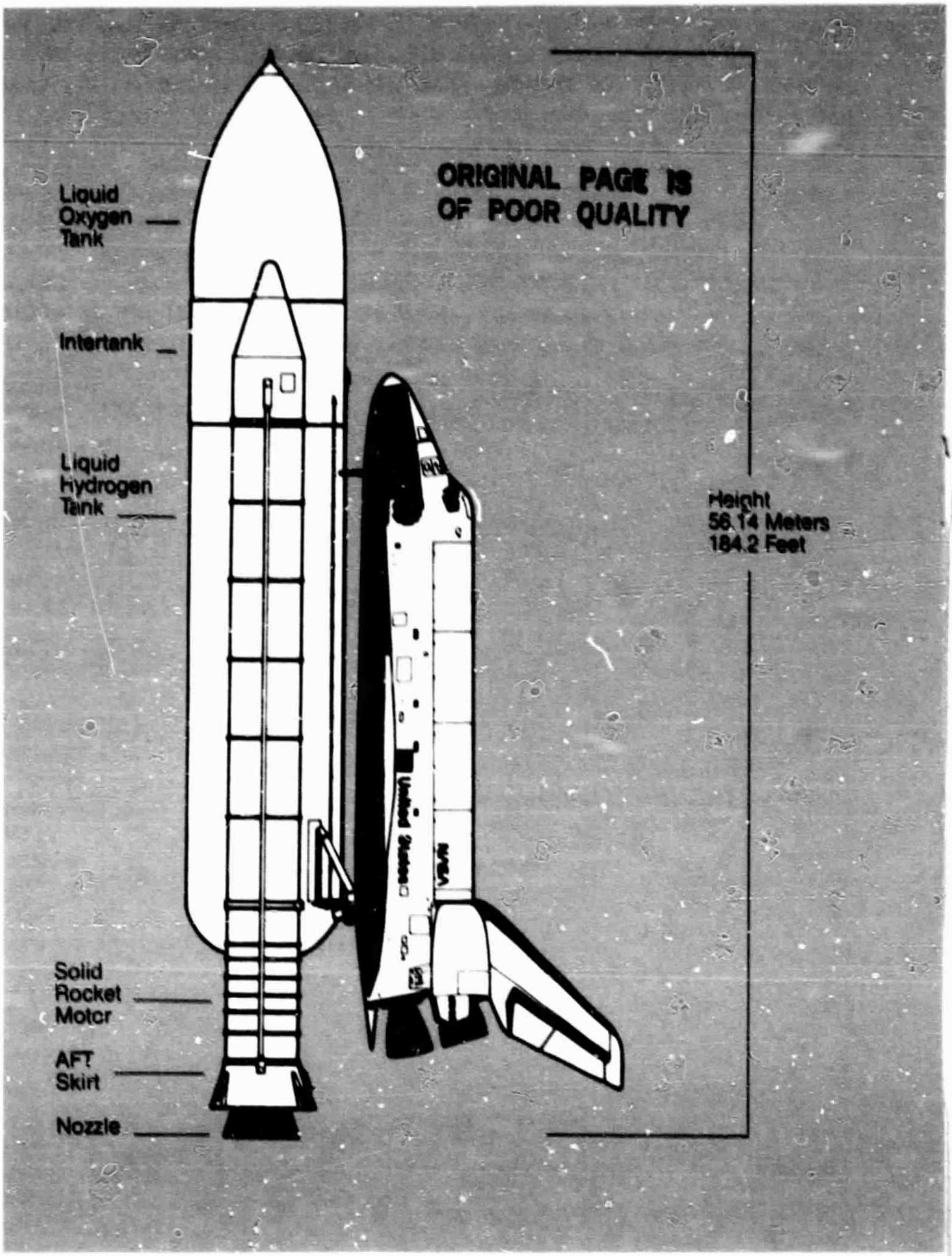
Originally scheduled for five days, the STS-2 mission had to be cut short because one of *Columbia*'s three electricity-generating fuel cells failed shortly after the vehicle reached orbit. Commander Joe Engle and Pilot Richard Truly still managed to achieve most of their flight objectives during the 54-hour mission from November 12 to November 14, 1981. Milestones for STS-2 were the first tests of the Remote Manipulator System's 15-meter (50 foot) arm and the successful operation of Earth-viewing instruments in the cargo bay. Most importantly, STS-2 proved the Shuttle's re-usability.

The third mission was the longest of the test series. Commander Jack Lousma and Pilot Gordon Fullerton were launched on March 22, 1982 and landed on March 30 at the White Sands Missile Range's Northrup Strip in New Mexico, a backup site chosen after rains flooded the normally dry lakebed at the prime landing site in

California. High winds at White Sands also caused a delay in landing, extending the week-long mission to eight days.

Just as STS-2 had featured the Shuttle's first Earth-viewing payload, STS-3 launched the first space-viewing instruments, a collection of astronomical and space-environment sensors designated OSS-1 (after their sponsor, NASA's Office of Space Science). STS-3 continued with testing of the Remote Manipulator System arm, carried the first student-developed experiment (a study of insect flight in weightlessness) in the Orbiter's mid-deck cabin, and began an important series of thermal tests of the spacecraft.

The fourth Shuttle mission, commanded by T. K. Mattingly with Henry Hartsfield, Jr. as Pilot, completed the OFT program. STS-4 was launched on June 27, 1982 and landed on July 4. Among the accomplishments of this last test flight were: continued thermal testing, validation of the Remote Manipulator System, the transport of Shuttle's first Department of Defense cargo, the first privately funded Getaway Special, and the first landing on a hard surface runway.



Getting Into Orbit: The Rockets

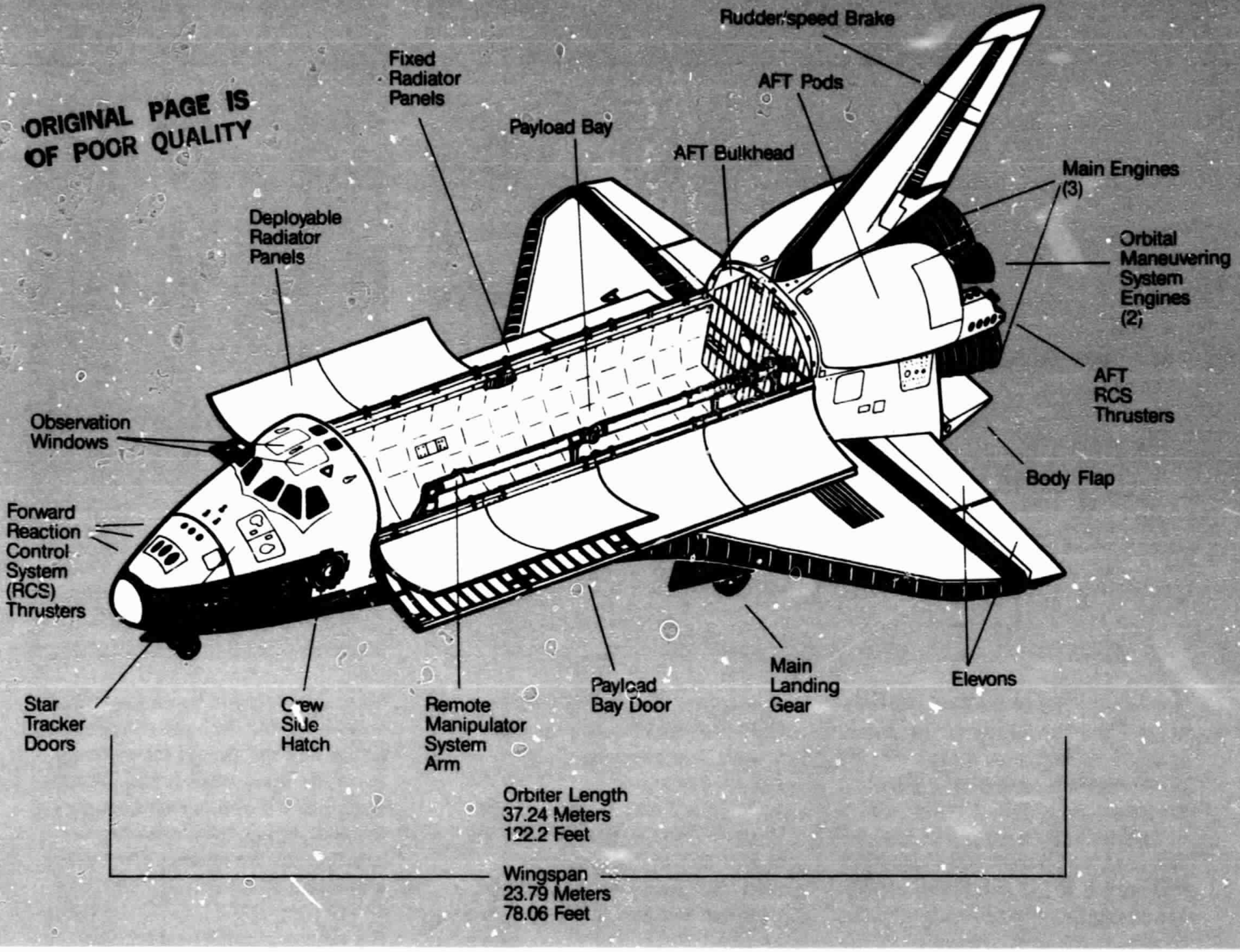
The sequence of events for a Shuttle launch begins with a start command to the Orbiter's three main liquid-fueled engines, followed by several seconds of thrust buildup before the twin Solid Rocket Boosters ignite, release from their hold-down mechanisms, and lift the entire Shuttle assembly from the pad.

An early and very significant finding of the test program was that the water deluge system designed to suppress the powerful acoustic pressures of liftoff would need to be revised, after the shock from the booster rockets was seen to be much larger than anticipated for STS-1. In the seconds before and after liftoff, a "rainbird" deluge system had poured tens of thousands of gallons of water onto the launch platform and into flame trenches beneath the rockets to absorb sound energy that might otherwise damage the Orbiter or its sensitive cargo. Strain gages and microphones were used to measure the acoustic shock, and they showed up to four times the predicted values in parts of the vehicle closest to the launch pad.

Although *Columbia* suffered no critical damage, the sound suppression system had to be modified before the launch of STS-2. Rather than dumping into the bottom of the flame trenches, water was now injected directly into the exhaust plumes of the booster rockets at a point just below the exhaust nozzles at the time of ignition. In addition, energy-absorbing water troughs were placed over the exhaust openings. The changes were enough to reduce acoustic pressures to 20–30% of STS-1 levels for the second launch, and they remained at acceptable levels for all subsequent missions.

STS-1 was the first opportunity to observe the Shuttle's array of solid and liquid rockets as a combined

Space Shuttle Orbiter, External Tank and Solid Rocket Booster

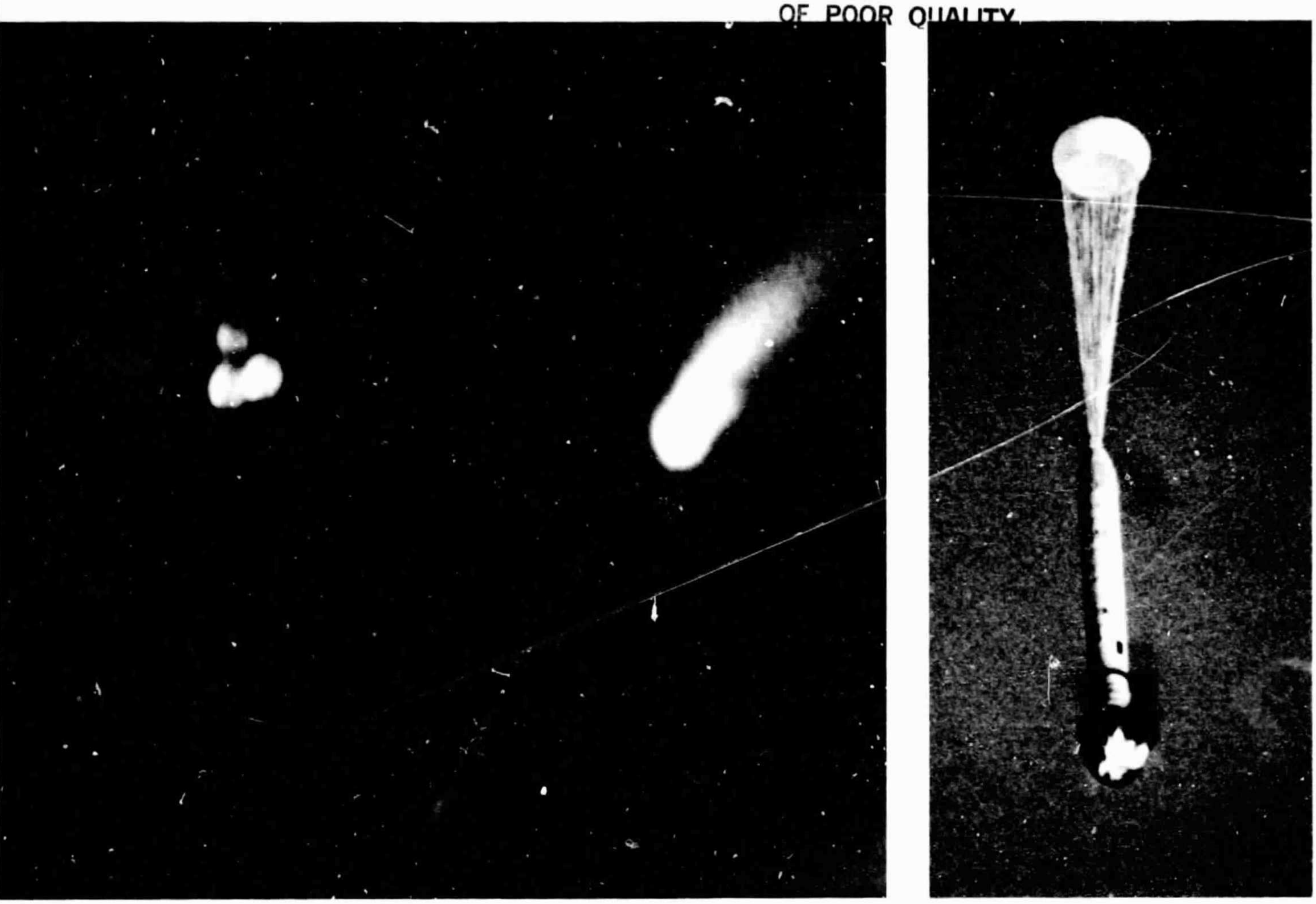


propulsion system. On all Orbital Flight Test flights, slow motion cameras mounted on the launch pad documented main engine and solid rocket firing as well as the Shuttle's ascent from the pad. Engine performance was assessed by examining the ascent trajectories for all four flights, reviewing vehicle data and by post-flight inspections.

Main Propulsion System

At the end of Orbital Flight Tests, *Columbia*'s main engines had been demonstrated successfully up to 100% of their rated power level (upgraded engines will throttle to 109% of this level on later flights) and down to 65%. Designed to provide 1.67 million Newtons (375,000 pounds) of thrust each at sea level for an estimated 55 missions, the engines were on target to meet these guidelines at the end of the test program. They met all requirements for start and cutoff timing, thrust direction control and the flow of propellants. As engineers learned more about the system's fuel efficiency, and as ground crews improved propellant loading techniques, extra fuel margins were also reduced.

The Shuttle was tested in its launch phase by planning increasingly more demanding ascent conditions for each test flight, and then by comparing predicted flight characteristics with data returned from ACIP and DFI instruments and ground tracking. *Columbia* lifted slightly heavier payloads into space on each mission. The altitudes and speeds at which the solid rockets and external tank separated were varied, as was the steepness of the vehicle's climb and main engine throttling times. All of these changes corresponded to a gradual increasing



Twin solid rockets separate from the External Tank, then parachute down to the Atlantic Ocean for recovery. Because there were problems with separation of the parachutes during the test flights, they were left attached to the rockets after water impact on STS-5.

over the course of the test program in the maximum dynamic pressure, or peak aerodynamic stress, inflicted on the vehicle. Maximum dynamic pressure for the STS-1 ascent was 607 pounds per square foot (psf). This was raised to 640 psf for STS-2, 650 psf for STS-3 and finally to 703 psf for STS-4. The Shuttle's operational limit is 819 psf. At no time did *Columbia* experience any significant problems with the aerodynamic or heat stresses of ascent.

A major milestone in the test program was the shift (after STS-2) from using wind tunnel data for computing *Columbia*'s ascent path to using aerodynamic data derived from the first two flights. On STS 1 and 2 the Shuttle showed a slight lofting—about 3000 meters (10,000 feet) at main engine cutoff—above its planned trajectory. This was due to the inability of wind-tunnel models to simulate the afterburning of hot exhaust gasses in the real atmosphere. Beginning with the third flight, the thrust of the booster rockets was re-oriented slightly to reduce this lofting.

On STS 3 and 4, however, the trajectory was seen to be too shallow, in part due to a slower than predicted burn rate for the solid boosters that had also been observed on the first two flights. Engineers continued to use OFT data after STS-4 to refine their predictions of this solid propellant burn rate so that ascent trajectories could be planned as accurately as possible on future missions. In all cases the combined propulsion of main engines, solid boosters and Orbital Maneuvering System engines delivered the Shuttle to its desired orbit.

STS-4 was the first mission to orbit at a 28.5° inclination to the equator. The first flights flew more steeply inclined orbits (38–40°) that took them over more ground tracking stations. The more equatorial STS-4 inclination is favored because it gives the vehicle a greater boost from the rotating Earth at launch. The first two flights also verified that the vehicle has enough energy to press on to an emergency landing in Spain or Senegal, as abort options, should two main engines fail during ascent. After STS-5 the crew ejection seats were removed from *Columbia*, eliminating the option to eject, and ending the need for astronauts to wear pressure suits during launch.

Solid Rocket Boosters

On each test flight, the twin Solid Rocket Boosters, the largest ever flown and the first designed for re-use, provided evenly matched thrust, shut off at the same times and

separated as planned from the external tank, then parachuted down to their designated recovery area in the Atlantic Ocean for towing back to the mainland and re-loading with solid propellant. Each booster has three main parachutes that inflate fully about twenty seconds before water impact. Prior to the test flights, these parachutes were designed to separate automatically from the boosters by means of explosive bolts when the rockets hit the water, since it was thought that recovery would be easier if the chutes were not still attached.

On the first and third flights, however, some parachutes sank before recovery. Then, on STS-4, the separation bolts fired prematurely due to strong vibrations, the parachutes detached from the rockets before water impact, and the rockets hit the water at too great a speed and sank. They were not recovered. As a result of these problems, the recovery hardware and procedures were altered beginning with STS-5. Instead of separating automatically with explosives, the parachutes remained attached to the boosters through water impact, and were detached once the recovery team arrived. There were also sections of the boosters strengthened as a result of water impact damage seen on the test flights.

External Tank

The Shuttle's huge external fuel tank at 47 meters (154 feet) high, is taller than many office buildings. The tank met all performance standards for OFT. Heat sensors have shown ascent temperatures to be moderate enough to allow planned reductions in the thickness and weight of the tank's insulation. Beginning with STS-3, white paint on the outside of the tank was left off to save another 243 kilograms (540 pounds) of weight, leaving the tank the brown color of its spray-on foam insulation.

Onboard cameras showed flawless separation of the tank from the Orbiter after the main engines cut off on each flight, and Shuttle crews report that this separation is so smooth that they cannot feel it happening. To assist its breakup in the atmosphere, the tank has a pyrotechnic device that sets it tumbling after separation rather than skipping along the atmosphere like a stone. This tumble device failed on STS-1, but worked perfectly on all subsequent missions. On all the test flights radar tracking of the tank debris showed it to fall well within the planned impact area in the Indian Ocean.

Orbital Maneuvering System

Shortly after it separates from the fuel tank, the Orbiter fires its two aft-mounted Orbital Maneuvering System engines for additional boosts to higher and more circularized orbits. At the end of orbital operations, these engines are called on again to decelerate the vehicle and begin its fall to Earth. The

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engines performed these basic functions during OFT with normal levels of fuel consumption and engine wear. Further testing included startups after long periods of idleness in vacuum and low gravity (STS 1 and 2), exposure to cold (STS-3) and exposure to the Sun (STS-4). Different methods of distributing the system's propellants were also demonstrated. Fuel from the left tank was fed to the right tank and vice versa, and from the Orbital Maneuvering System tanks to the smaller Reaction Control System thrusters (they both use the same combination of hydrazine and nitrogen tetroxide). On STS-2 the engine cross-feed was performed in the middle of an engine burn to simulate the engine's failure.

Orbital Operations: The Spacecraft

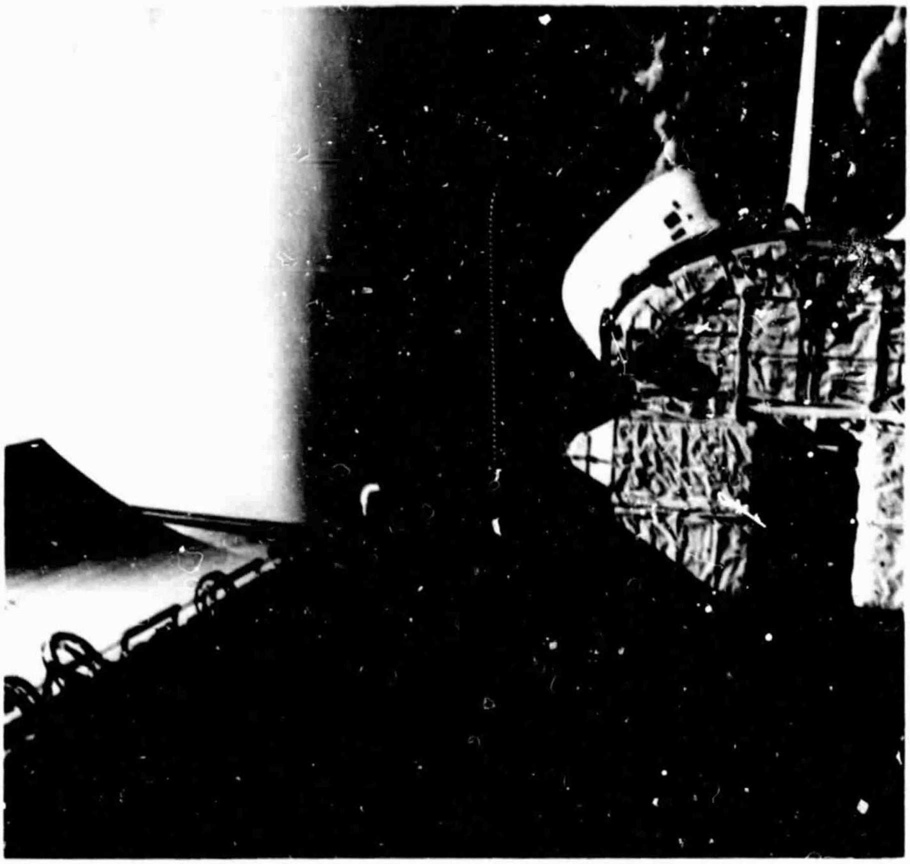
Once in space, an early priority for any Shuttle mission is to open the two large payload bay doors with their attached heat radiators. If the doors do not open in orbit, the Shuttle is not able to deploy payloads or shed its waste heat. If they fail to close at mission's end, re-entry through the atmosphere is impossible.

The STS-1 crew ran an important series of payload bay door tests during *Columbia*'s first few hours in space. The doors were first unlatched from the bulkheads and from each other. One at a time they were opened in the manual drive mode, while TV cameras and the crew recorded their motion. The movement of the doors was slightly more jerky and hesitant in space than in Earth-gravity simulations, but this was expected, and did not affect their successful opening and closing. The doors were closed and re-opened again one day into the STS-1 mission as a further test, then closed for good before re-entry. The crew verified normal alignment and latching of the doors as did the STS-2 crew during their door cycling tests, including one series in the automatic mode.

Door cycling was also tested after prolonged exposure to heat and cold. The doors are made of a graphite-epoxy composite material, while the Orbiter itself is made of aluminum. It was therefore important to understand how they would fit together after the aluminum expanded or contracted in the temperature extremes of space. At the beginning of STS-3 orbital operations the doors were opened as usual. The payload bay was then exposed to cold shadow for a period of 23 hours. When the port-side door was closed at the end of this "coldsoak" it failed to latch properly, as it did after a similar cold exposure on the STS-4 mission. Apparently the Orbiter warps very slightly into a "banana" shape with nose and tail bent upward toward each other, accounting in part for the doors' inability to clear the aft bulkhead.

The solution on both flights was the same, and has become standard procedure for closing the doors following a long cold exposure: the Orbiter holds a top-to-Sun position for 15 minutes to warm the cargo bay, then undergoes a short

Orbital Maneuvering System engines fire to place vehicle in orbit, to change orbits, and to break out of orbits at end of mission.



STS-1 tested payload bay doors and deployment of radiator panels (left). Photo also shows blanketed "box" of Data Flight Instrumentation (DFI) in the rear of cargo bay, and missing white tiles on aft engine pod (upper right).

"barbecue roll" to even out vehicle temperatures, allowing the doors to close and latch normally. In addition, there have been hardware changes to the doors and to the aft bulkhead designed to improve their clearance.

Thermal Tests

To understand the Shuttle's reaction to the thermal extremes of space was a key objective of the OFT program, and thermal tests accounted for hundreds of hours of mission time. The temperatures of spacecraft structures can change dramatically in space depending on their exposure to the Sun. Temperatures on the surface of payload bay insulation, for example, went from a low of 96° C(140°F) to a peak of 127°C (260°F) on the same STS-3 mission. The Space Shuttle keeps its components within their designed temperature limits through the active thermal control system. which includes two coolant loops that transport waste heat from Orbiter and payload electronics to the door-mounted radiator panels for dumping into space, and by the use of insulation and heaters.

The OFT program tested this ability to keep cool and keep warm under conditions much more extreme than the average mission's. STS 3 and 4 featured extended thermal "soaks," where parts of the Orbiter were deliberately heated up or cooled down by holding certain attitudes relative to the Sun. On STS-3 the Orbiter was first held with its tail to the Sun for 25 hours, heating its aft engines but cooling the nose and payload bay. Following that it held nose-to-Sun for 80 hours, cooling down those same Orbital Maneuvering System engines and reaction control jets. Finally, the payload bay was heated by holding the Orbiter's top to the Sun for 28 hours. These long thermal soaks were separated by shorter periods of "barbecue roll" for even heating. On STS-4 the thermal soak tests continued with long tail-to-Sun and bottom-to-Sun exposures.

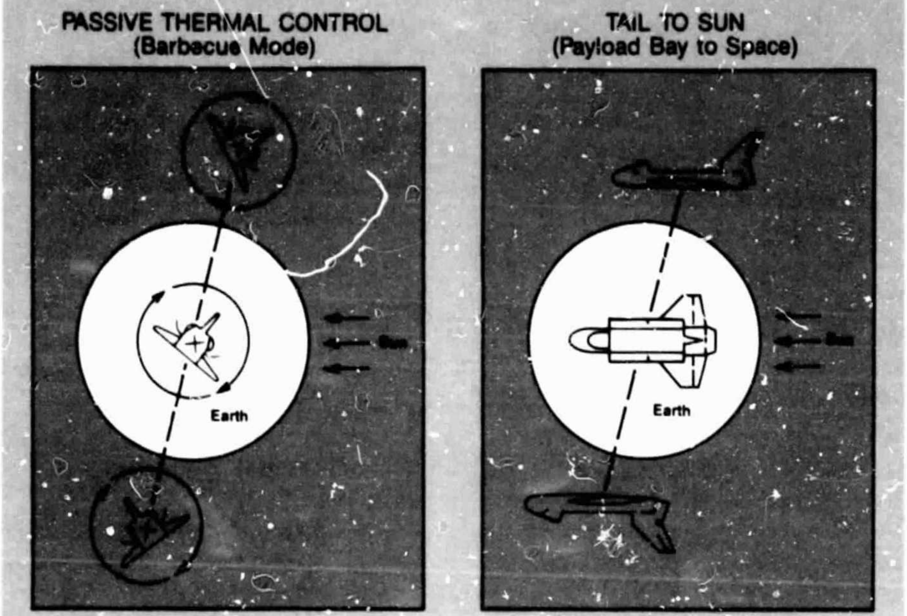
Overall, these hot and cold soak tests showed that the Shuttle has a better than predicted thermal stability. STS-3 readings showed that the Orbiter's skin kept considerably warmer during coldsoaks than had been expected and that many critical systems like the orbital maneuvering engines were also warmer. Most vehicle structures also tend to heat up or cool down at slower rates than expected.

The Active Thermal Control System, with its coolant loops and space radiators, proved capable of handling Shuttle heat loads in orbit even under extreme conditions. This is important to know for future missions where instrument pointing requirements may demand long periods of Sun or shadow on parts of the vehicle. On a mission with moderate heating and cooling such as STS-1 the total heat load on the Active Thermal Control System was found to be 15% lower than expected.

The space radiators were tested with all eight panels deployed, and they proved capable of shedding most heat loads with only half the panels deployed. These radiators are but one part of the thermal control subsystem. During ascent the Shuttle's flash evaporators transfer heat from circulating coolant to water, beginning about two minutes into the ascent when the vehicle first requires active cooling. These flash evaporators normally work until the space radiators are opened in orbit. Then, at the end of the mission the flash evaporators are reactivated and used down to an altitude of approximately 36,000 meters (120,000 feet) during re-entry. From that altitude down to the ground the heat is shed by boiling ammonia rather than water.

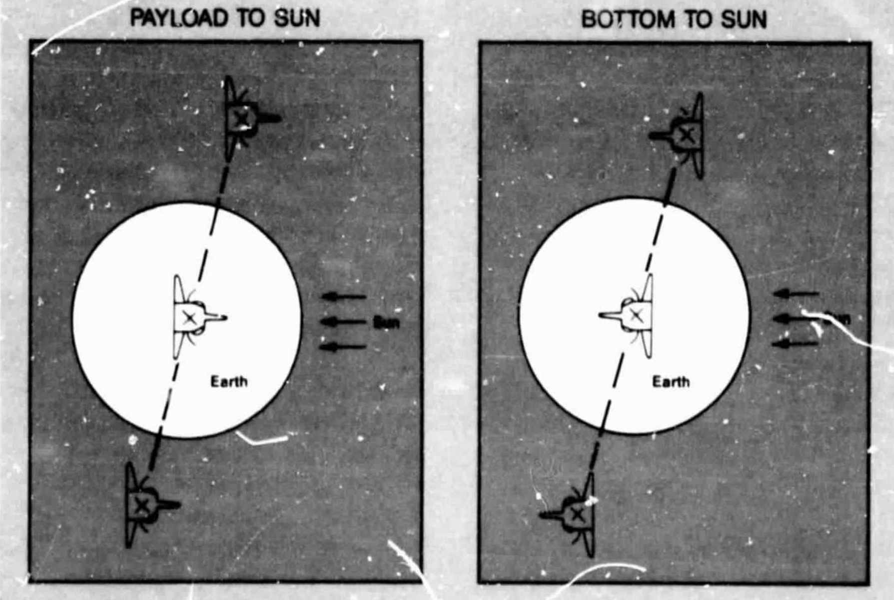
During OFT these different methods of cooling down were successfully tested as backups to each other. The flash evaporators proved capable of handling heat loads in space for a short while without help from the radiators, and

OFT Thermal Tests



PASSIVE THERMAL CONTROL (Barbecue Mode)

TAIL TO SUN (Payload Bay to Space)



PAYLOAD TO SUN

BOTTOM TO SUN

Thermal testing of Orbiter was accomplished by holding different attitudes relative to the Sun for long periods.

the (stowed) radiators were allowed to absorb some of the vehicle's internal heat loads during re-entry, bypassing the ammonia boilers.

Subsystems

All four of the two-man crews for the test flight program were kept busy every minute they were in orbit, testing and re-testing the Shuttle's main subsystems under varying conditions, like new car owners checking out their options. On the four OFT flights virtually every one of these systems—hydraulic, electrical, navigation and guidance, communications and environmental control—performed up to design standards or better.

The hydraulic subsystem that controls movement of the Shuttle's engine nozzles, its airplane-like control flaps and its landing gear functioned well during OFT launches and re-entries. Normally idle when the Shuttle is in orbit, the hydraulic system must keep its fluids warm and ready for action. The hydraulic system was tested successfully on STS-2 by cycling the eleven control surfaces while in orbit. On STS-4 the hydraulics were evaluated after a long coldsoak, when it was found that circulation pumps need only operate at minimal levels to keep the hydraulic fluids above critical temperatures. These minimal duty cycles for circulation pumps will save on electrical power.

Although an oil filter clog in the hydraulic system's Auxiliary Power Units delayed the launch of STS-2 by more than a week, the problem did not recur during the test program. The solution was to use tighter seals to prevent the oil from being contaminated by the units' hydrazine fuel.

The same STS-2 mission was cut short due to a failure of one of the three Shuttle fuel cells that convert supercold (cryogenic) hydrogen and oxygen to electricity. A clog in the cell's water flow lines (water for the crew is produced as a by-product of the fuel cell's generation of electricity) was the cause of the failure, and this problem was remedied during OFT by adding filters to the pipes. An uplanned-for benefit from this failure, though, was a test of the vehicle using only two fuel cells instead of three, which were enough to handle all electrical needs. One concern before OFT was that uneven mixing of the cryogenic hydrogen and oxygen in their storage tanks would hinder their flow to the fuel cells in low gravity. After two tests for this effect with the tanks nearly full and nearly empty, it did not appear to be a significant problem. Partly as a result of the Shuttle's thermal stability, electricity consumption by the Orbiter proved to be lower than expected, ranging from 14 to 17 kilowatts per hour in orbit as opposed to the predicted 15 to 20 kilowatts.

The ability of the Shuttle's computers to control virtually every phase of each mission from final countdown sequencing to re-entry was successfully demonstrated on all flights, with only minor programming changes being necessary during the test program. The on-orbit navigation and guidance aids were checked out thoroughly. The Orbiter "senses" its position in space by means of three Inertial Measurement Units (IMU's) whose accuracy is checked and periodically updated by a star tracker located on the same navigation base in the cockpit-like flight deck. This vital star tracker/IMU alignment was tested extensively on the first Shuttle mission, including once when the vehicle was rolling, and on all flights their agreement was good. The star tracker was able to find its guide stars both in darkness and in daylight. Its accuracy is better than expected, and the entire navigation instrument base showed its stability under extreme thermal conditions. Crew optical alignments of the IMU's were also demonstrated as a backup.

Radio and TV communication were successfully carried out on all four flights with only minimal hardware and signal acquisition problems at ground stations. Specific tests checked different transmission modes, radio voice through the Shuttle's rocket exhaust during ascent, and UHF transmission as a backup to the primary radio link during launch and operations in space. All were successful. On STS-4 there was also an evaluation of how different Orbiter attitudes affect radio reception in space, important for planning future missions.

The closed-circuit television system inside the Orbiter and out in the cargo bay gave high-quality video images of operations in orbit. In Sunlight and in artificial floodlighting of the payload bay they showed the necessary sensitivity, range of vision, remote control and video-recording capabilities.

Attitude Control

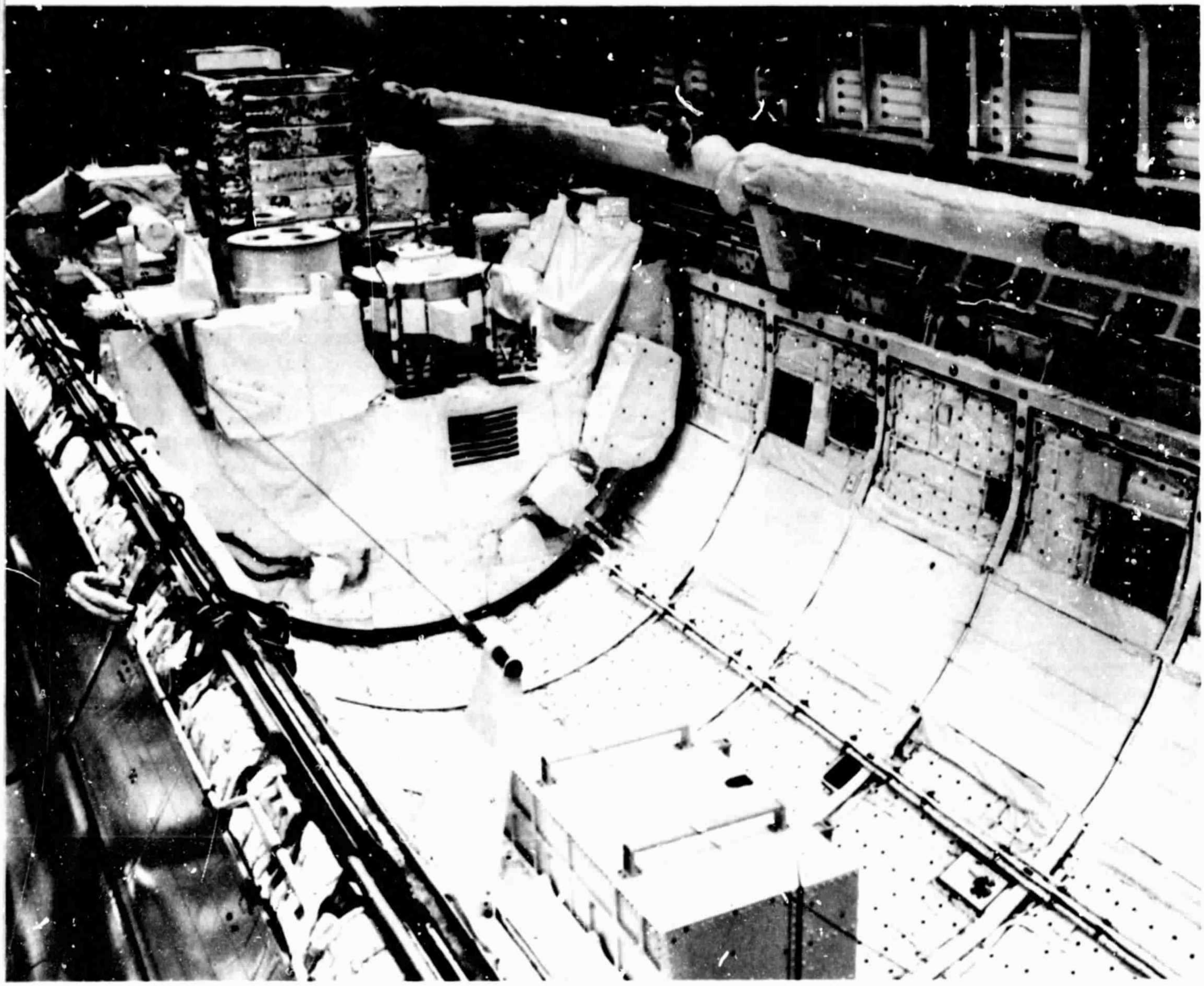
When in orbit, the Shuttle uses its Reaction Control System of 38 primary and 6 smaller vernier thrusters to control its position (attitude) and to make small scale "translations," or movements, in space. These jets are located in the Orbiter's nose area and on the aft pods near the other larger engines, and they fire in different combinations to move the Shuttle to nearly any desired position. "We haven't taught it to dance yet," says a Shuttle official "but it can do just about anything else." This important subsystem was the object of extensive testing beginning with STS-1.

The jets were evaluated in a general way by seeing how the Orbiter responded during a series of attitude maneuvers in space—vehicle rolls around all three axes—roll, pitch and yaw—and translations up-and-down, sideways, and forward-and-backward. Both primary and vernier thrusters were tested in these validation runs. Automatic and crew-commanded manual reaction control was demonstrated at different velocities. Under automatic controls *Columbia* successfully changed and held its position to support mission requirements, such as star tracking.

The thrusting power and propellant usage of both types of jets were as expected, with the smaller verniers more fuel-efficient than expected. Two of the four vernier jets in *Columbia*'s tail area were seen to have a problem with the downward direction of their thrust. The exhaust hits the aft body flap and erodes some of its protective tiles, which also cuts down on the power of the jets. One solution being considered after OFT was to re-orient these jets slightly on future Orbiters. In the meantime, a protective coating was applied to the tiles on the body flap.

The Orbiter's ability to come to rest after a maneuver was also demonstrated. At faster rates it proved nearly impossible to stop the vehicle's motion without overshooting, then coming back to the required "stop" position, particularly with the large primary engines. Both types of thrusters were used to keep the Orbiter steady in "attitude hold" postures. The small jets were particularly successful and fuel-efficient at this, holding the vehicle steady down to ⅓ of a degree of drift at normal rates of fuel use, which is three times their required sensitivity.

There was some concern after the test program about the lifetime of the vernier engines. When it was discovered that a protective engine coating had eroded substantially on two of these engines they were all replaced with new ones after STS-4, even though they had been designed to last 37 missions before being replaced. While testing continued to determine why the coating eroded, mission planners attempted to schedule more efficient use of the small jets—they were fired twice as often as planned during the test program, partly as a result of their need to compensate for "overshooting" and the need to hold very steady attitudes for long periods of time.



STS-3 test instruments and payloads. Note Canadian-built Remote Manipulator System arm at right.

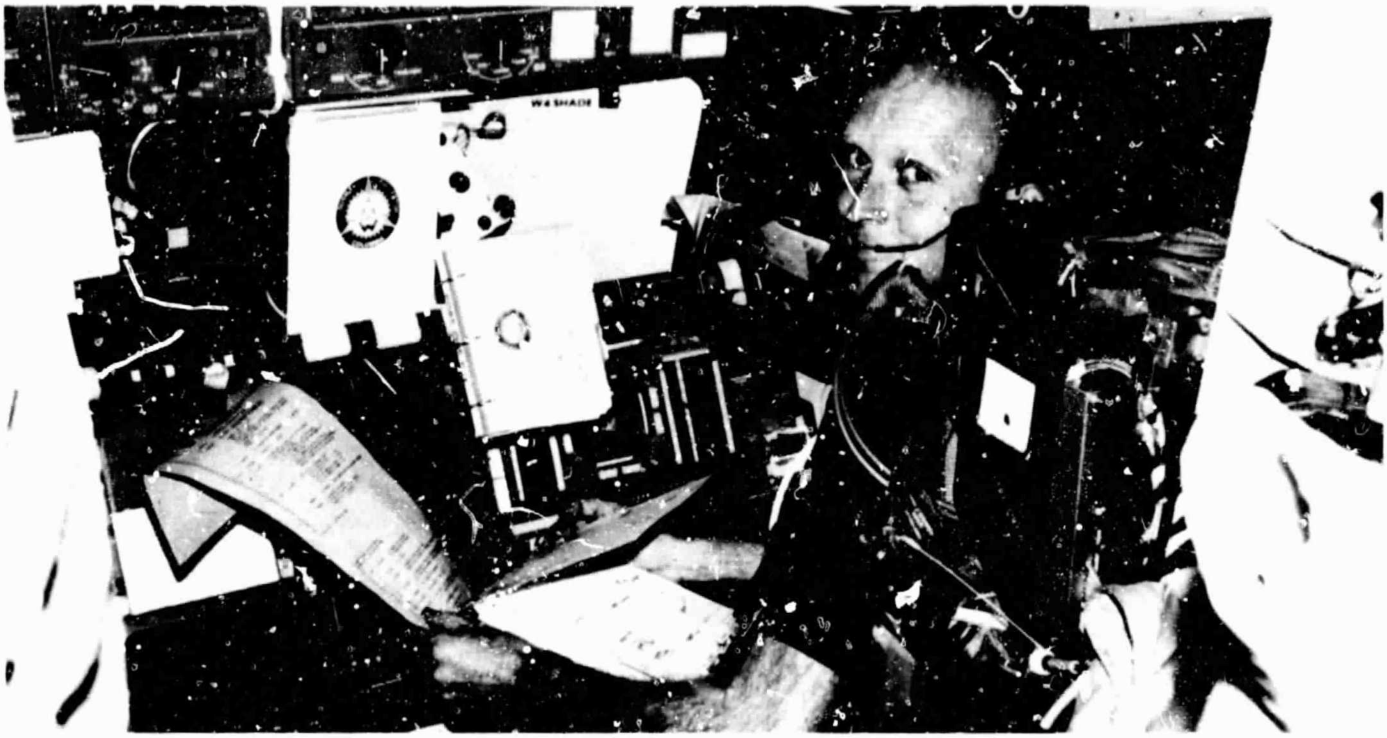
Further tests of the Reaction Control System assessed how well *Columbia* could hold steady *without* firing its jets, when differential forces of gravity tend to tug the 37 meter (122 foot)-long vehicle out of position. The results of these tests looked promising for the use of "passive gravity gradient" attitudes for future missions where steadiness for short periods of time is required without jet firings.

Remote Manipulator System

One of the most important as well as most time-consuming of all OFT test series involved the 15 meter (50 foot) mechanical arm of the Remote Manipulator System. This Canadian-built device, jointed like a human arm at shoulder, elbow and wrist, is attached to the Orbiter at various cradle points running the length of the inside of the cargo bay. It is an optional piece of equipment used only on missions where it is needed to move objects into or out of the cargo bay. In place of a hand the arm has a cylindrical "end effector" that grapples a payload and holds it rigid with wire snares. The arm is controlled by the crew from inside the Orbiter and can be moved freely around the vehicle in a number of modes, with or without help from the Shuttle computers.

All of the manual and automatic drive modes were tested during OFT, as was the arm's ability to grab a payload firmly, remove it from a stowed position, then re-berth it precisely and securely. Lighting and television cameras also needed to be verified—the crew relies on sensitive elbow and wrist cameras as well as cameras mounted in the payload bay to monitor day and night operations. For the test program there were also special Data Acquisition Cameras in the cargo bay for documenting arm motion.

The first mission to carry the arm was STS-2, and the crew of this shortened flight ran an extensive series of arm movements to test its mobility in space. Ground simulators



C. Gordon Fullerton, STS-3 pilot, with flight data and teleprinter copy at pilot's station.

are not able to practice three-dimensional maneuvers because the arm is too fragile to support its own weight in Earth gravity. The crew began by releasing the arm, then relatching it to the Orbiter, both in the joint-by-joint computer assisted mode (the preferred method) and in the direct wiring contingency mode that bypasses the computer. Once this ability to deploy and re-stow the arm was verified it was moved around *Columbia* in validation runs to test all joints in all drive modes at different rates of speed. Fully automatic runs were documented by videotape and by analyzing the motor rates for each joint. They agreed well with pre-flight predictions, and the crew watched as the arm accurately "flew" from one pre-programmed spot to the next. Braking of the arm was normal and smooth in both automatic and manual drive.

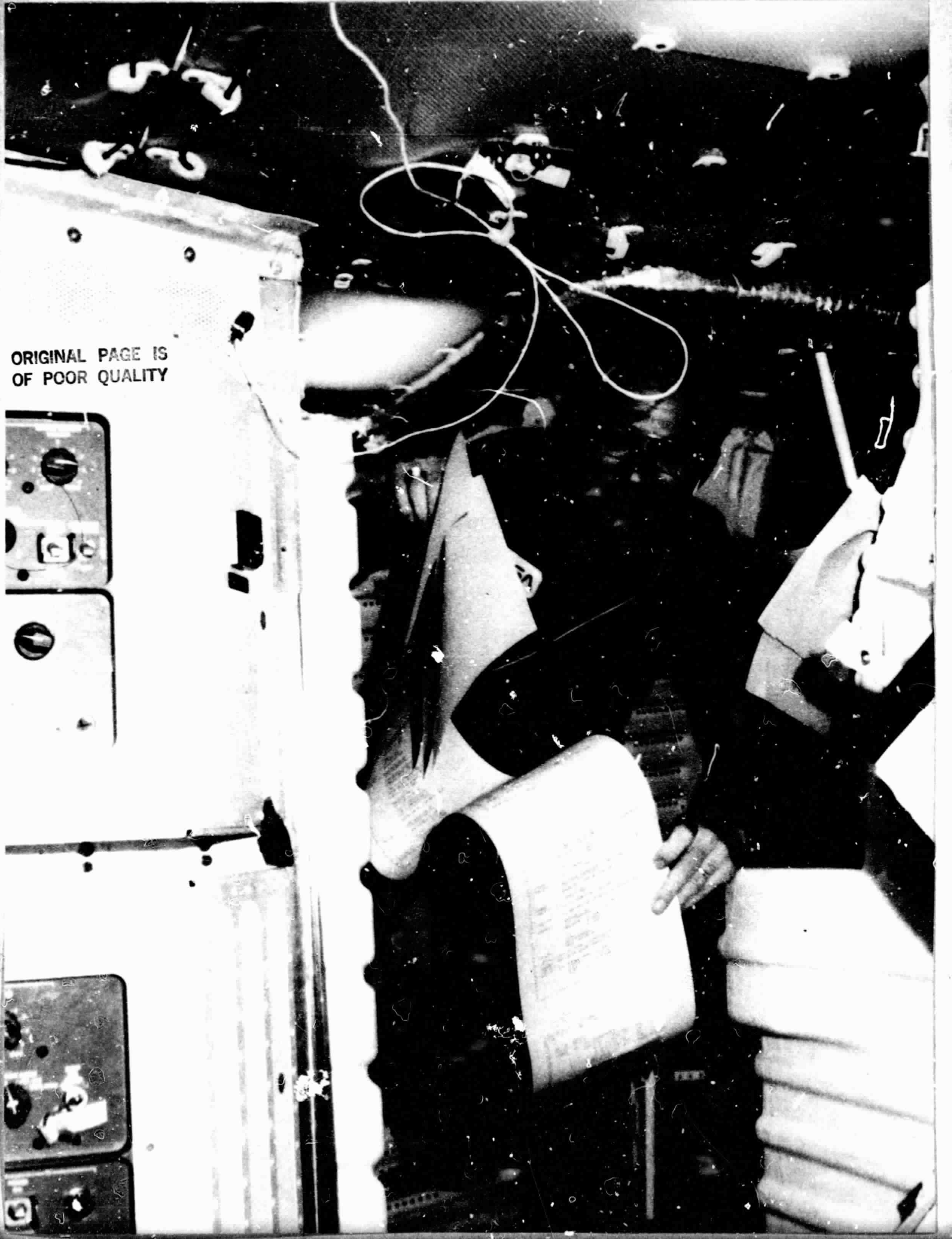
Although the STS-2 crew did not pick up a payload with the arm, both astronauts performed manual approaches to a grapple fixture in the cargo bay, and they found the arm to control smoothly, very much like ground simulators. The second crew also began tests to see how movement of the arm interacts with Orbiter motions. Problems with TV cameras reduced the documentation of these tests, but the crew reported that firings of the small vernier thrusters did not influence arm position, nor did arm motions trigger attitude adjustment firings by the Orbiter.

The prime objective of STS-3 arm tests was to test it "loaded" with a payload. First, though, the crew had to finish tests left over from the shortened STS-2 mission, particularly a verification of the computer's ability to automatically stop an arm joint from rotating past the limit of its mobility. The third crew completed 48 hours of arm tests, including one unplanned demonstration of the elbow camera's ability to photograph *Columbia*'s nose area during an on-orbit search for missing tiles.

A Shuttle payload, the 186 kilogram (413 pound) Plasma Diagnostics Package, was grappled by the end effector, removed manually from its berth in the cargo bay, and maneuvered automatically around the Orbiter in support of OFT space environment studies. Gordon Fullerton deployed and re-berthed the package a total of three times, and was impressed with the arm's ease and responsiveness. Before one such deployment the arm automatically found its way to within 3.8 centimeters (1.5 inches) of the grapple point, in accord with pre-flight predictions.

TV cameras provided excellent vision of arm operations in both sunshine and darkness, and the STS-4 crew reported that nighttime operations, although marginal, were still possible after three of the six payload bay cameras failed. The third and fourth crews continued evaluation of vehicle interactions with arm motion by performing roll maneuvers as the arm held payloads straight up from the cargo bay. This was done with the Plasma Diagnostics Package on STS-3 and with the twice-as-heavy Induced Environment Contamination Monitor on STS-4. In both cases the crew noted a slight swaying of the arm when the vehicle stopped, which was expected.

Further tests of these dynamic responses will be done on later missions. The Remote Manipulator System is designed to move a payload of 29,250 kilograms (65,000 pounds), but was tested only with masses under 450 kilograms (1000 pounds) during OFT. Future arm tests will graduate to heavier payloads.



some with grapple points fixed to simulate the inertias of even more massive objects.

The Shuttle Environment

In addition to these hardware check-outs, another objective of test program was to assess the environment the Shuttle travels through and creates around itself in space. This is important for planning missions that will carry instruments sensitive to noise, vibration, radiation or contamination. During OFT, *Columbia* carried two sensor packages for examining the cargo bay environment. The Dynamic, Acoustic and Thermal Environment (DATE) experiment—a group of accelerometers, microphones and heat and strain gages—established that noise and stress levels inside the bay were generally lower than predicted. The Induced Environment Contamination Monitor (IECM), normally secured in the cargo bay, was also moved around by the manipulator arm to perform an environmental survey outside the Orbiter on STS-4. The IECM looked for deposits on payload bay surfaces and had sensors for detecting humidity and trace gasses. No engine exhaust pollutants were found in the cargo bay during launch or re-entry. The IECM showed low levels of "outgassing" by payload bay surfaces and no sign of heavy molecule deposits. The particles that were observed, probably originating on the ground, were in the microscopic range (1–5 microns), and these deteriorated after a period of 15–17 hours in space. The monitor showed water to be the Shuttle's principal contaminant, and this was well within acceptable levels.

The IECM's survey of polluting particles and gasses was backed up by two other STS-3 instruments, the Contamination Monitor and the Shuttle-Spacelab Induced Atmosphere Experiment, and by post-landing inspections of the cargo bay. These inspections also revealed minor deposits and some discoloration of films and painted surfaces in the bay, which were still being studied after OFT. A new payload bay lining was added after STS-4.

Working in the Shuttle, Astronaut Henry Hartsfield, Jr. gathers print-outs from *Columbia*'s tele-printer, located in mid-deck area.

For measuring energy fields around the Orbiter STS-3 carried the Plasma Diagnostics Package (PDP). The PDP was positioned at various locations around *Columbia* and used in conjunction with the Vehicle Charging and Potential Experiment to map the distribution of charged particles around the spacecraft. These readings showed a vehicle that is relatively "quiet" electrically—it moves through the Earth's energy fields with interference levels much lower than acceptable limits. Another STS-3 highlight was the discovery of a soft glow around some of the Shuttle's surfaces that appeared in several nighttime photographs. An experiment added to STS-4 to identify the glow's spectrum supported a tentative explanation of the phenomenon as due to an interaction with atomic oxygen in the thin upper atmosphere. Positive identification of the cause awaited further experiments after OFT.

The flight test program will allow precise contamination data to be distributed to those designing sensitive Shuttle experiments. The suitability of the cargo bay for mounting both Earth- and space-viewing instruments was also demonstrated. A prototype of the Spacelab pallet gave adequate heating and power to its payload on both STS-2 and STS-3.

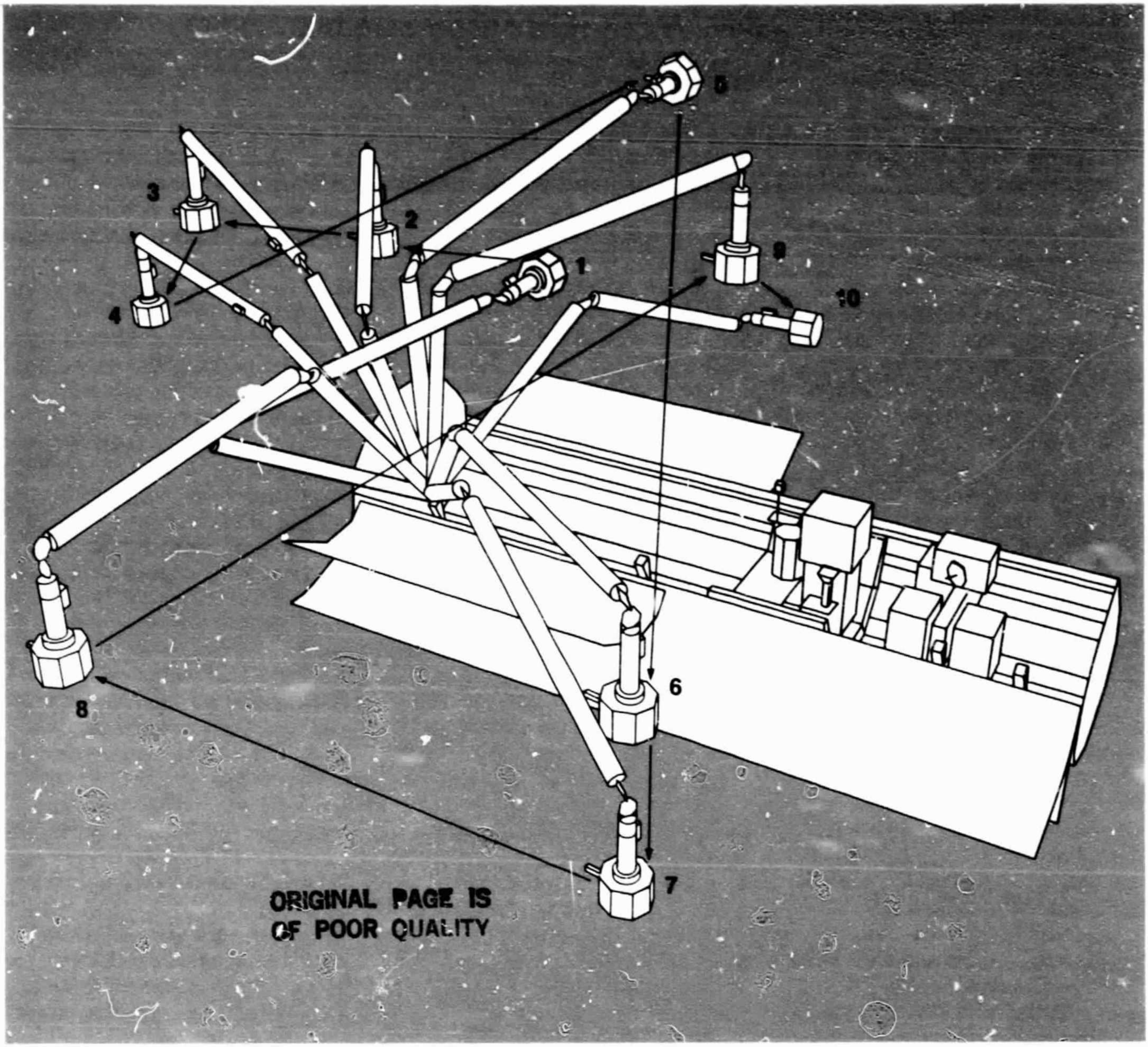
Inside the Shuttle, the cabin and mid-deck areas have proven themselves to be livable and practical working environments for a new generation of astronauts. The test flight crews monitored cabin air quality, pressure, temperature, radiation and noise levels and took films of their chores and activities in space, all to document the Shuttle's "habitability." Noise levels at certain locations inside the vehicle were higher than desirable, and continued testing was planned after OFT. Some items new to the Shuttle program also required minor adjustments, as happens often with a test program. New food packages generated large amounts of trash that required additional storage space; the Shuttle's toilet (Waste Collection System) needed several hardware adjustments before working correctly, and the STS-2 crew switched to wireless radio headsets after wires proved to be a nuisance to the crew of STS-1. On the positive side, the crews reported thtat their mobility inside *Columbia* was excellent, and they found that anchoring themselves in low gravity was easier than expected. There was almost no need to use special foot restraints, and crew members were able to improvise with ordinary duct tape attached to their shoes to hold themselves in place. Further re-design of low-gravity shoes continues.

In general, the eight astronauts of the test program found *Columbia* to be a comfortable place in which to live, work and perform experiments.

Return to Earth: The Airplane

At the conclusion of its business in orbit the Shuttle's payload bay doors are closed, the vehicle assumes a tail-first, upside-down posture and retro-fires its Orbital Maneuvering System engines to drop out of orbit. It then flips to a nose-up attitude and begins its descent through the atmosphere back to Earth.

In the early 1970's, the challenge of designing a re-usable spacecraft created the need for a special kind of insulation system that could withstand the burning friction of re-entry. Whereas earlier spacecraft used one-time-only shields that burned away, the Shuttle requires



STS-3 environmental survey using Plasma Diagnostics Package also tested arm motion in pre-programmed stops.

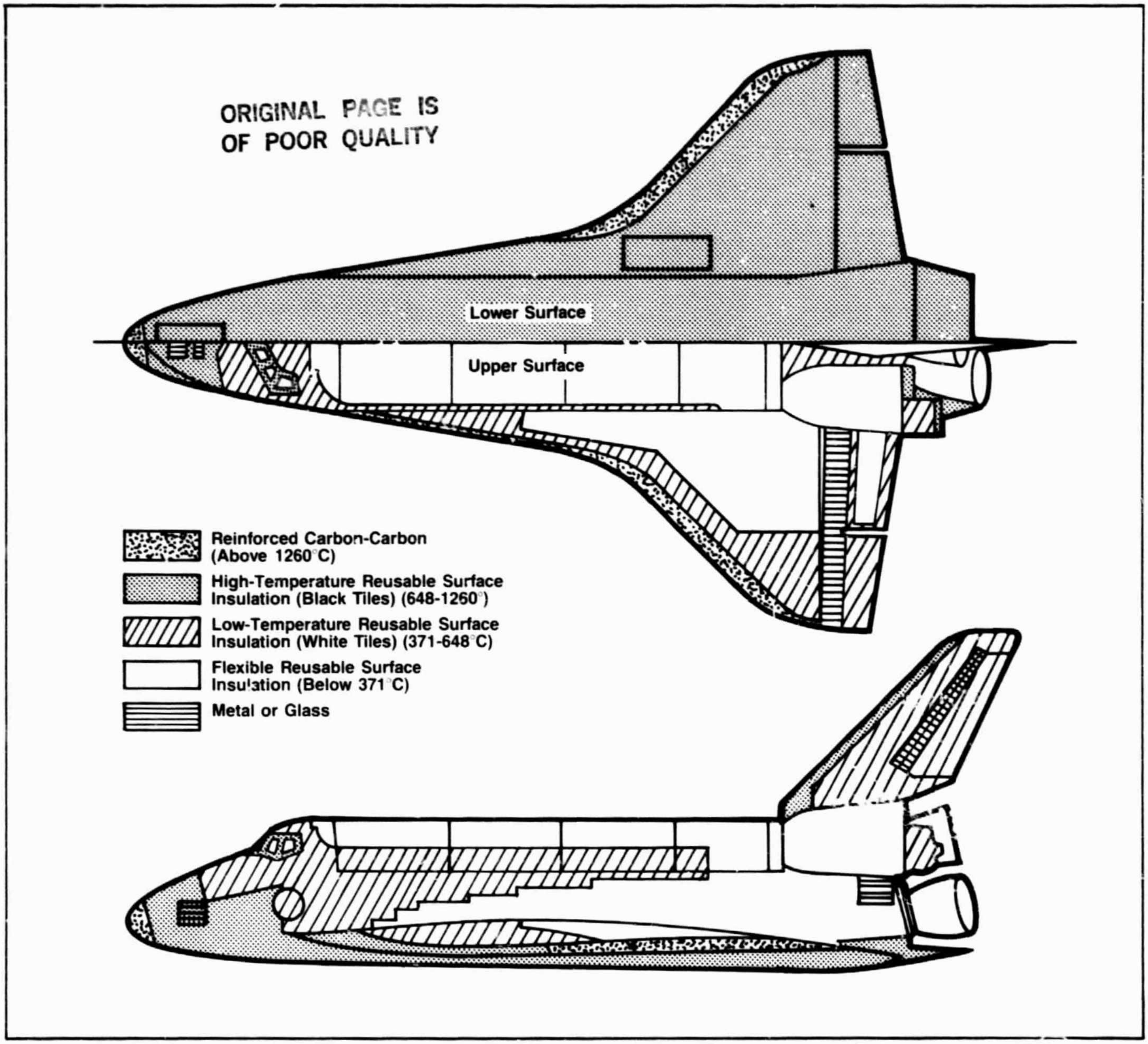
insulation that will survive intact to fly on the next mission.

Columbia's aluminum surface was covered with several different types of insulation during the test program, with their distribution based on predicted heating patterns. These included more than 30,000 rigid silica tiles of two types (black for high temperatures, white for lower) that account for over 70% of the Orbiter's surface area. Since these tiles were a critical new technology for the Space Shuttle, their performance was a major concern of the test program.

As soon as *Columbia* opened its payload bay doors in orbit on the first mission, TV cameras clearly revealed that several tiles were missing from the aft engine pods, having been shaken loose during the vehicle's ascent. These tiles had not been densified—a process that strengthens the bond between tile and Orbiter—as had all the tiles in critical areas, and every tile installed after October, 1979. None of the densified tiles were lost during the test flights.

On each flight there was some damage to tile surfaces during both launch and entry. Hundreds of pits and gouges were discovered during vehicle inspections after STS-1, then again after STS-2. While the damage was not critical, many tiles needed to be replaced. Crew reports, launch pad cameras and cockpit films recorded chunks of ice and/or insulation falling from the external tank during ascent as well as launch pad debris flying up and hitting the Orbiter, and these impacts were blamed for most of the tile damage.

Over the course of the test program various solutions to this problem were implemented. A general clean-up of the pad before launch and the removal of a particular insulation that had kept coming loose from the booster rockets cut down significantly on pad



***Columbia* was covered with several types of insulation during the test program, all with different heat load capacities. Reinforced carbon-carbon was used where temperatures exceeded 1260° C (2300° F), whereas a flexible insulation was adequate for the cooler engine pods.**

debris. On the external tank, certain pieces of ice-forming hardware were removed. As a result, impact damage to the tiles was greatly reduced. While some 300 tiles needed to be replaced after STS-1, fewer than 40 were replaced after STS-4.

Weather also inflicted its share of tile damage during the test program. Factory waterproofing of new tiles does not survive the heat of a re-entry, and so *Columbia* had to be sprayed with a commercial waterproofing agent after each mission so as not to absorb rainwater on the pad. The waterproofing agent was found to loosen tile bonds where it formed puddles, though, and STS-3 lost some tiles as a result. Then, while STS-4 sat on the pad awaiting launch, a heavy hail and rainstorm allowed an estimated 540 kilograms (1200 pounds) of rain water to be absorbed into the porous tiles through pits made by hailstones. This water added unwanted weight during ascent and later caused motion disturbances to the vehicle when it evaporated into space. Shuttle engineers now plan to use an injection procedure that will waterproof the interior of the tiles between future missions.

As a whole, the Thermal Protection System kept the Orbiter's skin within required limits during the OFT flights, even during the hottest periods of re-entry. For the test program's last three flights the crews performed short-duration "push-over/pull-up" maneuvers—changes in the vehicle's pitch angle—designed in part to test the effects of different attitudes on heating. Heating on the control surfaces was increased in stages over the four flights, and on STS 3 and 4 the angle of entry into the atmosphere was flown steeper to collect data under even more demanding conditions. On each flight hundreds of heat sensors placed around the vehicle, next to its skin and at various depths in the insulation contributed data on re-entry heating. In most areas these sensors reported temperatures consistent with pre-flight predictions. Notable exceptions were the aft engine pods, where some low-temperature flexible insulation was replaced with high-temperature black tiles after STS-1 showed high temperatures and scorching.

Data collected during the OFT program will allow engineers to continue with planned weight reductions and changes in insulation, including the replacement of the white tiles with an advanced flexible insulation.

Aerodynamic Tests

At the same time as Shuttle heating was being evaluated *Columbia* was also being tested as the world's most advanced glider during its return to Earth at the end of each mission. The major objective of aerodynamic testing was to verify controlled flight over a wide range of altitudes (beginning at 120,000 meters (400,000 feet) where the air is very thin) and velocities, from hypersonic to subsonic. In both manual and automatic control modes the vehicle flew very reliably and in agreement with wind tunnel predictions.

The OFT tests required large amounts of data from the Aerodynamic Coefficient Identification Package (ACIP) as well as ground tracking data and pilot reports on vehicle handling. Data analysis will continue many flights into the operational era as engineers refine their models.

Post-landing inspection of tiles on lower surface of body flap reveals damage caused by impacts and scorching of tile fillers.

In the early, computer-controlled phase of re-entry the Shuttle keeps its nose up at a steady "angle of attack" as it descended. This angle was 40° for the test flights, but it will often be shallower later in the Shuttle program. During this time the vehicle also executes several rolling S-turns designed to reduce lift and velocity. These were successfully tested as both manual and automatic maneuvers.

There were also a number of special test maneuvers—up to 23 on STS-2—performed on each flight either as programmed inputs by the guidance computer or as control stick commands by the crew, where the vehicle's flaps and rudder were positioned to stimulate more demanding flight conditions or to fill data gaps where wind tunnel testing was not adequate.

They included the "push-over/pull-up" changes in pitch angle that momentarily simulate a different vehicle center of gravity so that engineers can predict the aerodynamics with different payloads in the cargo bay. There were also stress tests on the rudder and control flaps at various speeds and pressures, and exercises where the "autopilot" was called on to correct the Shuttle's attitude after the crew deliberately induced other motions. These corrections were executed perfectly. On the first flight *Columbia* even made an unplanned-for correction in the angle of its aft body flap. While engineers had predicted an angel of 8 to 9° for the flap at high altitudes, the actual angle required to maintain the proper attitude was 14°. The computers made this adjustment automatically.

In the thin upper atmosphere the Shuttle uses its reaction control thrusters to help maintain its attitude. Over the four test flights these thrusters showed a greater-than-expected influence on the vehicle's motion in the atmosphere. This may allow engineers, as they learn more about Shuttle flight, to reduce the reliance on these thrusters or perhaps even phase out their use altogether during re-entry. This would save on reaction control fuel.

The Orbiter's navigation and guidance equipment also served well during re-entry. Probes that monitor air speeds were successfully deployed at speeds below approximately Mach 3 (three times the speed of sound), and navigational aids by which the Orbiter checks its position relative to the ground worked well with only minor adjustments.

Unlike returning Apollo capsules, the Space Shuttle has some crossrange capability—it can deviate from a purely ballistic path by gliding right or left of its aim point and so, even though it has no powered thrust during final approach it does have a degree of control over where it lands. The largest crossrange demonstrated during the test program was 930 kilometers (580 miles) on STS-4, and this will be increased on later flights. OFT astronauts flying the Shuttle in calm air reported that *Columbia* showed tighter control than had their Shuttle training aircraft, and called it a "fantastic flying machine."

The Space Shuttle has the capability to return to Earth with full computer control from atmospheric entry to the runway. During the test program, however, *Columbia* was not landed automatically. The STS-1 approach and landing was fully manual. On STS-2 the auto-land control was engaged at 1500 meters (5000 feet) altitude, and the crew took over at 90 meters (300 feet). Similarly, STS-3 flew on auto-land from 3000 meters (10,000 feet) down to 39 meters (130 feet) before the commander took stick control. It was decided after an error in nose attitude during the STS-3 landing that the crew should not take control of the vehicle so short a time before touchdown. The STS-4 crew therefore took control from the auto-land as *Columbia* moved into its final shallow glide slope at 600 meters (2000 feet). Full auto-land capability remained to be demonstrated after STS-5, as did a landing with a runway crosswind.

Stress gages on the landing gear and crew reports indicate that a Shuttle landing is very smooth—smoother than most commercial airplanes. Roll-out on the runway after touchdown was well within the 4500 meter (15,000 foot) design limit on each landing, but the actual touchdown points were all considerably beyond the planned touchdown points. This is because the Shuttle has a higher ratio of lift to drag near the ground than was expected, and "floats" farther down the runway.

Ground Work

Most of the work of the Space Transportation System is actually done on the ground, most of it at the Kennedy Space Center in Florida. The OFT program verified thousands of ground procedures from mating the vehicle before launch to refurbishing the Solid Rocket Boosters and ferrying the Orbiter form landing site to launch pad.

As the test program progressed many ground operations were changed or streamlined as engineers learned more about the vehicle's capabilities. Certain tasks that had been necessary for an untried vehicle before STS-1 could be eliminated altogether. As a result of this learning the "turnaround" time between missions was shortened dramatically—from 188 days for STS-2 to 75 days between STS-4 and STS-5.

Major timesaving steps included:

- Leaving cryogenic fuels in their onboard storage tanks between flights rather than removing them after landing
- Alternating the use of primary and backup systems on each flight rather than checking out both sets of redundant hardware on the ground before each launch
- Reducing the number of tests of critical systems as they proved flight-worthy from mission to mission

By the end of the test program, the Space Transportation System had demonstrated ontime launch and landing (STS-4). The next mission (STS-5) delivered a commercial payload into orbit and so inaugurated the operational Shuttle era. Many tests were still to be done. The Shuttle will gradually progress to heavier payloads. But, not until the third Orbiter *Discovery*, is a Shuttle scheduled to have full 29,250 kilogram (65,000 pound) capability, due to a combination of weight reductions and engine upgrading. Manned aspects of the program such as spacewalks and seven-person crews had not yet been verified, nor had the Tracking and Data Relay Satellite System (TDRSS) for on-orbit communication, or the first Spacelab. Satellite servicing, launches from California, and landings in Florida had not been tried.

But the Orbital Flight Test program did verify that the Space Transportation System is sound and ready for the scientific, commercial and defense applications of the 1980's. Engineers will continue using data from the test program to upgrade the current fleet of Shuttles and to begin designing the space vehicles of the next century.