The Space Shuttle System [and Discussion]

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The Space Shuttle system

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The development and subsequent operation of the Shuttle as America's primary space transportation system is the culmination of several decades of research, technology application and engineering. This vast endeavour, which has enjoyed unprecedented success to date, is one of the great team efforts in our technological history. From the pioneering efforts of Goddard and Tsiolkovsky, the critical contributions of von Karman, the insight of Faget, and the dedicated efforts of a multitude of others, the Shuttle has become a reality.

The initial phases of Shuttle development involved extensive analysis and testing with margins carefully engineered to provide for technical contingencies, and operational results have verified the elegance of the design.

Though its capability to carry cargo has received the most attention, the Shuttle's capabilities in orbit will undoubtedly play a key role in the development of entirely new technologies and associated industries peculiar to the space environment.

This paper will discuss the evolution of the Shuttle system and postulate its future contributions to the industrialization of space.

Introduction

Space vehicles with capabilities like the Shuttle's were conceived long before a technology base was available to make them a practical consideration. Through the successively more sophisticated Mercury, Gemini and Apollo programmes of the 1960s, propulsion technology was greatly advanced and much was learnt about re-entry of spacecraft into the Earth's atmosphere. The technical jump from the 60000 lb (27000 kg) Apollo Command Module to the 240000 lb (109 000 kg) Orbiter, with aeroplane geometry, was impressive in itself. But more importantly, unlike its predecessors, the Orbiter is a 100-mission reusable spacecraft designed for years of reliable, easily maintainable service.

The most versatile spacecraft ever designed, the Space Shuttle, is already expanding our thinking and planning about the future use of space. Along with its 65000 lb (29500 kg) payload capacity, the Shuttle provides access to and from space for men and equipment, relatively unlimited payload capability through multiple missions, and unmatched versatility of operations once in orbit. By making space flight a routine event, the Shuttle will transform the way we operate in space.

Shuttle development and testing

The development phase of the Shuttle programme was characterized by extensive tests of all major subsystems and led to the first orbital Shuttle flight in April 1981. I will highlight several areas of interest in design and verification testing and summarize the overall system flight-test results.

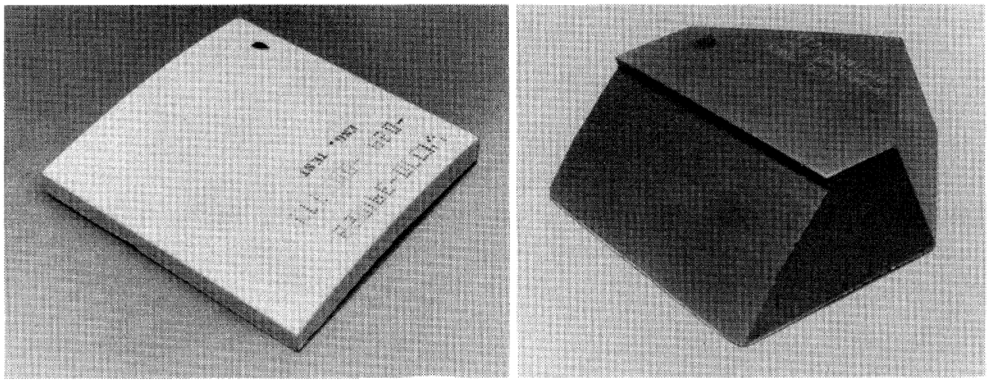

FIGURE 1. Two tiles from the Shuttle's thermal protection system.

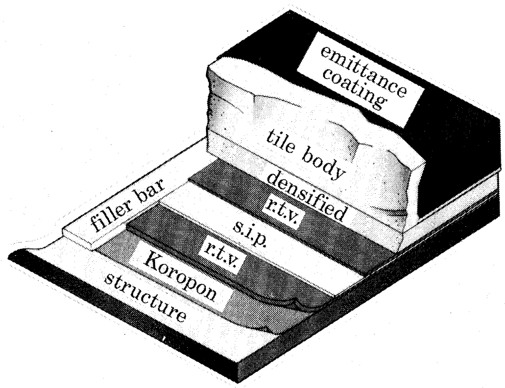

FIGURE 2. The tile fabrication process.

Thermal protection

The Shuttle's thermal protection system includes over 20000 tiles with a total mass of less than 15000 lb (6.8 Mg). The tile material is silica fibre with low tensile strength in the 15–30 lb f. in^{-2} (103–206 kPa) range. The basic purpose of the tile design is to provide thermal protection at the bond line of the aluminium structure. That requirement determines the thickness and often the shape of the tile. Therefore, essentially every tile in the system is different (figure 1); almost every one has a different part number and a different set of design loads. Furthermore, there are different coatings on the tiles with different optical properties for thermal control of the vehicle during the various flight phases.

Loads and stresses during nominal orbits, contingency orbits, return to launch sites, and other phases vary with time and flight condition for every tile. These variations required an analysis for each condition of 20000 individual tile systems; as can be appreciated, it was a major analytical endeavour.

The tile fabrication process is shown in figure 2. The basic structure has a Koropon coating that protects the aluminium. A room-temperature vulcanizer (r.t.v.) is applied to the Koropon so that a cohesive bond is established with the strain isolation pad (s.i.p.). The s.i.p. reduces the loads on the tile caused by structural deflection. The tile is bonded to the s.i.p. with additional r.t.v. A densified layer at the base of the tile distributes the loads uniformly into the tile. Finally, there is black borosilicate emittance coating. (It is interesting to note that, after five flights, the part numbers on Columbia's tiles were still legible (figure 3).)

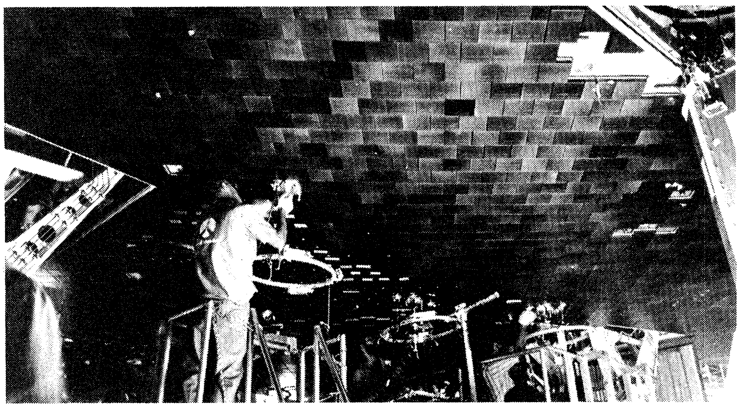

FIGURE 3. Tile installation.

Beginning with the second Shuttle Orbiter, Challenger, we began to replace some of the tiles on the upper portion of the vehicle with lightweight thermal blankets. The blankets are composed of the same silica material as the tiles, but are sandwiched between an inner and outer quilted blanket. They are designed to reduce fabrication and installation cost, and schedule time, and to further reduce vehicle weight. During Challenger's first orbital flight (STS-6) in April 1983, some blanket degradation, due to either vortex impingement or buffeting on the blunt forward face of the pods housing the orbital manoeuvring system and the reaction control system (figure 4), occurred. Analysis of the problem and flight testing of several blankets in selected areas of the vehicle during the STS-8 mission confirmed their integrity and gave us the confidence to continue the transition to blankets by replacing virtually all of the upper surface tiles on subsequent Orbiters.

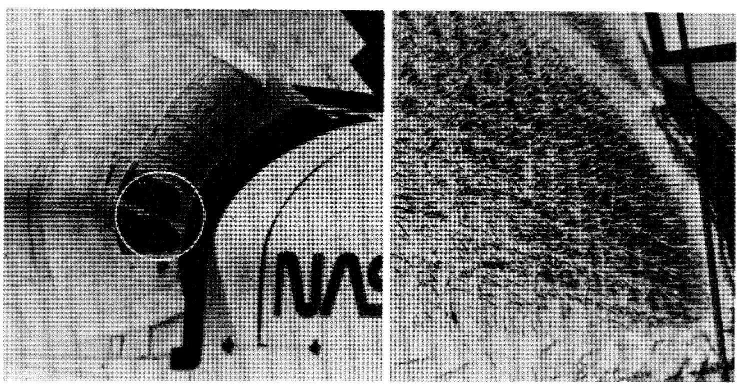

FIGURE 4. Unique aerothermal effects: blanket degradation.

Crew compartment

The crew compartment is an excellent example of a system engineering approach that involves many disciplines. Each mission phase – launch, in orbit, and re-entry to landing – represents a separate set of crew compartment requirements. At the heart of the crew compartment, other than the astronauts, of course, are the computers that form the nerve centre of the system. Today's Shuttle pilots soon become expert computer operators. The rotational hand controllers, rate gyros, and horizontal situation indicators give the impression of a conventional

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aeroplane cockpit. The selection switches for the autopilot modes are conveniently located on the display panel above the instruments. The three cathode ray tubes (c.r.ts) display anything the crew needs to know for operation: exactly where the vehicle is and where it is going to be. As the Orbiter approaches the landing site, for instance, the c.r.ts display where the vehicle will be in projected 20 s intervals if the present attitude is maintained. In addition, there is a 'heads-up' display so that the pilot can see flight information while looking through the forward window.

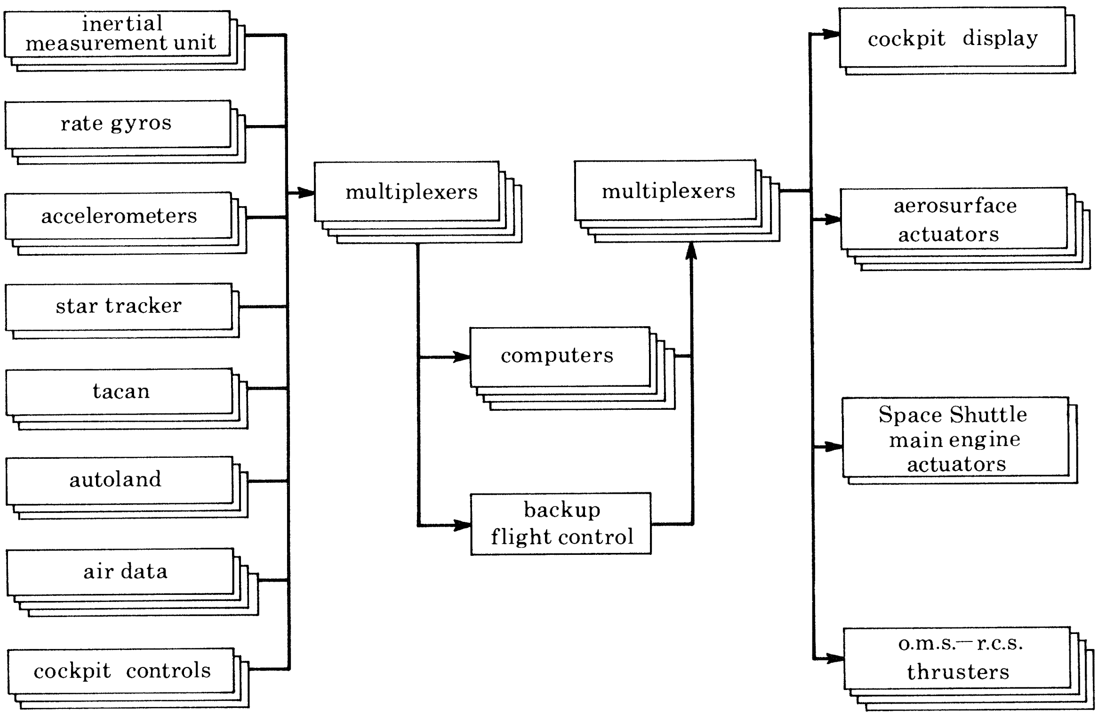

FIGURE 5. The navigation and control system.

Figure 5 is a simplified navigation and control system block diagram. The system redundancy provides a fail-operational/fail-safe system. In addition, a software back-up system constantly follows the primary system so that it can take over if a problem occurs. The back-up system uses separate software developed with a completely different approach so that a generic problem cannot arise in both primary and secondary systems.

The aft station is an integral part of the crew compartment. The c.r.t. and console displays give the astronaut full visibility and control of the payload bay. The astronaut also has a rotational controller to fly the Orbiter from this station. The windows, both above and facing the payload bay, allow rendezvous operations to be effected. The Shuttle's ability to carry a crew of seven is a major step forward in manned space operations (figure 6). In addition to the flight deck, there is a mid-deck for crew habitation and a lower compartment for equipment storage.

Main engines

The reusable main engines are a story in themselves (figure 7). They are very high performance engines, with oxygen pressures up to about 8000 lb f. in^{-2} (55.2 MPa) to feed the preburners. Very little enthalpy is lost; everything is recycled through the main combustion chamber to achieve the required maximum specific impulse. Furthermore, these engines are reusable. In previous space programmes, all engines finished up in the sea. Now that they are returned for inspection, we can refurbish and bring them that much closer to perfection for the next flight. We have never had that opportunity before.

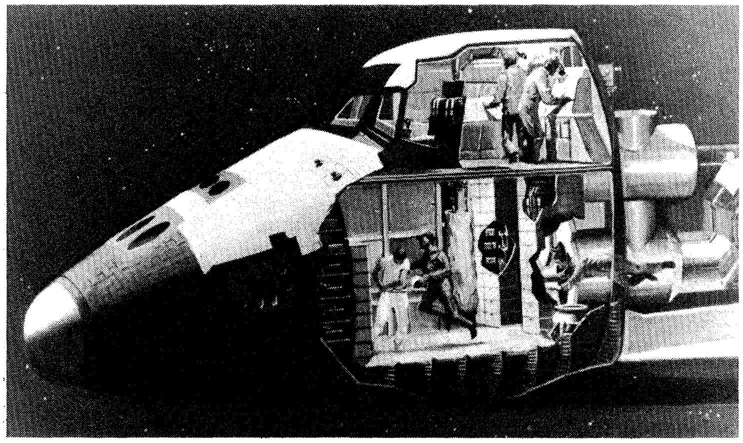

FIGURE 6. The crew compartment.

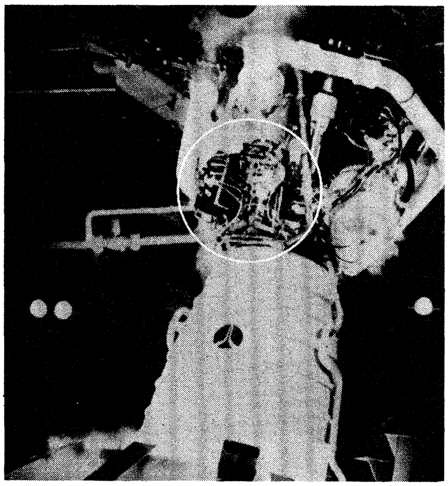

FIGURE 7. A main engine; it is reusable, lightweight, computer controlled and has a regenerative cycle.

The engines are also computer controlled. The computer is physically mounted on the engine, which is an unusual place to mount a computer, yet the engine performs so smoothly that the *g*-levels have been well below those the computer were designed to withstand. The main propulsion test stand in Mississippi includes the external tank and the actual aft end of the Orbiter vehicle, complete with the large 17 inch (43.2 cm) disconnecters, the engines, controllers, and other elements required for extensive combined system tests. Those tests have been very successful, and have lasted for about 165 ks in total. With engine performance verified, our testing now emphasizes their life and maintainability. There has been little trouble during boost; one of the basic reasons is that the engines have operated so well that the performance traces for them look like the computer plots calculated before flight. The jagged black line in

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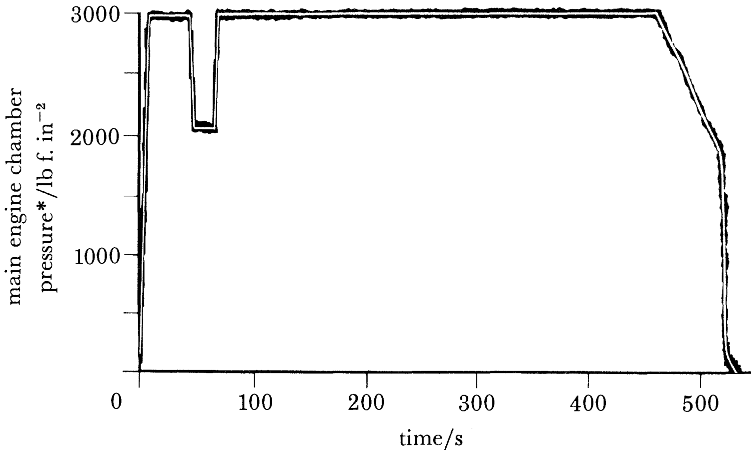

FIGURE 8. Comparison of theoretical main engine performance with actual performance. * 1 lb f. in^{-2} = 6.895×10^3 Pa.

FIGURE 9. The external tank.

figure 8 represents the actual preflight computer projections, while the straight line over it is a composite of main engine performance during the first five missions.

External tank

The enormous external tank (e.t.) supplies the fuel used by the Shuttle's main engines (figure 9). An imposing 155 ft (51 m) tall and 28 ft (9 m) wide, the e.t. contains approximately 1.58 million pounds (718 Mg) of usable propellant. The fuel, a combination of liquid hydrogen and liquid oxygen, is consumed by the main engines at a rate of 197 000 lb min^{-1} (90 Mg min^{-1}). After main engine cut off, at approximately eight minutes into flight, the e.t. is jettisoned and breaks up over the Indian Ocean. The e.t. is the only major Shuttle component that is not reusable.

Solid rocket boosters

Designed to be recovered and for use on twenty missions, the bulk of the 149 ft (33 m) long solid rocket boosters (s.r.b.) is the solid rocket motor (figure 10). Built by the Thiokol Corporation, the s.r.bs are the largest solid rockets ever to be flown and the first designed for re-use. A segmented case design affords maximum flexibility in fabrication and ease of transportation and handling.

S.r.b. tests entailed static firings of both a developmental and a qualification nature. Five developmental and four qualification firings were successfully made. In addition, to increase Shuttle performance by 5500 lb (or 2500 kg), a lightweight, filament-wound solid rocket motor is under development and is scheduled to become operational in late 1985.

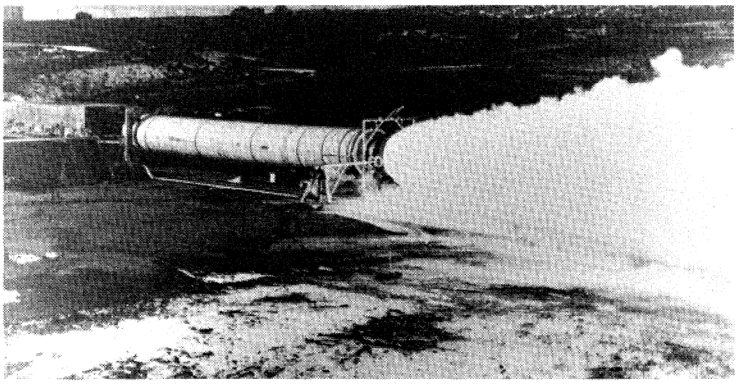

FIGURE 10. Solid rocket booster test firing.

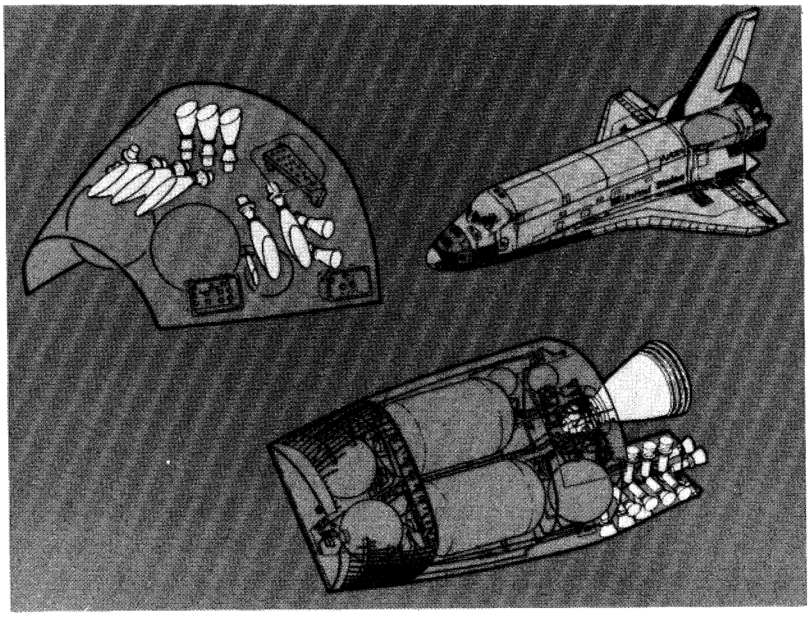

FIGURE 11. Orbiter manoeuvring capability.

Orbiter propulsion

The manoeuvring capability in orbit is made possible by two sets of engines (figure 11), the orbital manoeuvring system (o.m.s.) and the reaction control system (r.c.s.). The two o.m.s. engines provide the thrust for final entry into orbit, orbit circularization, orbit transfer, rendezvous and departure from orbit. Each o.m.s. engine produces 6000 lb (26.7 kN) of thrust. The o.m.s. is housed in two independent pods, located on each side of the Orbiter's aft fuselage, which also house the aft reaction control system.

The overall r.c.s. consists of a series of 44 engines that provide the thrust for attitude changes, manoeuvres (pitch, yaw, roll), and the thrust for small velocity changes along the Orbiter axis

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(translation manoeuvres) when the orbiter is above 70000 ft (21336 m). The forward r.c.s. module contains 14 primary thrusters and has two vernier thrusters, while the aft r.c.s. has 24 primary and 4 vernier thrusters. The primary engines provide 870 lb (3.87 kN) of thrust and the vernier engines provide 24 lb (107 N) of thrust. The r.c.s. engines are highly redundant; if one is lost, the capability of the system is not.

Development and test summary

To summarize, the two principal development results to date are that the system works and it is reusable. Refurbishment requirements are below those expected, which is reducing the turn around time. The consumables have been about 15% lower than expected, which presages a longer time in orbit. Nine missions have been flown to date; six of these were on one spacecraft. There are at least 94 to go, so there is a long way to go.

Flight accomplishments and results

STS-1 (12–14 *April* 1981)

The first Shuttle mission was truly remarkable for the first flight of a winged vehicle in a hypersonic environment in which no vehicle had been flown before. The STS-1 mission verified the integrity of the vehicle as all systems met or exceeded test goals.

STS-2 (12–14 *November* 1981)

The second Shuttle mission carried a 30 ft (9.14 m) long Imaging Radar antenna that was very successful in that it revealed sub-surface features of the Earth that had previously gone undetected. In the Sahara Desert, the radar uncovered ancient rivers that have been covered by sand for nearly 5000 years. Because the Sahara is the most arid region of the world, the radar was able to penetrate the sand as deep as 2 to 6 m. Analysis since this discovery has determined that there were flowing rivers in the area during the time of the pyramids, approximately 5000 years ago. Because of the great success of the radar antenna, it is being upgraded and will fly again on a Shuttle mission in summer 1984.

STS-3 (22–30 *March* 1982)

During STS-3 Commander Jack Lousma and Pilot Gordon Fullerton put the Shuttle's Canadian built robot arm through tests with a 400 lb (180 kg) test article. The arm is 50 ft long, (16 m) 15 inches in diameter (40 cm) and has mass 994 lg (452 kg). Four arms are being built by the Canadian government with an investment of approximately $100 million. It is operated in both automatic and manual modes from the Orbiter crew compartment. A mission specialist operates the arm by using dedicated controls, closed circuit television monitors and direct viewing through aft and overhead crew compartment windows.

The arm is a major Shuttle subsystem that will enhance payload servicing and repair, provide support for activities outside the spacecraft, and in the near future will be used to build large structures in space.

STS-4 (27 *June to* 4 *July* 1982)

President Reagan attended the fourth Shuttle landing, which completed its orbital flight tests on 4 July 1982. During his address he compared that landing to the driving of the golden spike that completed the first transcontinental railroad. To round the day off, the President gave consent for the second Shuttle Orbiter, Challenger, to begin its piggyback journey on a 747 to Florida in preparation for its maiden flight the following year.

STS-5 (11–16 *November* 1982)

The fifth Shuttle mission ushered in the operational phase of the Shuttle programme by delivering two communications satellites to orbit. The first satellite to be deployed by the Shuttle is owned by Satellite Business Systems (S.B.S.) of Virginia. S.B.S. is a joint venture of Comsat, I.B.M. and Aetna Life Insurance. This $40 million satellite was the third in a six satellite system that provides computer data, voice, video, and electronic mail services to American firms.

The fifth Shuttle mission also carried a satellite for Telesat of Canada, the Canadian phone company, which is used to relay television and phone messages throughout the North American continent.

STS-6 (4–9 *April* 1983)

During the sixth Shuttle mission we deployed the Tracking Data and Relay satellite, the largest non-military satellite ever built. The satellite was the first of a three-satellite system designed to replace N.A.S.As 20 year old ground-based tracking network.

The activities outside the Shuttle on the sixth Shuttle flight were the first by U.S. astronauts in nine years. They showed the importance of attention to detail: handholds, tethering provisions, and foot restraints, for example, engineered into the payload bay. Many mechanical functions were tested by using special tools designed for use in the absence of gravity. The 3.5 h test outside the Shuttle was a precursor to a capability that will come much more into play as this man–machine system's assignments in orbit evolve.

STS-7 (18–24 *June* 1983)

The five astronaut crew on the seventh Shuttle flight included the first American female astronaut, Sally Ride. The Shuttle's Canadian robot arm was again used, this time to actually deploy and retrieve a German satellite, the Shuttle Pallet Satellite known as SPAS; it was built by the West German firm, M.B.B. It is planned to use SPAS as the basis of a low cost commercial remote sensing platform (SPAR-X).

We received exceptional photography from cameras on the SPAS as it and the Orbiter played a game of 'orbital tag', which demonstrated the Shuttle's rendezvous and docking capability. The SPAS will fly again on the next Shuttle mission (STS-11 in January 1984). During STS-11, an astronaut with a backpack manoeuvring device will use the SPAS to practice docking procedures without a tether. STS-11 is a pathfinder mission that will lay the groundwork for the Shuttle's first satellite repair mission scheduled for April 1984.

STS-8 (30 *August to* 5 *September* 1983)

On this mission we deployed a satellite for India that incorporates the combined functions of telephone and data communications, direct broadcast television, and weather observation in one satellite. I understand that the satellite is operating successfully today, as are all six of the satellites deployed by the Shuttle to date. The eighth mission also demonstrated the ability of the Shuttle to deploy and berth very large payloads, shown by using the Payload Flight Test Article, which has a mass of more than over 7000 lb (3.175 Mg).

During the re-entry phase of this mission, Astronaut Donald Peterson noticed flashing in the overhead windows. Strapped down, he managed to take advantage of the opportunity and take excellent photographs of this pulsating wake, by pointing his camera in the aft direction. This phenomenon occurred early in the re-entry phase between the altitudes of 400000 to 250000 ft (122 to 76.2 km). At this point, the Orbiter travels at approximately Mach 24 and just begins to encounter the upper reaches of the atmosphere. The resulting high-temperature–low-pressure environment causes the air molecules to ionize and a plasma to build up that emits this pulsating sequence.

The Orbiter's glowing nose cone was revealed during landing by the use of infrared cameras. The glow is caused by the intense heating of approximately 2800 °C experienced by the nose cone during re-entry. STS-8 accomplished the first Shuttle night landing, which proved its capability to land at any time, an important requirement when the Shuttle begins landing in Florida where the weather is often better at night.

Delivery of Discovery

The third Shuttle Orbiter, Discovery, was delivered to the fleet on 1 November 1983; it will enable the flight rate to be increased to 10 missions in 1984 and 12 in 1985. A fourth Orbiter, Atlantis, is under construction and will be delivered next December to further expand the Shuttle fleet to meet the ever growing demand for the Shuttle's unique capabilities.

The Shuttle as a space transportation system and more

The STS was initially called a transportation system for a number of different reasons. That label is somewhat unfortunate because it is so much more than that. In addition to providing access to and from space for men and equipment, with its relatively unlimited payload capability through multiple missions, this spacecraft has unmatched versatility of operations once in orbit. Some of these capabilities will now be reviewed.

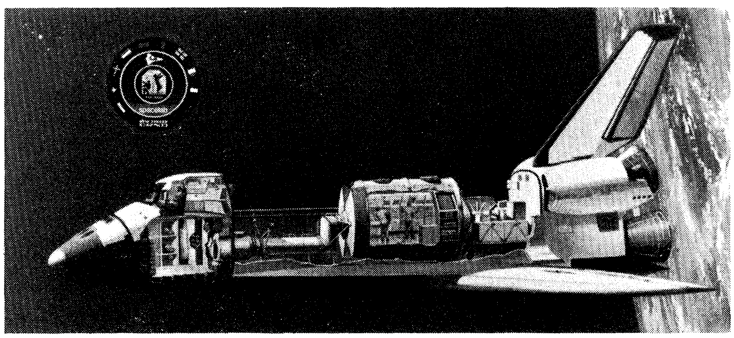

Figure 12. Spacelab 1 configuration.

Spacelab: a laboratory in space

The inauguration of the Shuttle–Spacelab era is the culmination of ten years of effort by the European Space Agency. The first Spacelab mission, STS-9, has just shown how versatile the system is (figure 12). Scientists from Europe, Japan, Canada, and the United States provided over 70 experiments covering astronomy, solar physics, space plasma physics, atmospheric physics, life sciences, and material sciences.

Spacelab was developed on a modular basis and can be varied to meet specific mission requirements. Its two principal components are the cylindrical module, which is pressurized to provide an environment in which astronauts can work without special clothing, and the U-shaped pallets in the back that directly expose telescopes, antennas, and sensors to space.

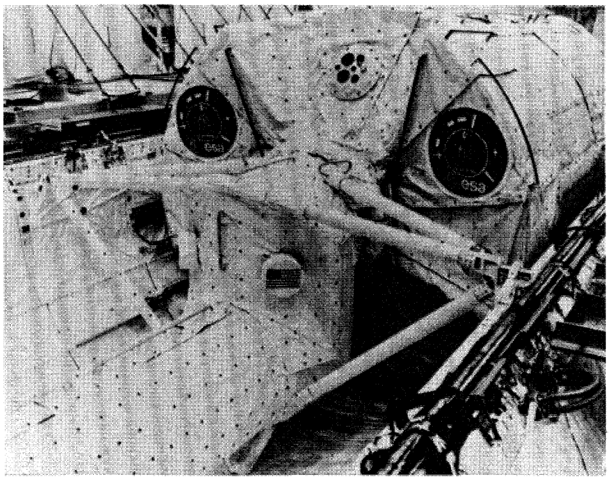

FIGURE 13. European Space Agency's Spacelab in the cargo hold of the Shuttle.

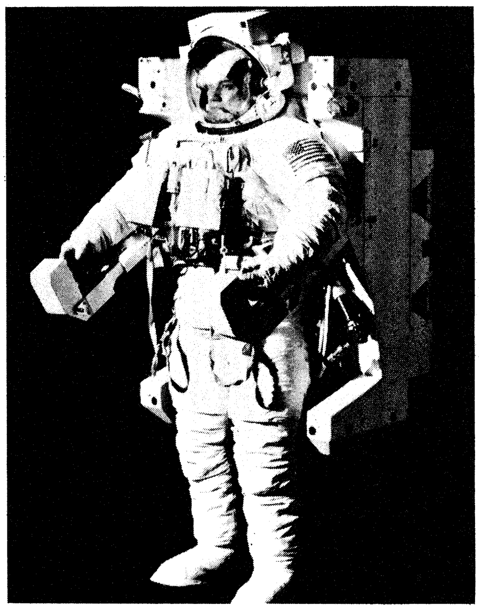

FIGURE 14. An astronaut wearing an m.m.u. to be used on the Solar Maximum mission.

The Shuttle–Spacelab combination will go a long way towards demonstrating the feasibility of international cooperation in space and will provide the foundation for manned and unmanned space stations of the future (figure 13).

Solar maximum repair

A key Space Shuttle service in orbit is the forthcoming rescue and repair of the Solar Maximum satellite planned for the STS-13 mission in 1984 (figure 14). Activities outside space vehicles by means of a manned manoeuvring unit (m.m.u.) will enable a crew member

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to fly to and stabilize the Solar Maximum satellite for attachment to the remote manipulator system and placement in the cargo bay. Once the satellite is secured on the payload bay mount, repair work will be initiated and checked. The Solar Maximum satellite will be redeployed by the remote manipulator system and returned to full operation as a solar observatory.

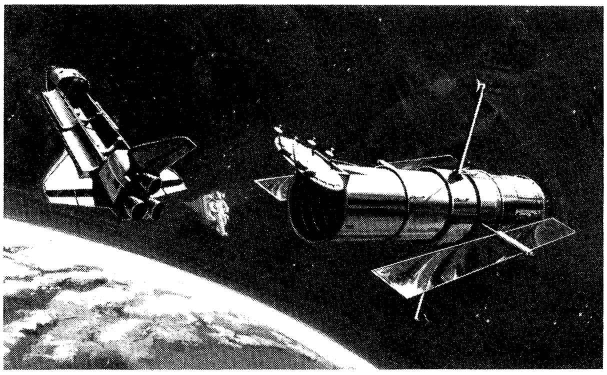


FIGURE 15. To illustrate the servicing capability of the Shuttle.

Space Telescope

Spacecraft such as the Space Telescope will be routinely serviced in orbit for extended use (figure 15). Orbiting spacecraft may have sensors, experimental packages, high resolution film, and other elements retrieved, and may be resupplied with new experiments, film, or provisions.

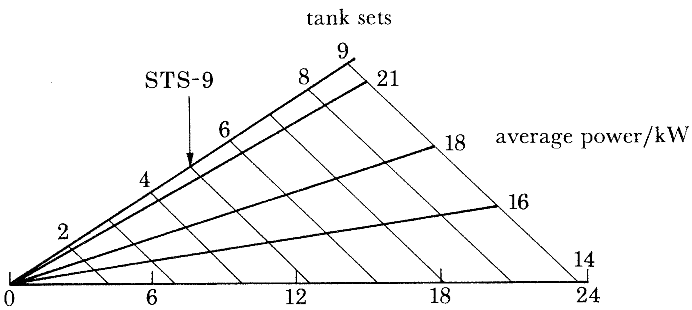


FIGURE 16. Increases in time spent in orbit.

Extended duration Orbiter

The time spent in orbit will be extended as orbital activities evolve; Shuttle users will definitely need to stay in space longer as experimentation becomes more rewarding and complex (figure 16). A cryogenic wafer can be added to the spacecraft that will extend the present 7 to 10 d capability up to approximately 15–18 d. A solar sail and battery combination with gaseous cryogens could provide 30 to 45 d in orbit. This aspect of Shuttle's capability, when added to the Skylab foundation, will assist in parallel the concept and development of permanent manned stations of the future. It will serve as a bridge between now and the date when a permanent station is a reality.

Expanding Shuttle operations

The Shuttle has already proven its ability to deliver and retrieve satellites (figures 17*a* and *b*). Both of these capabilities will dominate the early operational years of the Shuttle.

Satellite repair and servicing will begin early next year with the Solar Maximum repair mission (figure 17*c*). This first step will pay increased dividends in the future as satellite designers begin optimizing their satellites not only for repair, but also for routine improvements. The Spacelab era is here, and it will enhance our ability to explore all disciplines on a greatly expanded scale (figure 17*d*). Such work will lead to the commercial use of the space environment.

Until the advent of the Space Shuttle, the use of space had been limited by launch system capabilities. The Shuttle system has greatly expanded these limits (figure 17*a–f*). But in addition, the Shuttle provides the opportunity to have human wisdom and will in space. This allows us to perform assembly in orbit and thereby remove size and weight constraints for space structures.

It is my hope that through these advances, we will witness in the coming decades the realization of large-scale international space operations to further our scientific knowledge, to open commercial opportunities, and to enhance and improve life on Earth.

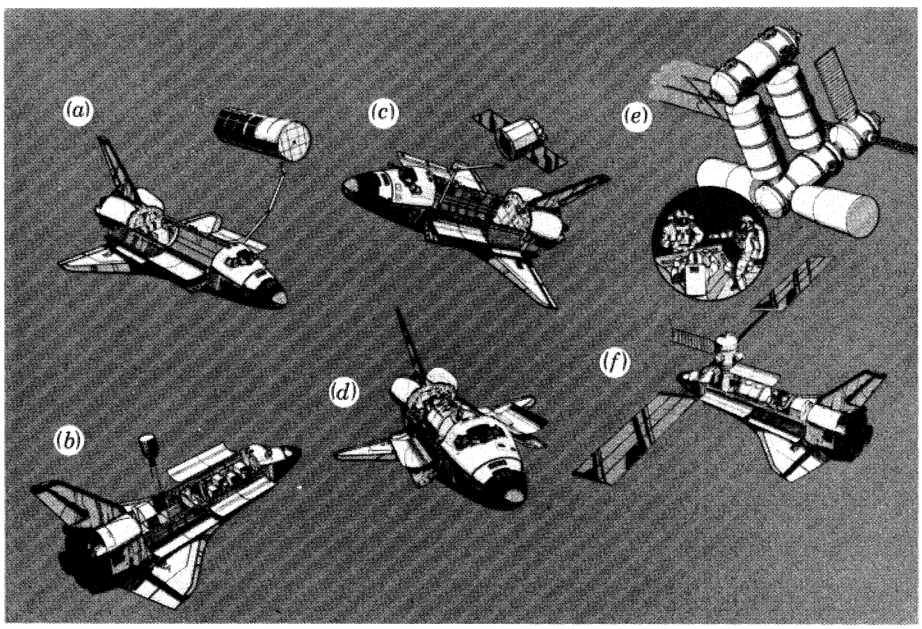


FIGURE 17. The Shuttle's uses: (*a*) retrieval; (*b*) satellite placement; (*c*) repair and servicing; (*d*) laboratory; (*e* and *f*) assembly.

Discussion

F. MILES (*Independent Television News, London, U.K.*). We have recently read and heard many inaccurate reports of a so-called 'emergency' facing Soviet cosmonauts aboard Salyut 7. I hasten to add that although we at I.T.N. are constantly ahead of others in reporting Russian space activities, we never once suggested the cosmonauts' lives were at stake. But we were puzzled by an extraordinary rumour published by others that Columbia was being made ready to rescue the 'stranded' cosmonauts. Could Mr Meechan comment on this and on the feasibility that at some time in the future a Shuttle might be used for a rescue mission and, if it could, how people would be transferred from one craft to another?

C. J. Meechan. At this time, the Shuttle Orbiter has no docking provisions to attach to other space structures. In the Apollo–Soyuz programme, we did develop such a mechanism to connect the two spacecraft. This was an androgenous connector, meaning that neither vehicle had a male or female connector (a story in itself). So, it can be done. However, at this point, retrieval of astronauts in space from another vehicle would require that the astronauts had space suits. Then they could be transferred into the Orbiter and returned to Earth.

C. Ledsome (*The Design Council, London, U.K.*). About fifteen years ago, as one of the final parts of the Apollo applications programme, the company I then worked for, now known as Teledyne Brown, produced a design for a spacecraft docking port that could be docked with itself rather than needing a mating port. This was used on the Apollo–Soyuz mission and the intention then was to fit such a port on all future spacecraft to facilitate rescue from any craft by any other craft. I understand from your previous remarks that such ports are not fitted on the Shuttle. Could you comment please?

C. J. Meechan. That is correct, we had such ports for the Apollo–Soyuz mission. We do not have such connectors on the Shuttle, but we have proved that it can be done and we could return to a similar concept in the future.

D. O. Fraser (*British Aerospace p.l.c., Dynamics Group, Space and Communications Division, Bristol, U.K.*). Is there anything being done to develop a recoverable first stage for the Shuttle?

C. J. Meechan. There have been studies conducted to recover or further utilize the external tank, which I believe you refer to. It is not practical to recover it, but it may be practical to continue its boost into low Earth orbit and use the structure for other purposes. Also, there always remains some fuel in the tank and this residue might be utilized in orbit. Work along these latter directions continue and I would expect that further utilization of the external tank will occur in this decade.

D. Whitehouse (*Mullard Space Science Laboratory, Dorking, Surrey, U.K.*). Could you comment on the total number of Space Shuttle launches, their frequency and the lifetime of the shuttle system?

C. J. Meechan. First, let me say that we have just delivered the third Orbiter, Discovery, to N.A.S.A. and will deliver the final one on order, Atlantis, in late 1984. In 1984, the three Orbiters will be used in 10 launches. In subsequent years we expect the launch rate to grow to over 20 launches per year with this fleet. We plan for 100 mission design life with refurbishment and standard maintenance, which, if all goes well, should take us well into the next century with the current fleet. However, prudent planning would suggest that we should build additional Orbiters in this time period.

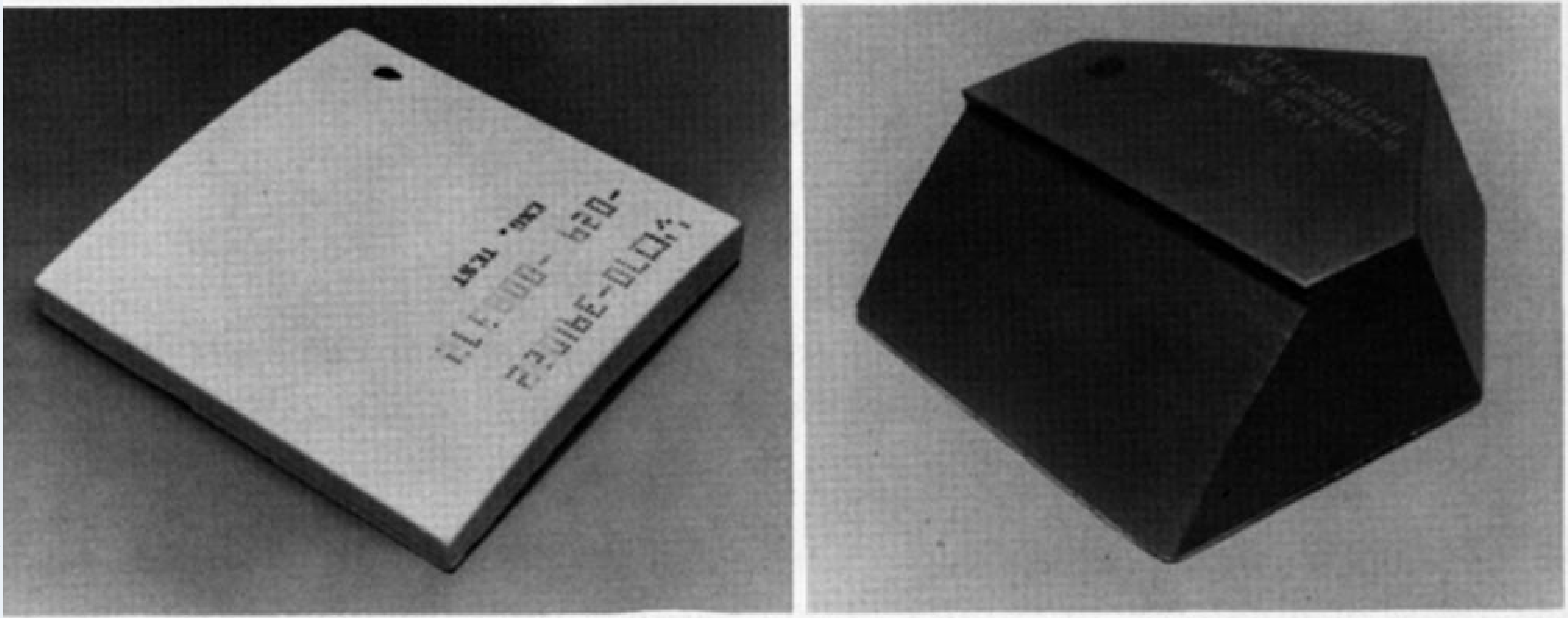


FIGURE 1. Two tiles from the Shuttle's thermal protection system.

FIGURE 3. Tile installation.

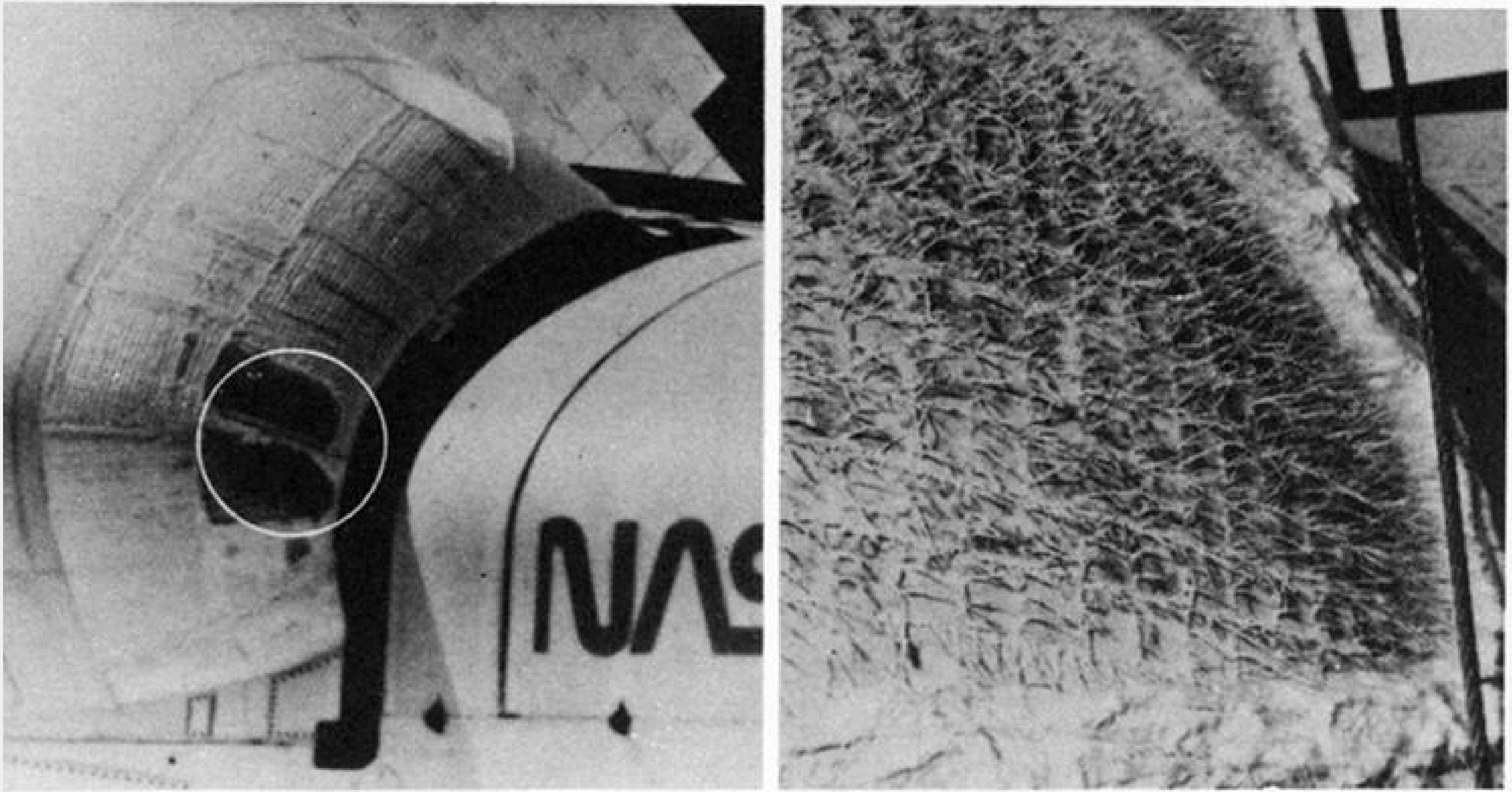


FIGURE 4. Unique aerothermal effects: blanket degradation.

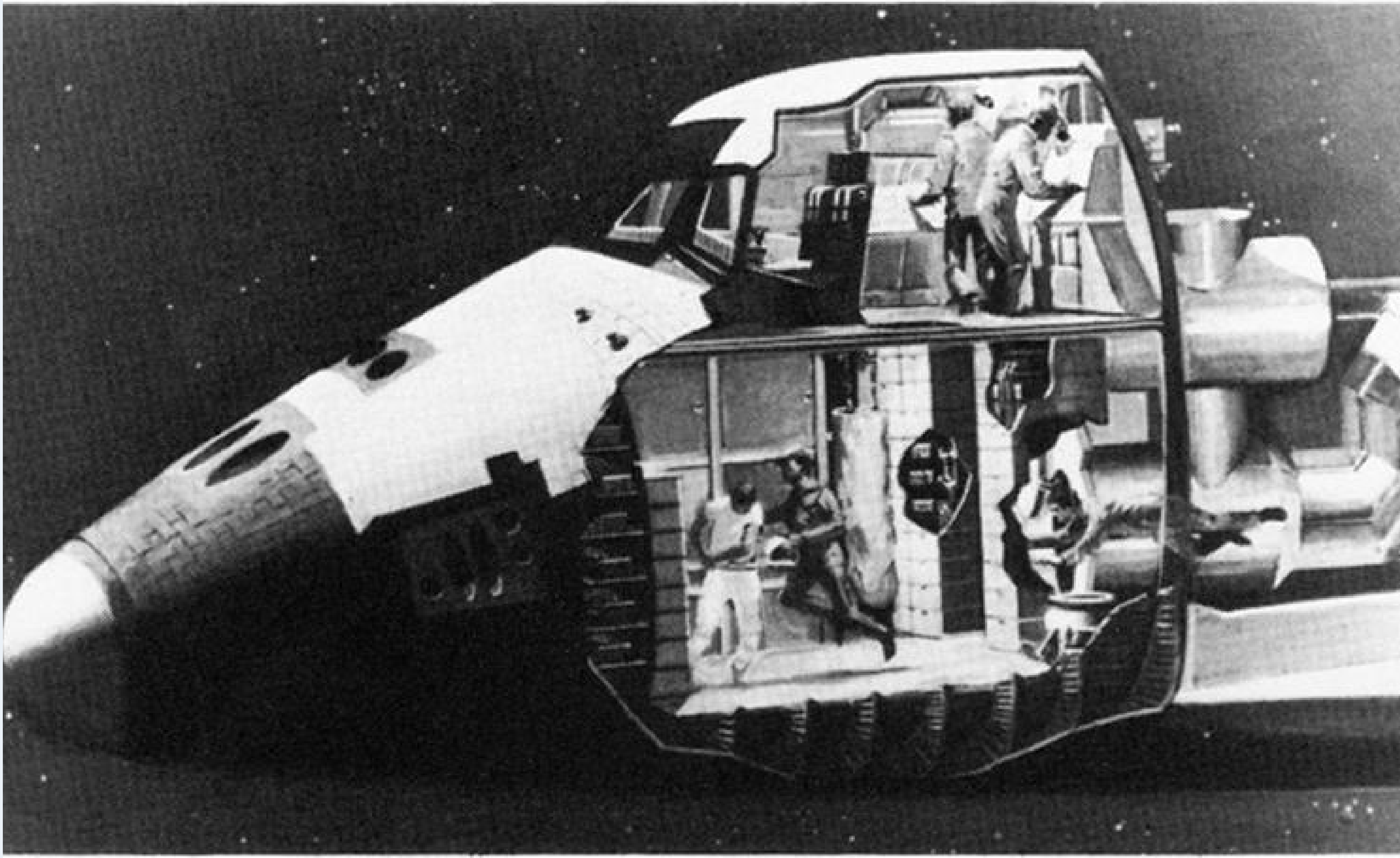
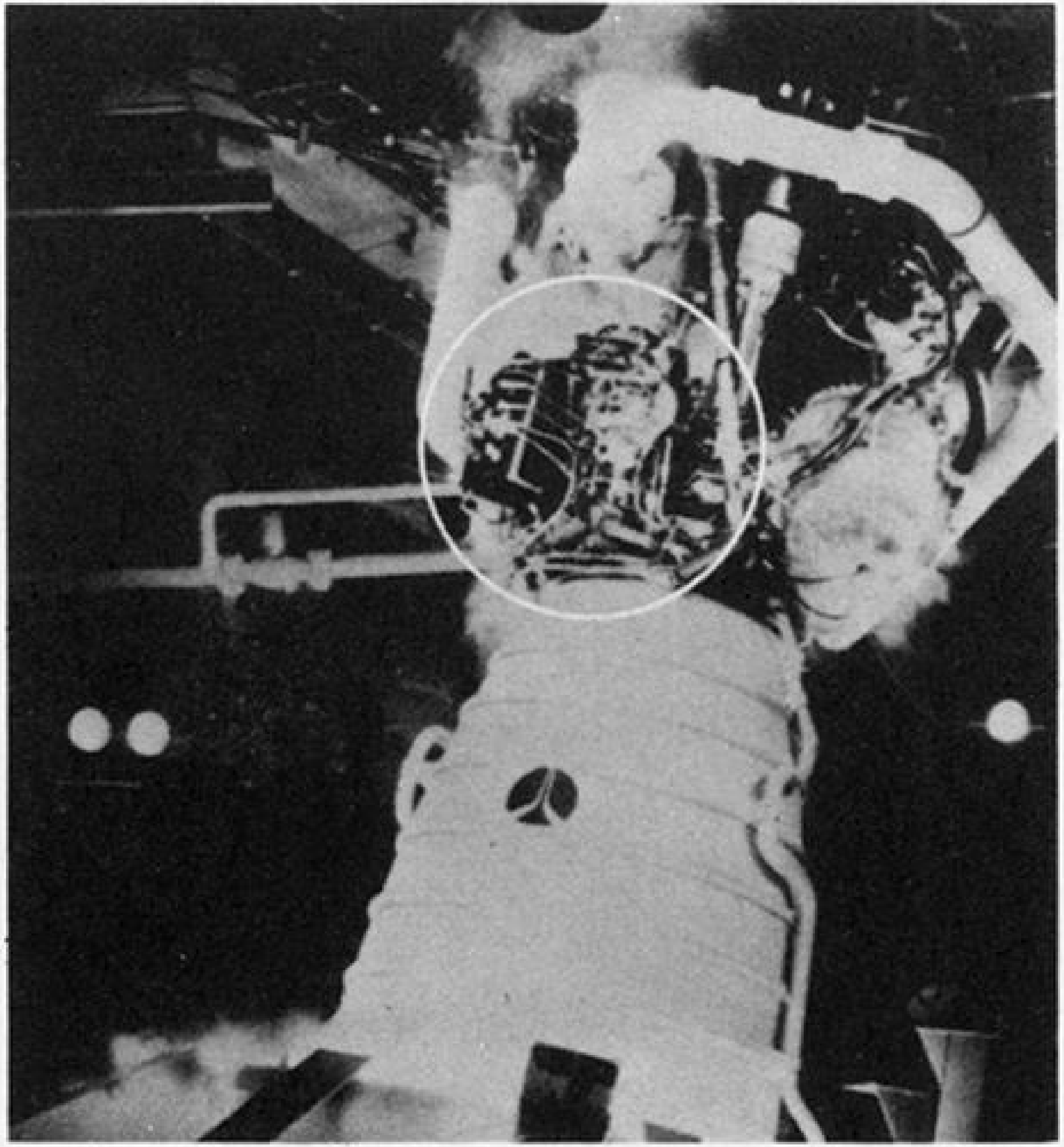


Figure 6. The crew compartment.



IGURE 7. A main engine; it is reusable, lightweight, computer controlled and has a regenerative cycle.

FIGURE 9. The external tank.

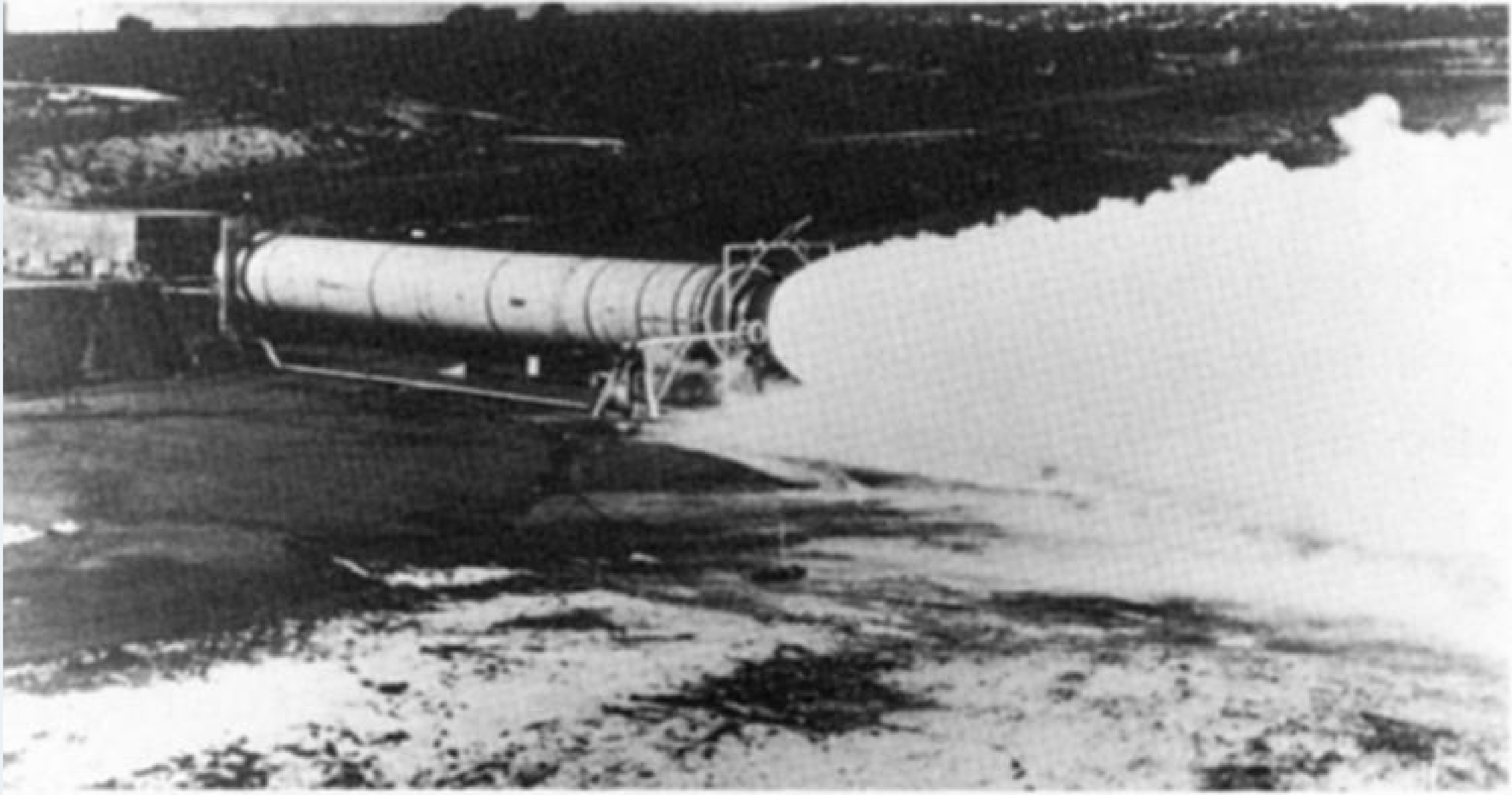


FIGURE 10. Solid rocket booster test firing.

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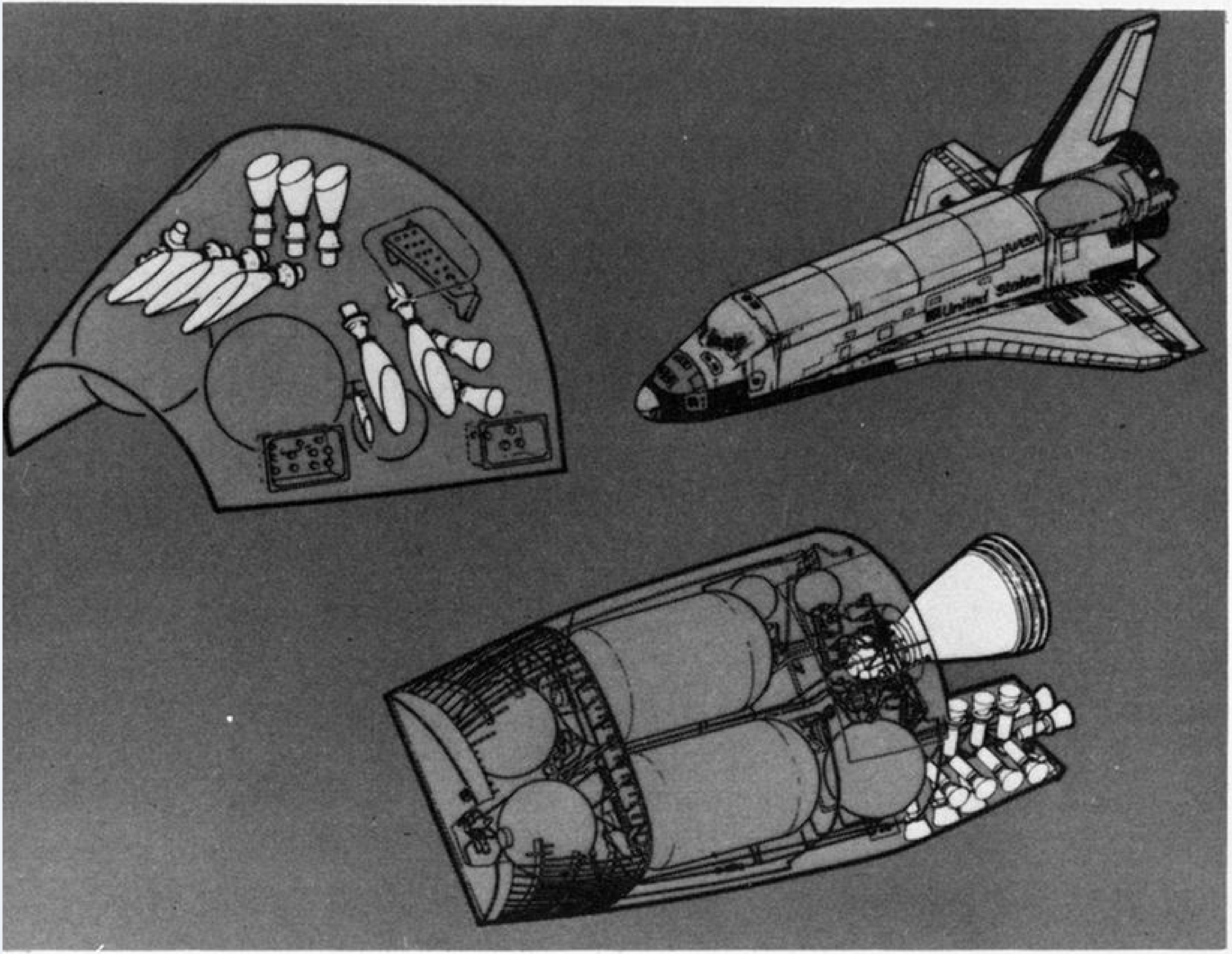


FIGURE 11. Orbiter manoeuvring capability.

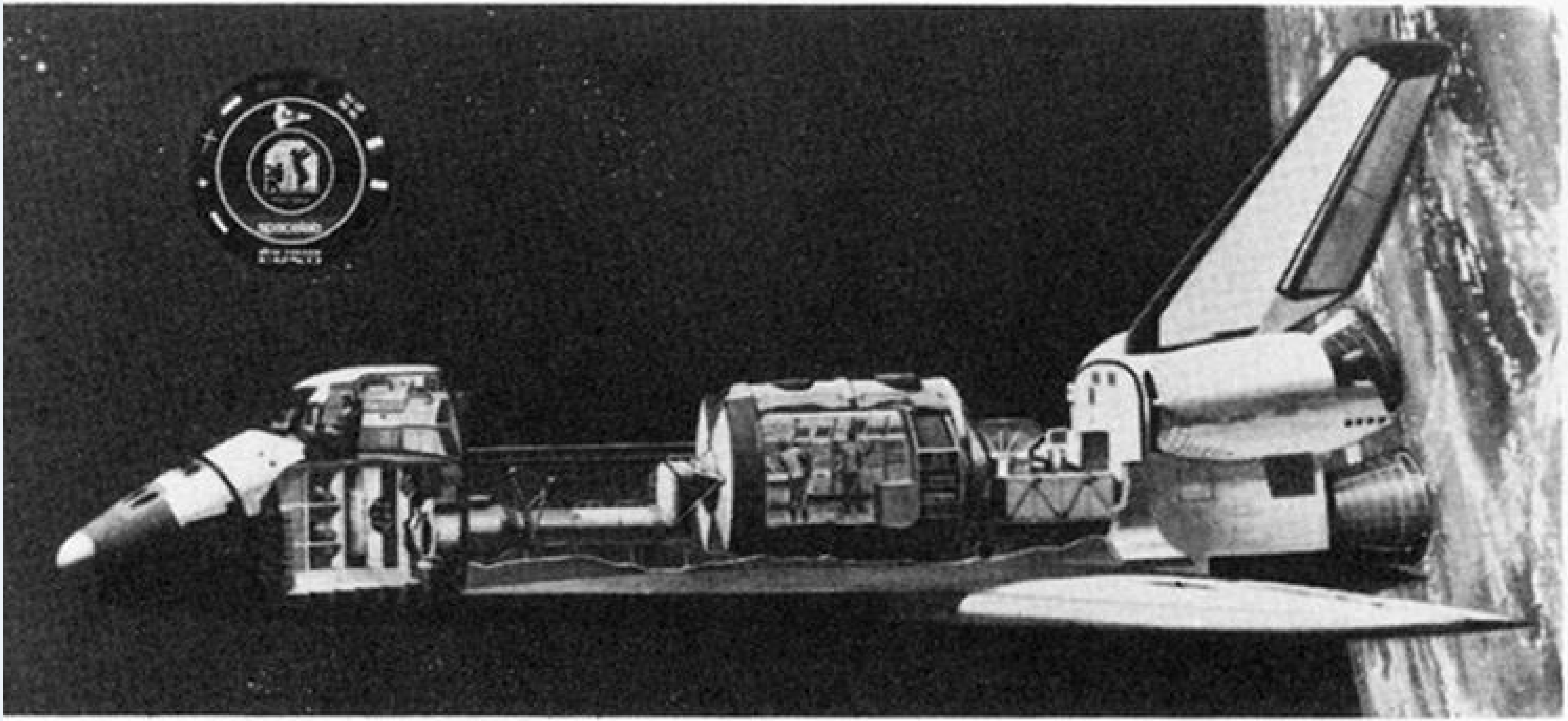
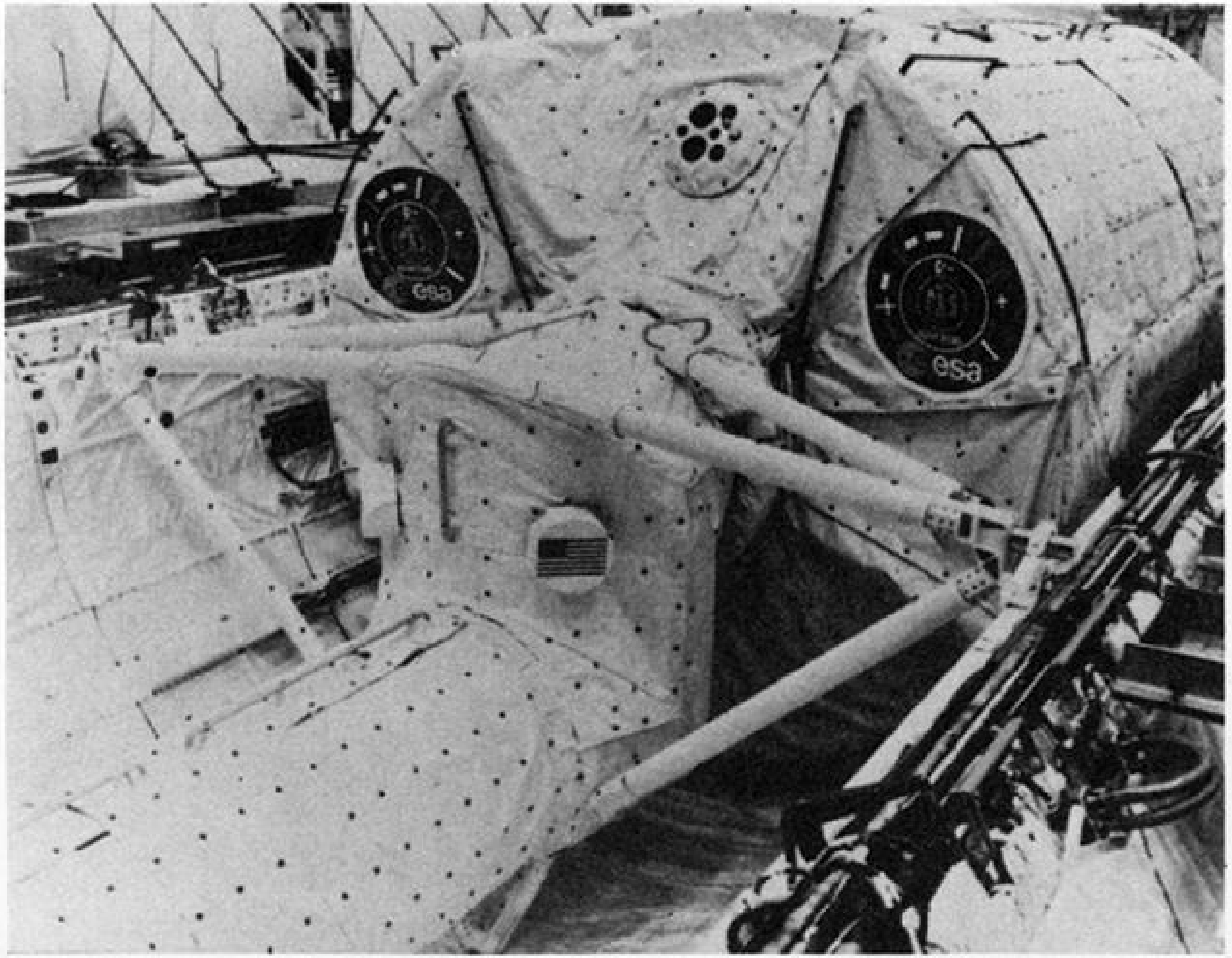


FIGURE 12. Spacelab 1 configuration.



IGURE 13. European Space Agency's Spacelab in the cargo hold of the Shuttle.

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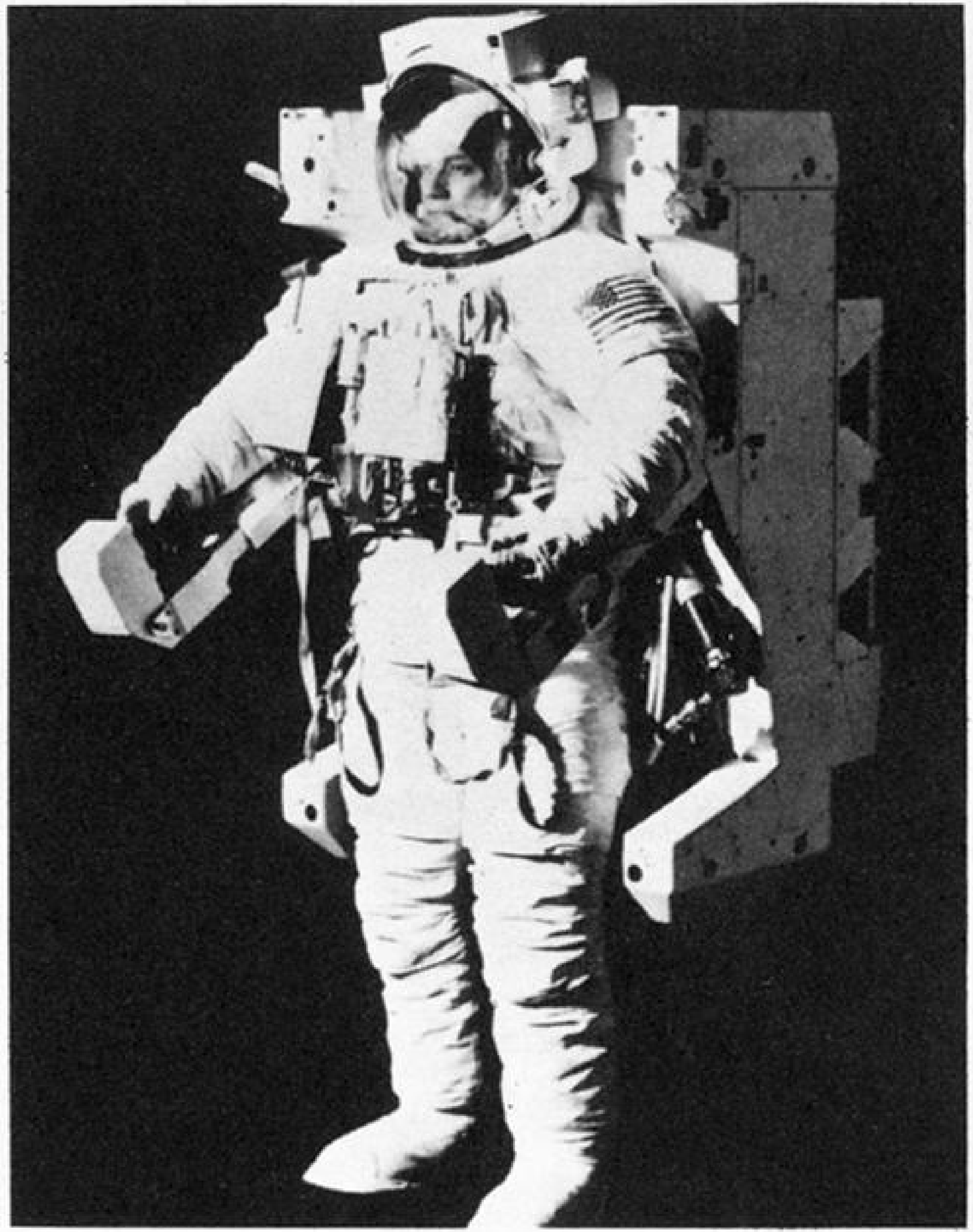

'IGURE 14. An astronaut wearing an m.m.u. to be used on the Solar Maximum mission.

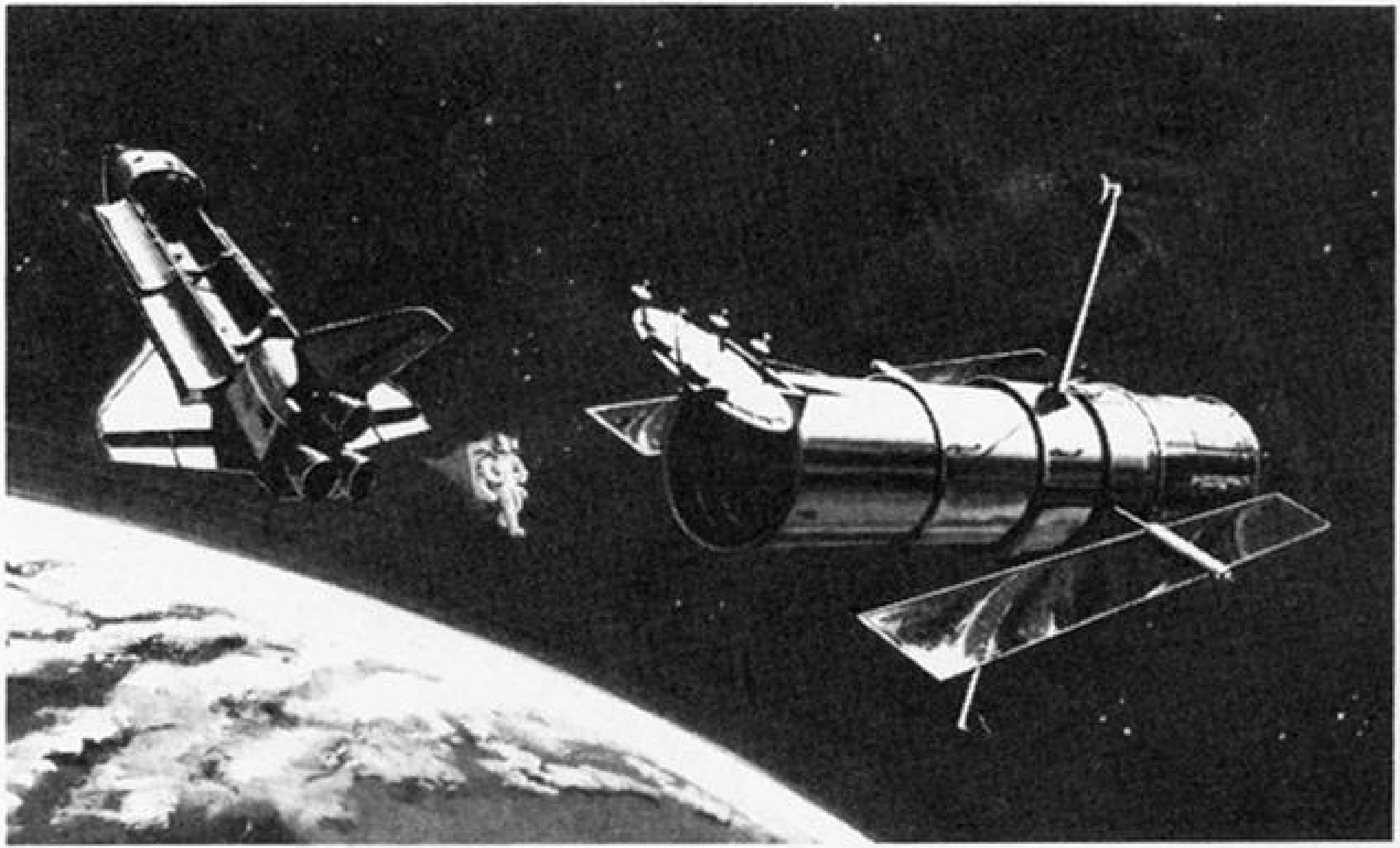

FIGURE 15. To illustrate the servicing capability of the Shuttle.

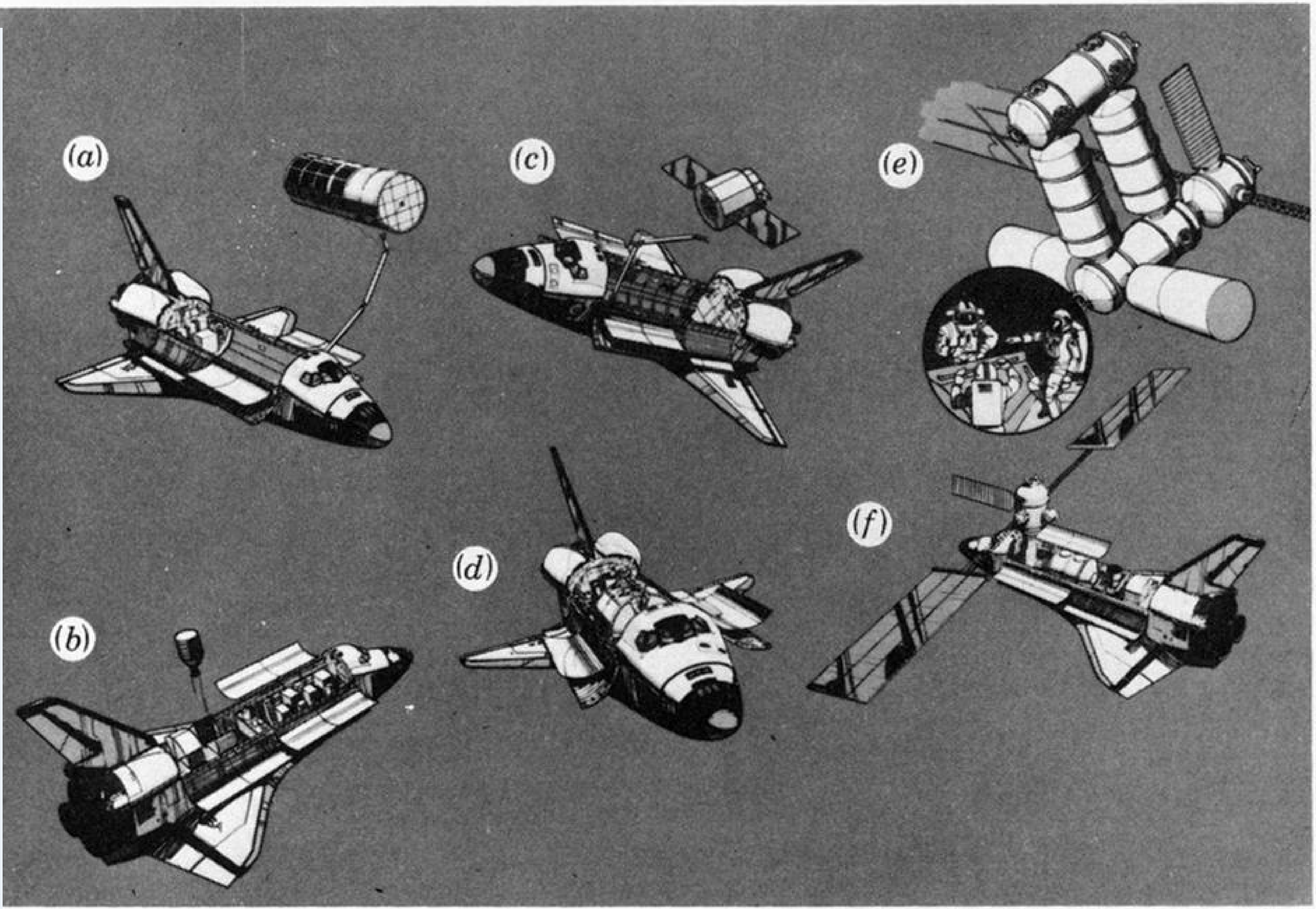

FIGURE 17. The Shuttle's uses: (*a*) retrieval; (*b*) satellite placement; (*c*) repair and servicing; (*d*) laboratory; (*e* and *f*) assembly.