DOCUMENT RESUME

ED 184 888 SE 030 569

AUTHOR Allaway, Howard
TITLE The Space Shuttle At Work.
INSTITUTION National Aeronautics and Space Administration, Washington, D.C.
REPORT NO NASA-EP-156; NASA-SP-432
PUB DATE 79
NOTE 82p.; Colored photographs will not reproduce well.
AVAILABLE FROM Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402 (Stock No. 033-000-00779-5; No price quoted).

EDRS PRICE MF01/PC04 Plus Postage.
DESCRIPTORS Aerospace Education; *Aerospace Technology; Aircraft Pilots; Astronomy; Aviation Technology; *Futures (of Society); Science Education; Scientific Research; Secondary Education; Secondary School Science; *Space Sciences; *Technological Advancement

ABSTRACT

This report describes the Space Shuttle vehicles and is prepared by the Scientific and Technical Information Branch and Division of Public Affairs of the National Aeronautics and Space Administration. The book is divided into nine chapters including information about the launching, flight, and orbit of the ships; the satellites and previous space missions that preceded the Space Shuttle; cost and design and what influenced the design; typical projects in space; and future possibilities in space. The text is accompanied by photographs and illustrations both in color and black and white. A large fold-out diagram of the inside of the Orbiter is included. (SA)

ED184888

NASA SP-432
NASA EP-156

The Space Shuttle At Work

Howard Allaway

Scientific and Technical Information Branch and
Division of Public Affairs
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 1979

Library of Congress Cataloging in Publication Data

Allaway, Howard.
The space shuttle at work.

(NASA SP ; 432)
Includes index.
1. Reusable space vehicles. I. Title. II. Series: United States. National Aeronautics and Space Administration. NASA SP ; 432.
TL795.5.A39 629.44 79-18459

☆ U.S. GOVERNMENT PRINTING OFFICE : 1980 O - 302-273

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price

Stock No. 033-000-00779-5/Catalog No. NAS 1.19:156

Foreword

With the first orbital flight of the Space Shuttle, the curtain rises on an era that will shape U.S. space exploration for the next decade, and perhaps for the remainder of the century. *Columbia* and her sister ships will be far more than odd-looking heavy-lift launch vehicles, though they will be that. Each Space Shuttle will be an element in a total transportation system linking Earth with space: vehicles, ground facilities, a communications net, trained crews, established freight rates and flight schedules—and the prospect of numerous important and exciting tasks to be done.

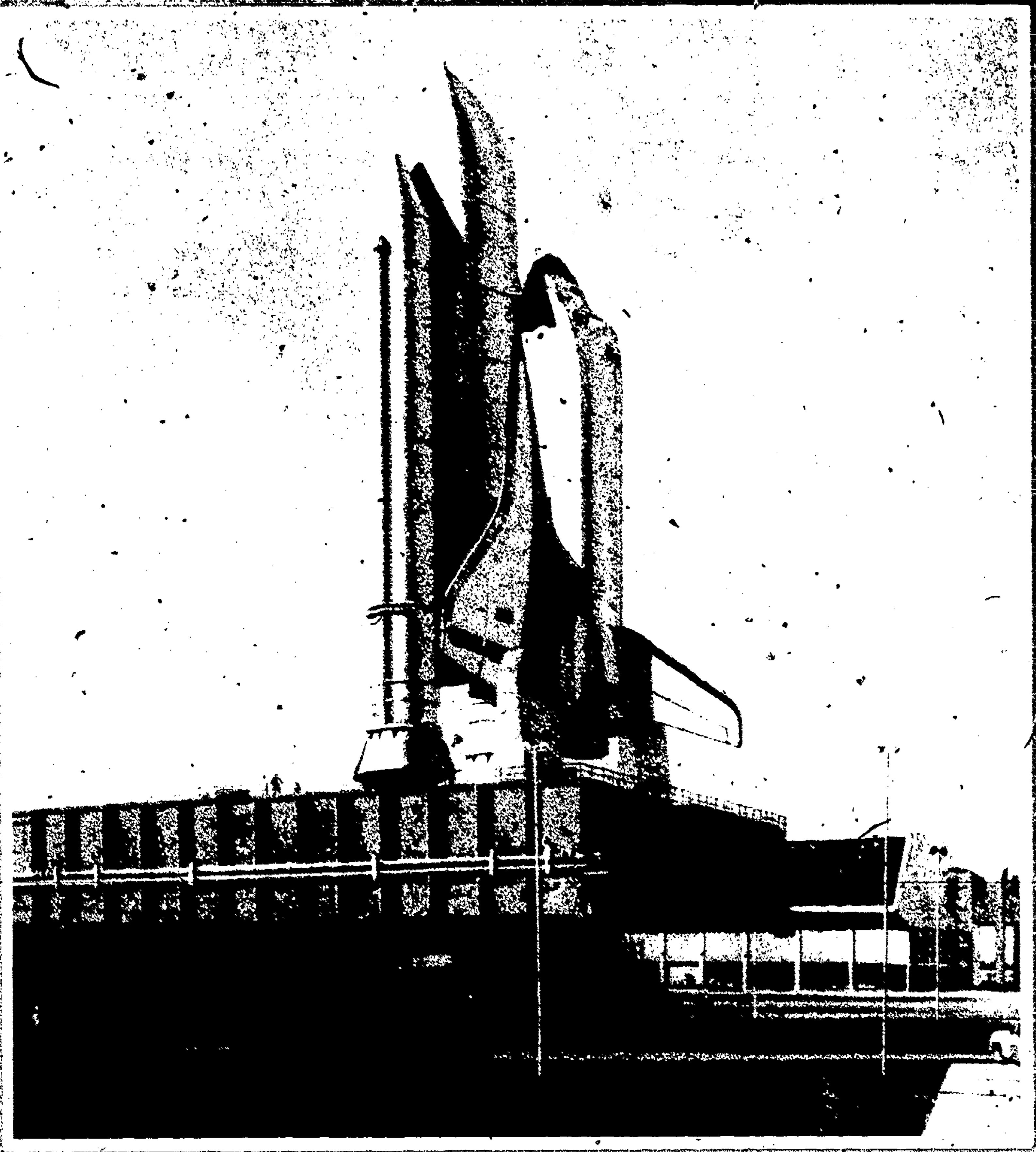
Columbia will be as different from previous one-use space vehicles as an ocean freighter differs from the *Clermont*. Although the Space Shuttle has been a long time in development and won't be workaday for several years, it will transform space travel. We will go into space not just to meet the challenge of exploration but to do many useful and productive jobs, at reduced cost, returning again and again. We are initiating an era of "routine utilization" of space, and it signifies a new epoch in the history of the planet.

As the Space Shuttle first ascends above the atmosphere, it is fitting to describe the new space transportation system: how it came to be, why it is designed the way it is, what we expect of it, how it may grow. This book is such a description. All new technologies can be expected to undergo change and adaptation. It is natural for an endeavor as revolutionary as the Space Shuttle to develop in different and unforeseen ways. For this reason, an account of the initial expectations for this remarkable venture should have value. I commend the following narrative that describes how the United States plans to make space an extension of life on the Earth's surface.

June 1979

ADLAI E. STEVENSON
Chairman, Subcommittee on
Science, Technology and Space
United States Senate

Contents



1. A Week's Work

AN UNLIKELY LOOKING FLYING MACHINE stands on its tail above the watery, thicketed Florida sandscape. The time is the mid-1980s, and the Space Shuttle preparing for launch is one of a fleet of four that now plies routinely, about one round trip a week, between the United States and Earth orbit. 1

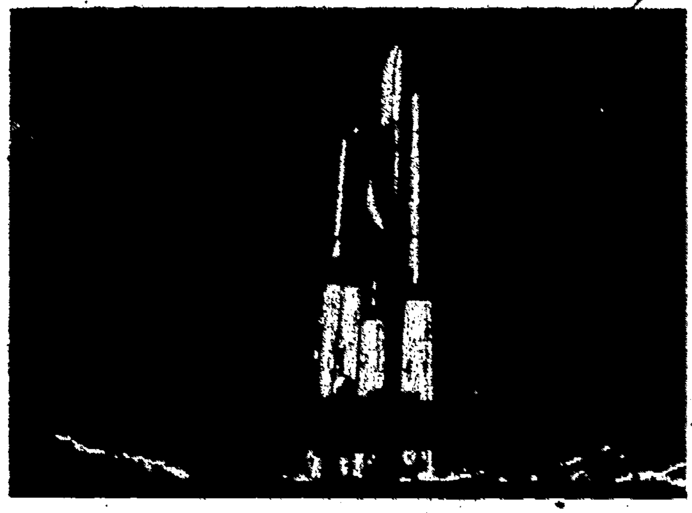
The first true aerospace vehicle, the Shuttle takes off like a rocket, operates in orbit as a spacecraft, and lands like an airplane. To do this takes a complex configuration of three main elements: the Orbiter, a delta-winged spacecraft-aircraft, about the length of a twin-jet commercial airliner, but much bulkier, and built to last for at least 100 flights; a dirigible-like expendable External Tank, containing half a million gallons of propellants, secured to the Orbiter's belly; and, attached to the sides of the tank, a pair of reusable Solid Rocket Boosters, each longer and fatter than a railway tank car.

The countdown clocks blink to zero on the consoles in Launch Control at the Kennedy Space Center, in Mission Control at the Johnson Space Center, Texas, and in the Shuttle's cabin. Three main engines in the Orbiter's stern ignite, gulping liquid hydrogen and liquid oxygen from the External Tank through feedlines thicker than a man's body. As they build to 90 percent of full power, in about four seconds, the two Solid Rocket Boosters begin firing in a storm of flame and smoke. The whole assemblage rises from the same mobile launching platform that was once used for Saturn V rockets that sent Apollo astronauts to the Moon.

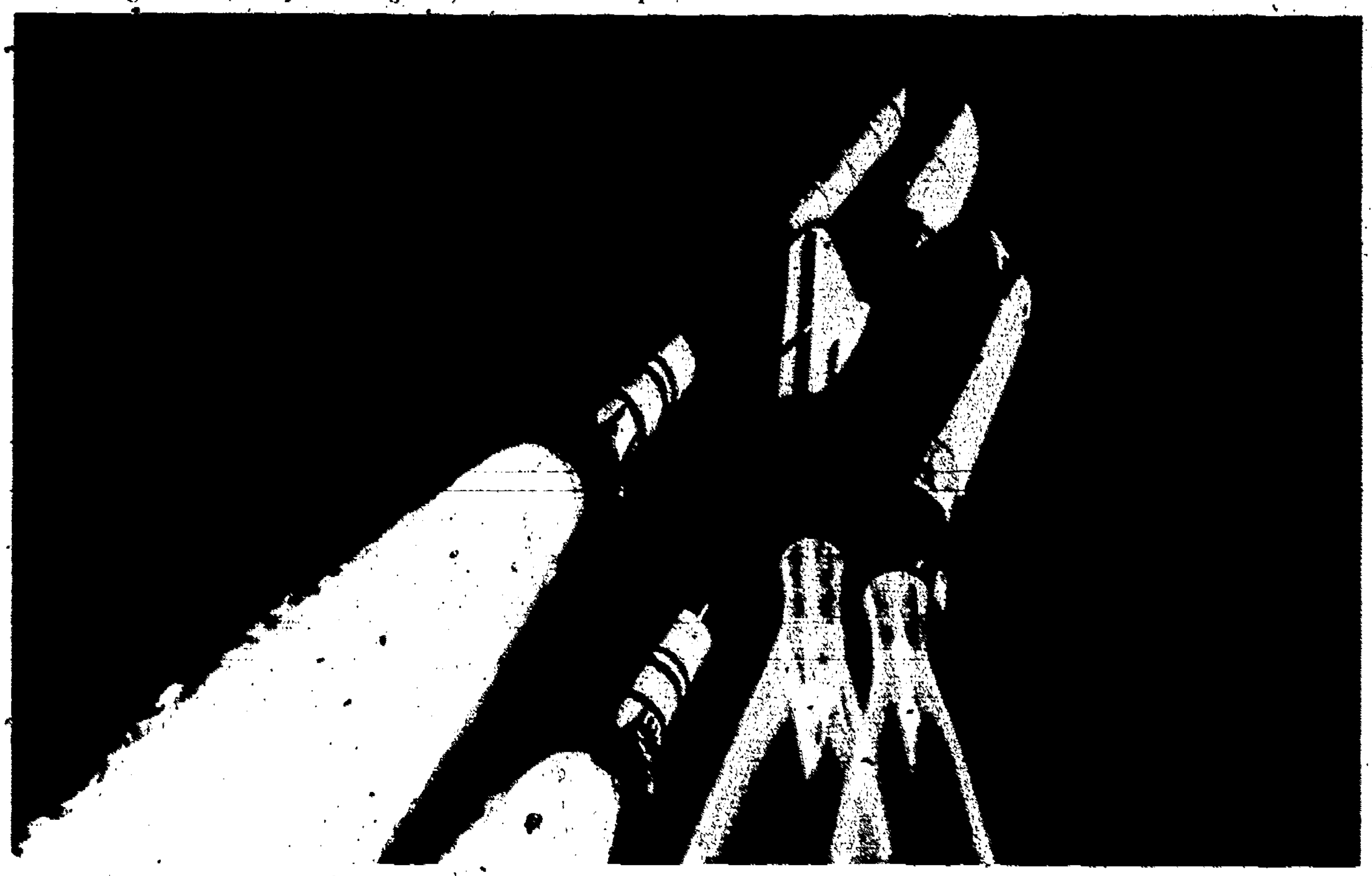
Clear of the servicing tower, the Shuttle turns toward its destination in space and begins arcing over on its back—the crew heads-down, the tank and boosters on top of the upside-down Orbiter—and slants up over the open Atlantic, its direction controlled by slight swiveling of the engines and rocket nozzles. In their spacious cabin up front, the crew of three astronauts and a scientist feel no more acceleration than a comfortable three times normal gravity. They wear ordinary clothes, work at room temperature, and breathe normal air at sea-level pressure.

After two minutes of flight, 50 kilometers (31 miles) up, the two solid-fuel boosters, their work done, burn out, are cut loose from the tank by explosive separation devices, and are pushed clear by small rocket motors. The spent boosters coast upward to about 67 kilometers, then drop back toward the sea. At 4.7 kilometers each discards its nose cap and ejects a small parachute; this pulls out a larger chute that, in turn, 2 pulls out three bigger main chutes. These lower the burned-out rocket case, nozzle first, into the ocean about 280 kilometers (175 miles) from the launch site. Waiting tugs collect the parachutes, attach lines to the rocket cases, and pump in air so that they float horizontally while being towed ashore to be repacked with propellant for reuse.

The Orbiter's three main engines continue firing until about eight minutes into flight, then shut down just before orbital velocity is reached. Ten to fifteen seconds later the big External Tank, almost empty, is cast off, like the booster rockets



In a storm of flame, *five giant rockets deliver almost seven million pounds of thrust at the moment of lift-off.*



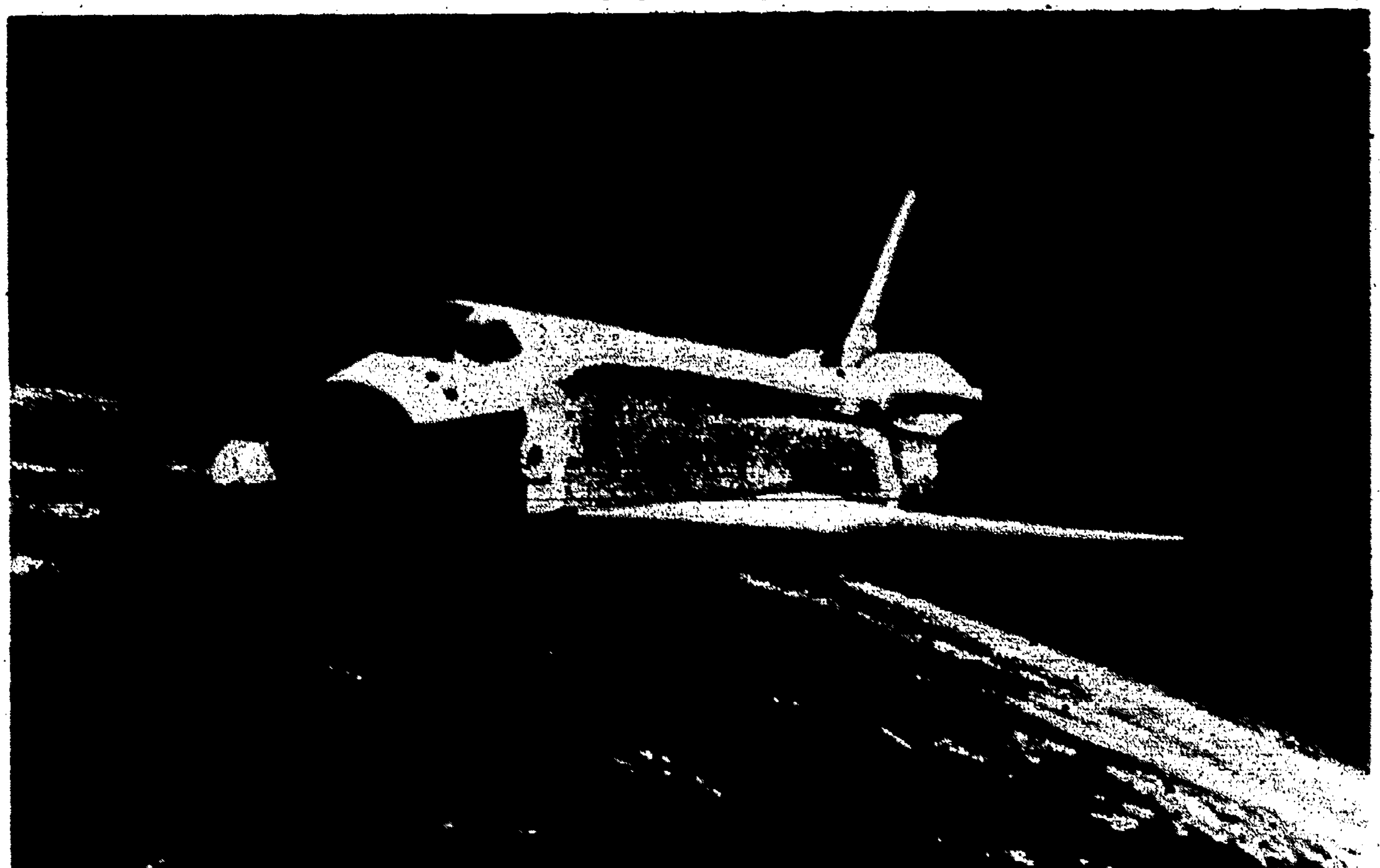
A slow roll *to the heads-down position occurs as the vehicle, accelerating at a relatively mild 3-g rate, climbs toward space.*

After two minutes, *about 30 miles up, their work done; the two solid rockets are cut loose and shoved aside by small rockets. They'll be recovered by parachute.*

earlier, and follows a ballistic trajectory 18 500 kilometers down range. Unlike the boosters, it breaks up reentering the atmosphere, its surviving fragments falling into a remote ocean area—the only main element of the Shuttle that doesn't return to Earth to be used again. 3

Free of the tank, the Orbiter, after coasting for a short-time, fires its two small maneuvering engines—fed from internal tanks—for about 105 seconds to reach orbital velocity of 7847 meters a second (17 500 mph). The initial elliptical orbit ranges from 110 km (60 n. mi.) at its lowest point to

The Orbiter in orbit, *with cargo bay doors closed. In airless and weightless space, its thrusters can orient it in any direction desired. The trip up from the pad takes less than 10 minutes.*



4 280 km (150 n. mi.) at the apogee. A second firing of 95 seconds, half way around the world from the launch site, reshapes the egg-shaped flight path to a circular orbit, and the Space Shuttle is ready to go to work.

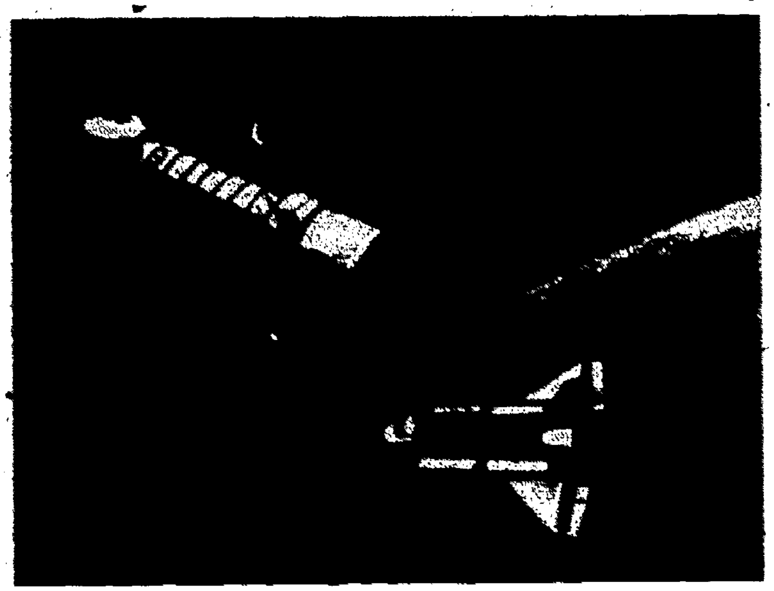
From forward-facing seats, much like those in an airliner cockpit, the NASA astronauts serving as ship commander and pilot now shift to occupy orbital work stations facing aft. The commander, on the left as usual, handles the Orbiter's maneuvering and attitude controls. The pilot directs the motions of a triple-jointed, 15-meter (50-ft) mechanical arm in the cargo hold that lifts payloads out and in. An astronaut mission specialist and a scientist payload specialist, seated behind the commander and pilot during ascent and maneuvering, now work at stations on either side of the flight deck, conducting checks and other chores concerned with experiment packages carried in the hold and with satellites to be deployed, retrieved, or serviced in orbit.

Over Australia, an hour after liftoff, a pair of clamshell doors, split along the top of the fuselage and hinged at the sides, swing outward to open the full length of the cargo bay, as big as a trailer truck. On this flight the payload to be deployed is another in a series of the oldest kind of workaday spacecraft, a communications satellite for relaying telephone calls and television programs between continents. Attached to it is a solid-fuel rocket, called an upper stage, that will propel the satellite into a higher, geosynchronous transfer orbit. There, at 35 900-kilometers (22 300 mi) altitude after the apogee motor is fired, velocity will exactly match Earth's rotation, keeping the satellite always over the same area of land or ocean.

After a final on-board check-out, the satellite and attached upper stage are nudged out of the bay by ejection springs and left free to drift in space. When the crew has determined that the satellite and its upper stage are precisely aimed, and the Orbiter has moved off to a safe distance, the upper stage is ignited by radio signal from the Orbiter as all cross the equator over South America.

Next day—if one can measure time by days in a world where the Sun rises every hour and a half—the crew change orbit to rendezvous with a 9100-kg (10-ton) space telescope 14 meters (46 ft) tall that was brought up on an earlier Shuttle flight. This huge and powerful observatory has been designed both to be serviced in orbit and periodically brought

At work aloft, *the Orbiter prepares to deploy the exciting unmanned Space Telescope. Two space-suited mission specialists perform a final check.*



Moving gently away, *the Orbiter leaves the big telescope in space, its solar panels and antennas deployed, its Sun shields working well.*

back to Earth for overhaul and relaunch over a lifetime of fifteen to twenty years. Above the hazy, turbulent atmosphere that blurs the view of telescopes on Earth, the space telescope, its five extremely sensitive instruments aimed and focused by radio, can see into several hundred times the volume of space viewed by the largest ground-based ones, observing objects so far away that their light has taken billions of years to reach us. The data, transmitted by radio and shared by U.S. and European astronomers, are used, among other things, to study events that happened soon after the universe was created, to watch for new galaxies being formed, and to see whether other stars like our Sun also have planets.

When the Shuttle's flight path has been matched precisely with the telescope's, the manipulator arm is extended to capture the satellite and stand it upright into the cargo bay. The pilot and mission specialist put on space suits and crawl into the bay through an airlock that lets them out while keeping the air in the cabin at sea-level pressure. In the first of two six-hour work periods they inspect and photograph the telescope, open its access doors, and make minor corrections and adjustments while the scientist, a woman astronomer with no formal astronaut or pilot training, watches from the flight deck and talks with them by intercom.

In a second six hours next day, after having gone back to the Orbiter cabin to eat and sleep, the pilot and mission specialist, again in their space suits, reenter the bay, remove one of the telescope's instruments, and replace it with an improved model that hadn't been ready for the original launch. After they have returned again to the cabin, the telescope's various circuits and mechanisms are tested remotely by the astronomer on the flight deck and by ground controllers. It is then powered up, lifted out of the hold by the manipulator arm, and set free again in orbit. The Orbiter stands by while the crew make sure all is working properly, then pulls away to prepare for its next task.

After the crew relaxes, eats, and sleeps, the Shuttle's small engines are fired briefly to readjust the orbit and rendezvous with a free-flying spacecraft—also brought up on an earlier flight—that has no maneuvering ability, attitude controls, power supply, data-collecting equipment, communications, or instruments of its own. This is the Long Duration Exposure Facility: an empty aluminum canister resembling a huge Japanese lantern, 9.14 meters (30 ft) tall and polygonshaped, its outer surfaces divided into bays that hold shallow trays, seventy-two of them around the periphery and two on each end. The trays, 3 to 8 centimeters (1 to 3 in.) deep, some open and some closed over, contain experiments provided by scientists and engineers of U.S. and foreign government agencies, universities, and industrial companies. Their purpose is to expose various instruments, materials, electronic parts, and dust collectors to the space environment—high vacuum, near-zero gravity, solar radiation, cosmic rays, micrometeoroids—for six months or more.

The Orbiter moves close to the passive free-flyer, grasps it with the manipulator, and hauls it into the cargo hold. The crew take breaks for meals and sleep. Then they close the cargo-bay doors, move into their seats, fasten their belts like any airline passengers, and prepare to head home.

Half way around the world from the Florida base, the small attitude-control thrusters are fired in short bursts to turn the spacecraft tail-first. The larger orbital maneuvering engines then are fired for about two minutes to slow the ship and lower its flight path in a slow curve toward Earth. Half an hour later, about 150 kilometers up and the ship again flying nose-first, the crew begin to feel the drag of the thin top layer of the atmosphere.

Now begins the most critical and demanding part of the voyage. Why this is so was explained by the director of the Space Shuttle Program, Myron S. Malkin, in a vivid account of the last half hour of a Shuttle flight from here to touchdown:

The Orbiter must change from a spacecraft to an aircraft while slowing from its orbital speed of nearly 8000 meters a second (18 000 mph) to about 100 meters a second (225 mph) for landing. Above the atmosphere, maneuvering is done by firing small rockets in the nose and tail; in the atmosphere, attitude and direction are controlled by a conventional aircraft rudder and flaps. At middle speeds and altitudes, during reentry into the atmosphere, rocket and aerodynamic controls must be skillfully blended. The commander and pilot are aided in this tricky task by five computers on board that decide which rockets should be fired and for how long, and how much to move the control surfaces, to keep the craft steady and headed in the right direction.

Edging into the atmosphere, the pilot uses the attitude-control thrusters to angle the nose up so that the craft pushes

Spending its speed, *the Orbiter prepares to change from spacecraft to aircraft. This is the angle of attack used toward the end of the reentry process.*

into the thickening blanket of air at about a 40-degree angle of attack, the term aeronautical engineers use to describe the upward slant of an aircraft's lifting surfaces in relation to its direction of movement. Air friction heats the Orbiter's heavily insulated underside to more than 1000° C, and ionization of the surrounding atmosphere blacks out communication with the ground for some seconds. At about 93 kilometers (58 mi) altitude the air becomes dense enough so that aerodynamic controls take hold, and the Orbiter becomes a heavy glider.

(Without fuel for its main engines, the craft wouldn't be able to go around for a second landing approach in case of a miscalculation, as an airliner could; it can, however, shift as

Final approach *sees the Orbiter lined up with its long runway at Kennedy. The runway end used depends in part on wind direction.*

The same runway *can also be approached from the opposite direction. NASA has assessed potential emergency runways around the world.*

much as 2000 kilometers (1200 mi) to the right or left of its entry path to make an emergency landing at any of several U.S. airports or military air bases. In such an event, it would be ferried to its home base on the back of a specially fitted NASA 747 air transport.)

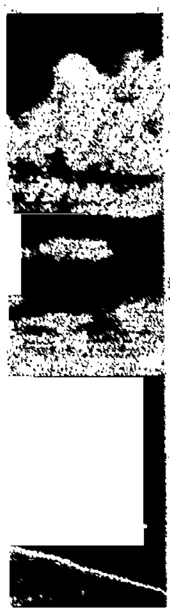
About 48 kilometers above Earth, the Orbiter's nose is pushed down to reduce the angle to about 14 degrees. At 24 kilometers (15 mi) height the final approach begins, with the craft about 92 kilometers (57 mi) from the Kennedy Space Center. The great glider dives for the runway nose down at 22 degrees and an airspeed of about 158 meters a second (355 mph). At 520 meters (1700 ft) the pilot begins to flatten the glide to only 1.5 degrees, extends the speed brakes, and settles the ship for a landing. At 90 meters (300 ft) the landing gear goes down, and seconds later the tires touch the 4572-meter (15 000 ft) concrete strip—just thirty busy minutes from the smooth, silent weightlessness of space.

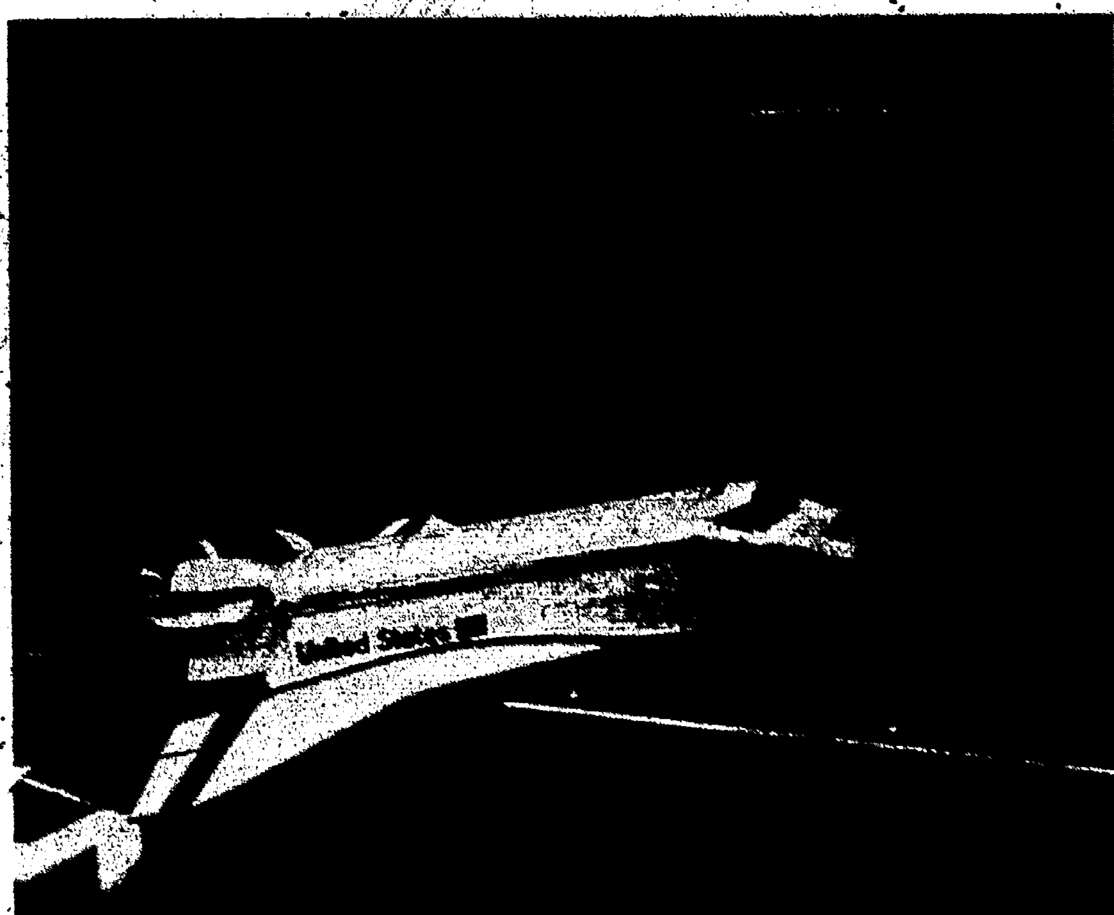
Immediately after the landing, ground cooling equipment like that used for airliners is attached, and the Orbiter is towed into a servicing building. Leftover propellants are drained from the tanks and feedlines, and any unused explosive actuators are removed. The cargo doors are opened, the Long Duration Facility is hoisted out, and the experiment trays are distributed to the scientists who will study how the contents were affected by their stay in space. After general maintenance work on the Orbiter, a new payload is lowered into the bay. For the coming flight it is the Spacelab, a completely fitted-out laboratory, designed and built by members of the European Space Agency, in which four scientists can work for a week to a month in an Earthlike atmosphere but in the zero gravity of orbit.

The Orbiter, with its new payload, is next towed to the Vehicle Assembly Building, originally designed for stacking Saturn/Apollo vehicles. Here it is rotated to a vertical position and mated with a new External Tank and reloaded Solid Rocket Boosters on the mobile launching platform.

Erect on the platform, as big as a baseball diamond and carried by four enormous crawler tracks, the space vehicle moves slowly to the launching pad. More than 700 tons of super-chilled propellants are pumped into the tank, a new crew of three astronauts and the four scientists board, and the Space Shuttle is ready, two weeks after its landing, for another working voyage.

Speed brakes extended *(note split halves of the rudder), the Orbiter whistles to the runway at more than 200 knots. Computers aid the pilots.*





Landing gear drops *only seconds before touchdown, with the main gear touching first and then the nose. The Kennedy strip is almost three miles long, affording plenty of braking time.*

2. The Uses of Space

11

IN CONTRAST TO THE ROUTINE TWO-WAY TRAFFIC made possible by the Shuttle, every payload sent into orbit for the first two decades of the space era—every bug, plant, and animal; every man, woman (one, a Russian), and automated laboratory—rode on the nose of a one-trip rocket that was discarded after a working lifetime measured in minutes. However costly, those pioneering ventures into space sent back startling news of the universe and brought countless changes for the better in the ways we live: changes in the economy, in health and safety, in science and technology, in education, in the protection and use of natural resources, in national defense and international cooperation.

The first was a revolution in communication.

In the middle of the night of July 10, 1962, television relay stations at Goonhilly Downs, Cornwall, and Pleumeur-Bodou, Brittany, picked up a black-and-white picture of an American flag flapping in the breeze to the accompaniment of the Star Spangled Banner. The program was a demonstration being transmitted skyward from a huge horn-shaped antenna in Maine to a glistening new Earth satellite, Telstar I, and down to a receiving dish in New Jersey for distribution to U.S. viewers. Though not intended, the signal also was being bounced from Telstar across the Atlantic to England and France.

Next day the experimental satellite relayed the first TV pictures westward from Europe, black-and-whites from both France and England, and within a week the first in color. Before the month was out, mass audiences on both sides of the Atlantic watched with awe the first international exchange of live TV. Viewers in Europe saw the Statue of Liberty, a baseball game between the Phillies and the Cubs in Chicago, a press conference by President Kennedy, buffalo roaming the South Dakota plains, the Mormon Tabernacle Choir singing from Mount Rushmore. Americans, in turn, got glimpses of Big Ben from one of London's Thames bridges, the Coliseum in Rome, the Louvre in Paris, the Sistine Chapel in Vatican City, Sicilian fishermen reefing their nets, reindeer roaming near the Arctic Circle in Norway.

The trouble with Telstar (and its early successors) was that it could be used only when its relatively low-altitude orbit of 945 by 5600 kilometers (580 by 3500 miles) brought it within range of both U.S. and European ground stations for a few minutes during each 158-minute circuit of the globe. This problem was solved the next year by the Syncoms, whose speed in circular orbits of 35 800 kilometers (22 300 miles) above the equator kept pace with Earth's rotation, so that the spacecraft seemed to hover stationary over the same place on Earth: hence the description as geostationary or geosynchronous. Thus one satellite could be used continuously by ground stations within its view, which covered almost a third of the globe. The Syncoms set the pattern for more than fifty commercial and research communications satellites launched during the next fifteen years.

Before the end of the 1970s a global communications satellite system, Intelsat, was being used by nearly 100 countries—from Afghanistan to Zambia—to exchange TV news, telephone calls, and business data. It was continuously expanded to meet a growing demand for services. More than a billion people, one out of every four on Earth, could see a major event as it happened: "live via satellite." Worldwide investment in communications satellite systems was more than $1 billion, and revenues were more than $200 million a year. Despite inflation, international telephone calls were cheaper than when the first Intelsat began service in 1965.

In 1972 Canada launched the first space relay station whose beam could be focused to fall within a single country. It now has three such domestic communications satellites and a network of fifty ground stations serving the entire country, including far northern settlements formerly reached only by unreliable radio. Four companies soon were operating domestic communications satellites in the United States, and a dozen other countries had them. In some developing nations it was easier to make a phone call to a city a thousand miles away than to the next town.

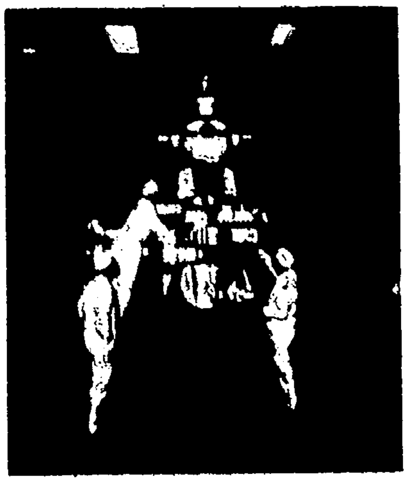
Meantime, a series of NASA research satellites demonstrated how space communications could be useful for such varied purposes as transmitting educational programs and medical instructions directly to isolated villages via low-cost local receiving stations; providing emergency communications in disaster areas; searching for lost aircraft and disabled ships and guiding rescuers to them; exchanging classroom lectures between colleges thousands of miles apart; directing air traffic far at sea; and bringing businessmen in different cities face-to-face electronically for two-way conferences, saving travel time and fuel.

Weather observation from orbit quickly followed space communications into everyday operational service to millions

Scanning *the whole Earth, the LANDSATs assessed planetary resources, and gave clues to changes that were taking place.*

Perched jauntily *on its carrier 747, Space Shuttle* Enterprise *stops in Texas on its way to the Cape. Crowds were heavy at each stop, for the U.S. public has high expectations for the gains to be made by the new American space transport.*

Other satellites *(a two-ton Nimbus is shown below) studied behavior of the atmosphere.*



of people around the world. Since 1966 the entire Earth has been photographed daily from space, and no tropical storm has escaped detection and tracking. Thousands of lives and billions of dollars—there is no way to count them precisely—have been saved by improved forecasts, early storm and flood warnings, reports to shippers on wind conditions and iceberg hazards, advice to farmers on when to plant, irrigate, fertilize, spread insecticide. 13

One kind of meteorological satellite circles the globe on north-south tracks, looking down as Earth turns underneath. Its reports are assembled by computers in the United States, to make a complete picture of worldwide weather conditions every twelve hours and also are transmitted directly to hundreds of inexpensive local stations in scores of countries as the spacecraft passes overhead. A second kind of weather satellite, in geosynchronous orbit, appears to stand still in space, keeping continuous watch on a large area—two of them cover all of North and South America and the adjacent oceans. They return a fresh picture every half hour, day and night, to produce, among other uses, the time-lapse movie strips now commonly seen on television weather programs.

Besides cloud cover and movements, weather satellites report air and sea-surface temperatures, wind speeds, atmospheric pressure and moisture content, rainfall, snow cover, and ice fields. Some collect data from untended sensors and gauges in remote areas, at sea, and on balloons. The pictures and measurements are used not only for routine local, regional, national, hemispheric, and global forecasts but also to track dangerous fast-moving storms: hurricanes and short-lived severe thunderstorms that may set off tornadoes.

In the mid-1970s observations of large wheat-growing areas of the world from both weather and natural-resources survey satellites were combined with surface information to measure acreage and estimate yields in a successful demonstration that crop forecasts could be improved with data from space. Information was gathered not only over the United States but also over Canada, Russia, China, India, Australia, Brazil, and Argentina. Obviously, early production estimates made regularly in this way could be of significant help in planning food distribution and avoiding the market shocks of unforeseen shortages and bumper harvests.

Pictures and computer data from a series of Earth resources survey satellites and also from the manned Skylab space station were used in dozens of ways in the 1970s to help federal agencies, state and local governments, regional planning authorities, private industry, and foreign countries manage limited natural resources and monitor the threatened environment.

Examples:

- Mapping mountain snow cover to forecast spring runoff available for irrigation and power generation;
- Detecting oil slicks at sea;
- Compiling a global atlas of glaciers;
- Making inventories of standing timber and grasslands;
- Monitoring offshore dumping of sewage sludge and industrial wastes;
- Mapping floods to help in evaluating damage and planning relief;
- Checking on the environmental effects of developing new energy sources, such as strip mining;
- Detecting potential earthquake zones as an aid in planning future construction;
- Measuring forest-fire damage and the extent of clear-cutting and gypsy-moth defoliation;
- Tracing air pollution and lake silting;
- Mapping land-use changes as an aid to wiser urban planning;

Gathering data by satellite is speedy. *Here cold and winds have piled up new ice on the east shore of Chesapeake Bay.*

- Counting and measuring the area of dams and lakes;
- Watching glaciers for signs of rapid movements that could dam up melt waters and later cause floods;
- Mapping uncharted coastal shoals that could endanger shipping;
- Making and updating other maps and navigation charts;
- Making low-cost soil surveys and geologic maps.

The savings, compared with the cost of aerial surveying, made mapping from space attractive. New Jersey, for instance, saved $2.8 million by using satellite images to calculate beach erosion. Another state found that fourteen space pictures and one and a half man-years of work, costing $75 000, could produce a land-use map that would have taken 20 000 aircraft photos, forty-four man-years, and $1.7 million.

Half a dozen foreign countries built their own ground stations for receiving transmissions directly from the Earth survey satellites when overhead. All the pictures and data were put on sale to anyone anywhere by the U.S. Department of Interior. To no one's surprise, the biggest buyers were oil and mining companies, looking for likely new places to drill and dig; orders were strong for information on the vast unexplored reaches of Alaska. Clearly, monitoring Earth's shrinking natural resources from orbit was the next area of space activity ripe for routine use. Government agencies and private groups began discussions of how an operational service, like those of

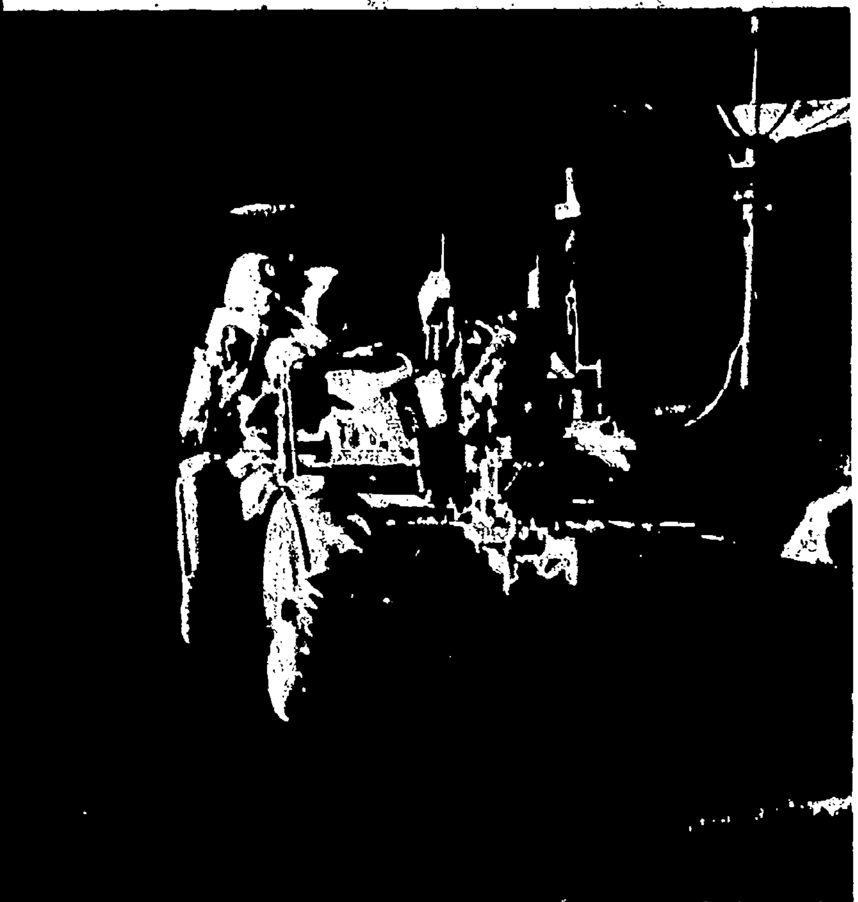
Detailed land-use map *of parts of four states shows 11 categories of use and growth, invaluable to local governments and planners. It was made in days from LANDSAT data, would have taken months and cost 10 to 15 times as much if based on conventional aerial photos.*

communications and weather satellites, should be organized and managed and the information distributed.

Other Earth-oriented satellites demonstrated space-based navigation for ships and planes; made precise measurements of the globe's size, shape, bumps, and hollows; detected slight movements of large land masses—tectonic plates—in search of the causes of earthquakes; collected data on ocean surface winds, currents, and waves; measured the daily heating and cooling of rocks for clues to oil and mineral deposits; mapped worldwide air pollution; and—in a demonstration—tracked an arctic explorer and his dog sled across the North Pole. The military services put up their own satellites for rapid global communication and reconnaissance to verify arms-control agreements.

This quick sketch of American achievements in space during the 1960s and '70s has emphasized activities leading to immediate benefits in daily living. Much of the money, manpower, and ingenuity spent on the nation's space program, however, during the years of reliance on expendable launch vehicles, before the coming of the reusable Shuttle, was devoted to scientific exploration of the solar system and the universe beyond and to demonstrating that man can live and work in space.

No longer a total mystery, *the Moon has given way to unprecedented scientific assault. Here Apollo 15's Scott and Irwin explore the Hadley-Apennine site.*



The results were spectacular and potentially rewarding.

Increasingly complex automated laboratories, from the first simple Explorers to the almost-human Vikings, mapped interplanetary radiation and magnetic fields; analyzed the turbulent Sun from above Earth's obscuring blanket of air; photographed the entire Moon from lunar orbit, then landed gently on its cratered surface; observed Venus, Mercury, Mars, and Jupiter closeup and sent back magnificent pictures; tested the Martian soil for signs of past or present life; and probed the heavy atmosphere of Venus down to the planet's broiling surface. Orbiting observatories extended enormously the depth and breadth of astronomers' vision and discovered mysterious energy sources at incredible distances. New knowledge of other worlds will lead to better understanding of our own, as observations of other planets' atmospheres are already opening fresh insights into the mechanisms of Earth's weather.

A succession of twenty-eight U.S. manned flights from Mercury through Apollo-Soyuz proved that people can perform useful tasks together in space and survive long periods of weightlessness without serious or lasting harm. The Gemini flights worked out the techniques of maneuvering in orbit. Apollo's heroes, as all the world knows, explored the Moon first-hand, gathered samples of its soil and rocks for analysis back home, and set up science stations that continued to radio data long after the last men left. Three Skylab crews produced useful medical knowledge about the body's reaction to stress, studied the Sun with a large manned telescope and Earth with multispectral scanners sharper than the human eye, and demonstrated the possibility of manufacturing in zero-gravity new and better products that cannot be made on the ground.

The handshake in orbit by an astronaut of the last Apollo and a cosmonaut of Russia's Soyuz symbolized more than a promise of future international cooperation in space. America's program of the 1960s and '70s was conducted in the open and the results shared with all the world. NASA launched scientific and communications satellites for a dozen nations. U.S. spacecraft carried experiments by scientists of twice that many countries, including the Soviet Union. Two hundred fifty foreign researchers from twenty-one nations participated in Skylab investigations; 600 scientific and technical groups in more than 130 countries used images from the Landsat natural-resources satellites. In a year-long demonstration a U.S. experimental communications satellite transmitted educational television programs to 5000 villages in India where most people had never seen a TV picture. As the two decades ended, Canada and members of the European Space Agency were at work on major roles in the Shuttle-based Space Transportation System.

Meeting the time schedules, safety requirements, and performance goals of space exploration stretched and pushed American technology in all directions. Yankee ingenuity had to come up with strong new alloys and composites, lubricants that wouldn't evaporate in a vacuum, long-lasting batteries, tiny yet highly reliable electronic parts, ultrasensitive fire detectors, more efficient solar-power panels, compact computers, foods that keep fresh without refrigeration, high resolution cameras, low-power communications equipment, improved welding and wiring techniques, miniature sensors, lightweight pumps, tough fireproof fabrics. The list could go on for pages. Thousands of innovations in materials, devices, and procedures were described in NASA publications and catalogued in computer-tape libraries open to U.S. industry. Hundreds of them, called spinoffs, soon were turning up in commercial uses and medical products from the silvery dome of the Detroit Lions' new stadium to rechargeable heart pacemakers.

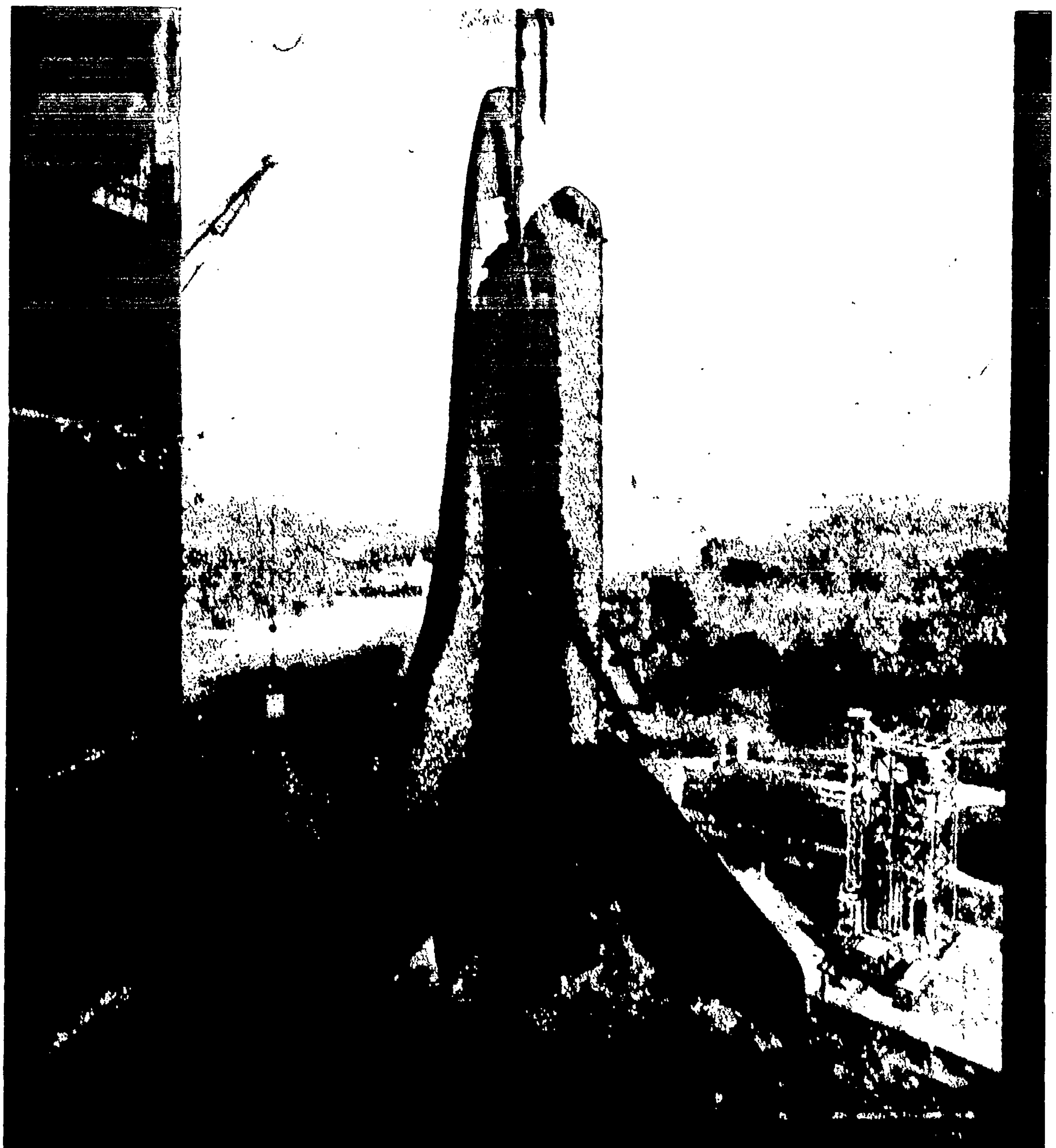
Spending on space projects, including the Shuttle transportation system, stimulated the economy both directly and indirectly. The dollars were not shot off into orbit when they might better have been spent on Earth, as some critics liked to say, but went mainly to pay workers—more than 400 000 at the peak of the Apollo program—in every state. And because aerospace wages were relatively high, much of the money tended to be passed along promptly, creating more

Handshake in Earth orbit, *above, between U.S.A.'s Stafford and USSR's Leonov symbolizes cooperation between foremost spacefaring nations. At right, a hand-held snapshot of Russian Soyuz spacecraft as seen from a window of the Apollo command module.*

jobs. Moreover, as economists have long known, technological advance is the primary source of higher productivity and economic growth. High technology industries also contribute more than others to the nation's export trade, helping to offset imports of raw materials, minerals, and fuels.

But perhaps the greatest gift from the space pioneers to men, women, and children of all nations was a new view of their home planet. President Carter, at a ceremony in which he awarded Congressional Space Medals to outstanding astronauts, expressed it this way:

> We went to the Moon, in part, as a matter of national pride. But when we got there, we discovered something very interesting. Through the eyes of the cameras of the astronauts, we looked back at the Earth, above the strange horizon of the Moon in a pitch black sky; we saw our own world as a single delicate globe of swirling blue and white, green, brown. From the perspective of space our planet has no national boundaries. It is very beautiful, but it is also very fragile. It is our special responsibility to the human race to preserve it. Of all the things we have learned from our exploration of space, none has been more important than this perception of the essential unity of our world.



3. More, Better, Cheaper

IF AMERICA MANAGED to do so many things in space with expendable launch vehicles, as recounted in the previous chapter, why the Shuttle? The answer begins—but by no means ends—with the lowered cost of simply delivering payloads into orbit.

Freight rates for the Space Transportation System are based on recovering its operating costs and the U.S. investment in the Shuttle fleet and ground facilities, though not the original research and development expense, over a period of twelve years. Under the resulting price schedule, the Shuttle will place satellites in orbit for one- to two-thirds the cost of launches aboard the Delta, Atlas-Centaur, and Titan rockets used for most recent U.S. civilian and military missions and NASA launches for other countries. The expense of keeping up a varied inventory of launch vehicles and their different ground systems is eliminated. Based on traffic projections of more than fifty Shuttle flights a year when the system comes fully into use, the launch savings alone could be half a billion dollars a year or more, depending on inflation.

Since about 80 percent of the cost of space missions has been going into payloads, and only about 20 percent into launch costs, still bigger savings—30 to 40 percent of total payload program costs—will result from changes in spacecraft design made possible by the Shuttle's great cargo capacity and by what it can do that one-way launch vehicles can't.

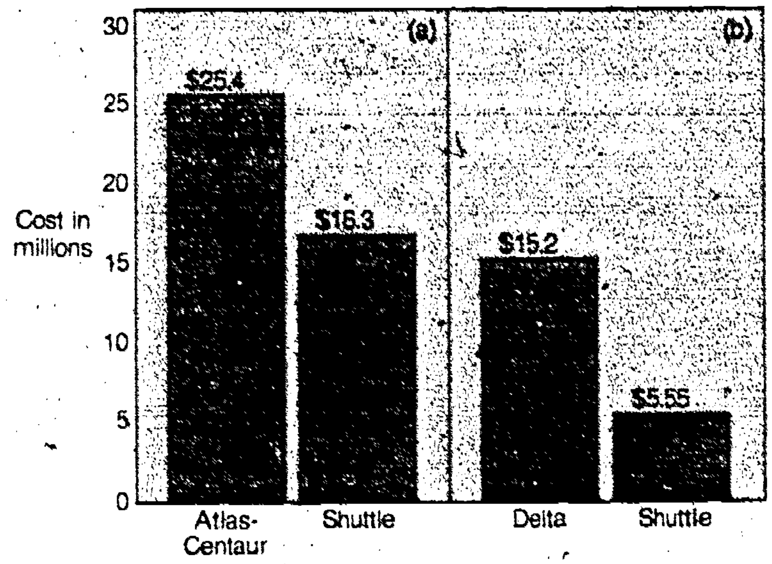
Thanks to the Shuttle's relatively gentle acceleration, designers of the spacecraft it carries may be able to use some off-the-shelf parts rather than creating and testing costly and rugged one-of-a-kind equipment. Because of the Orbiter's large payload bay and great lifting ability—twice that of the biggest expendable vehicle commonly employed—satellites can be simpler: less tightly packed, less limited in weight. Standardized parts and modular components may be used, and virtually the same spacecraft can be employed for different purposes by changing only its cameras or other sensors. The Shuttle's ability to check out satellites in space while they are still in the Orbiter and again after they are deployed, to repair them in orbit, and to return them to Earth for overhaul also justifies designers in relaxing some reliability precautions, such as redundant circuits. This too saves money. Studies of how past spacecraft could have been designed differently if the Shuttle had been available to launch and service them showed that their costs could have been reduced substantially.

22 Still other payload savings are possible. Working models of instruments intended for long unattended operation in orbit can be deployed and left in space for weeks or months, then be retrieved and returned to Earth for examination and reworking if necessary. This will improve the reliability of future satellites and lengthen their lifetime at little cost while also reducing the time for development and ground testing. Prototypes of new instruments can also be tested in space for briefer periods while still attached to the Orbiter. Persistent problems can be pursued with early reflights. Satellites can be retrieved at the end of their planned mission for refurbishment and reuse. Or modular components can be replaced in orbit, reducing out-of-service time, without bringing back the entire spacecraft. Satellites can be updated in orbit as technology advances, increasing their performance and prolonging their usefulness.

When all launches are made aboard the Shuttle and all spacecraft are designed to take advantage of its capabilities, there should be greatly reduced risk of costly total failures in spacecraft operations. Even a failure of the Shuttle vehicle itself need not be catastrophic: the crew could carry out one of the abort procedures described in Chapter 7, landing safely with the payload intact. A study of 131 failures of the 1960s and '70s found that seventy-eight of them, related to the launch or to malfunctions early in the mission, could have been detected during checkout in the Orbiter or just after deployment. They were problems that could have been corrected immediately or by bringing the spacecraft back to the launch site for repairs. The other fifty-three were later failures or erratic behavior that could have been corrected by retrieving the satellite for repair and relaunch.

An interesting example was cited by the deputy director of NASA's Shuttle Program, LeRoy E. Day. Two out of three Orbiting Astronomical Observatories launched between 1966 and 1970 suffered fatal mishaps. A battery charger failure after two days on the first OAO could have been corrected by returning the satellite from orbit and repairing it. The third one failed to reach orbit because the shroud that protected it during launch wasn't discarded at the right time; this would have been avoided if the Shuttle had been the launch vehicle, since the spacecraft would have been carried inside the Orbiter and have needed no shroud. The second OAO performed beautifully, but even the problems that

Space Shuttle launch costs *compared to (a) the Atlas-Centaur and (b) the Delta launch vehicle (1975 dollars).*



occurred beyond its planned operating lifetime could have been corrected in orbit, extending its service, if the Shuttle had been available and the spacecraft had been designed for such maintenance.

The Shuttle has other unique virtues. It can be prepared for launch on relatively short notice. Thus it could conceivably carry out a rescue mission, one Orbiter bringing safely home the crew of another Orbiter disabled in space and unable to return. It can be sent off quickly on a special mission to gather information needed in an emergency on Earth, such as a flood or crop blight. It requires no elaborate and expensive operation at sea to recover the crew after each mission, as in Apollo and other past manned flights. And it can take scientists and engineers into space routinely to conduct their own experiments and observe the results first-hand, to test instruments of their own design and make immediate adjustments. The mission plan can be changed during a flight to cope with problems or take advantage of opportunities.

Early piggyback flights, *and later drop tests, were done cautiously and systematically, because of aerodynamic uncertainties. Note fairings added over Shuttle's main engines, and the clearance hurdle imposed by the 747's tall stabilizer and rudder.*

Both the Orbiter's large weight and volume capacity and the price schedule for flights encourage use of the Space Transportation System by a wide variety of customers. A number of spacecraft can be carried on the same flight, and sharing by different users is encouraged. Experiment packages intended to remain within the cargo bay can be fitted in with primary payloads. To stimulate early use, rates are frozen for the first three years, and are the same for U.S. and foreign commercial firms; later they will be adjusted annually on the basis of operational experience. A user that books a full flight and finds there is some room left over can sublet it. Discounts are offered to shared-flight customers who agree to fly their payloads on a space-available (standby) arrangement. Applicants who propose an exceptional new use of space or a first-time use of great potential value to the public are considered for special rates. NASA has established a small technical group to advise and help people with little or no experience in space research.

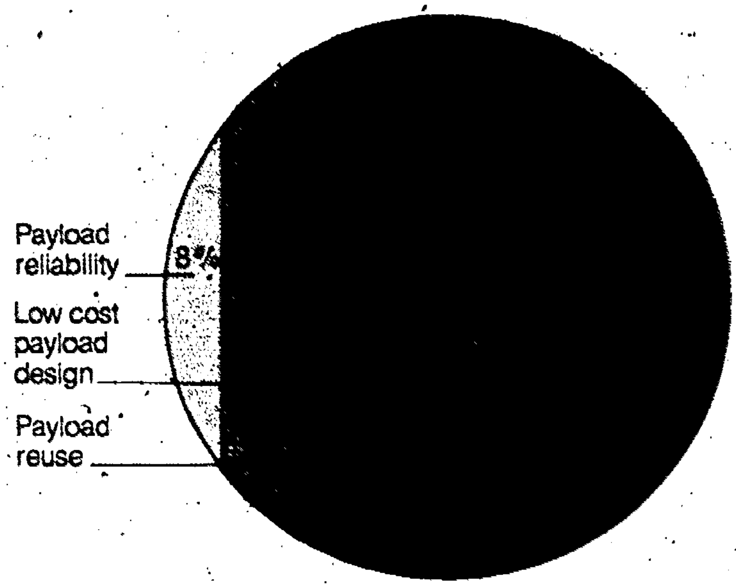
Small self-contained experiments will be flown as standbys for $3,000 to $10,000 (in 1975 dollars), depending on size and weight. Of the first 250 reservations, a quarter were for educational purposes and a fifth were from individuals planning to test new concepts in the space environment. Some were donated to high school and college students developing experiments as part of their academic work. Fifty-one were from foreign countries: Germany, Denmark, the United Kingdom, Canada, Japan, Israel, and Egypt. The payloads must be for research or development—no commercial gimmicks. Said the director of NASA's Space Transportation System Operations, Chester M. Lee: "We have had to turn away a few speculators who wanted to send up hunks of metal and later sell pieces as souvenirs or who wanted to send up postage stamps and sell them at high profit."

By early projections, about half of the payloads will be for NASA, about a fourth for the Department of Defense, and the rest for other U.S. government agencies, U.S. private organizations, and foreign governments or companies. Civilian users, large and small, are expected to include communications networks, research foundations, universities, observatories, state agencies, county and city planners, public utilities, farm cooperatives, medical research groups and health services, the fishing and transportation industries, oil and mining interests, manufacturing and aerospace firms, chemical and pharmaceutical companies, water conservation and power generating authorities, and private citizens. Developing countries can begin space programs of their own at affordable costs by sharing Shuttle missions with other users and flying modest payloads that are exposed to space from the Orbiter, then later perhaps move up to more ambitious projects like domestic communications satellites.

The returns from America's investment in the new Space Transportation System, then, come not only from reduced launch, spacecraft, operations, and man-in-space costs. They will come also from both the increased and wider use of space stimulated by ready access to reliable, frequent, flexible, economical two-way freight and passenger service between Earth and orbit. And they will come, ultimately, from new ways of using space—including uses not yet thought of. NASA Administrator Robert A. Frosch spoke to a committee of Congress about changes in the basic approach to space flight:

> For twenty years we have had to reach for the benefits of space in small, expensive, prepackaged increments. Each mission has been such an increment, with its long lead time, one-way transportation system, weight and volume constraint, demands for redundancy, extraordinary test rigors, and conservative failure margins. . . . The early Shuttle missions we will see are relatively straightforward evolutionary extensions of present approaches. . . . It will take time

In a special change-out room, *payloads are removed and different ones installed with the least delay.*



Payload factors *affecting Space Shuttle economics expressed in percentage of Shuttle benefit over expendable vehicles.*

before we recognize that we can afford in space an approach to experiments similar to those we use on the ground, because of the easy presence of the human experimenter, supervisor, technician, or repairman. We will have to stop thinking in terms of discrete space missions, each with its own spacecraft, its own control center, its own ground network, its own clientele. . . .

In parallel with the changes in how we will be operating in space are the implications for what we can do there. Perhaps the best current example in science is that of the space telescope. . . . It is important to realize that astronomers have been planning for the telescope since the early '60s—and that only the advent of the Shuttle revisit for orbital maintenance has made it practical. The space telescope is our first facility in space, now not much more remote from human attention than the more limited instruments we have built on mountain tops around the world. . . .

We are at the beginning of another revolution today as well: one in communications. It would be appropriate to term this the "second communications revolution," since the satellite developments of the past fifteen years have already completely changed domestic and international point-to-point telecommunications traffic. . . . Just around the corner . . . is the next quantum jump in this field. . . . The geometry of the world and the space around it, coupled with the technological capability to build large antennas and supporting facilities in space while vastly simplifying and reducing ground terminal size and complexity, make the possibility of hemispheric interconnections at the "CB" level a reality. Concepts of public service telecommunications like electronic mail, medical information service delivery, continuing interactive education, and broadly based information access now await implementation decisions rather than technological feasibility demonstration.

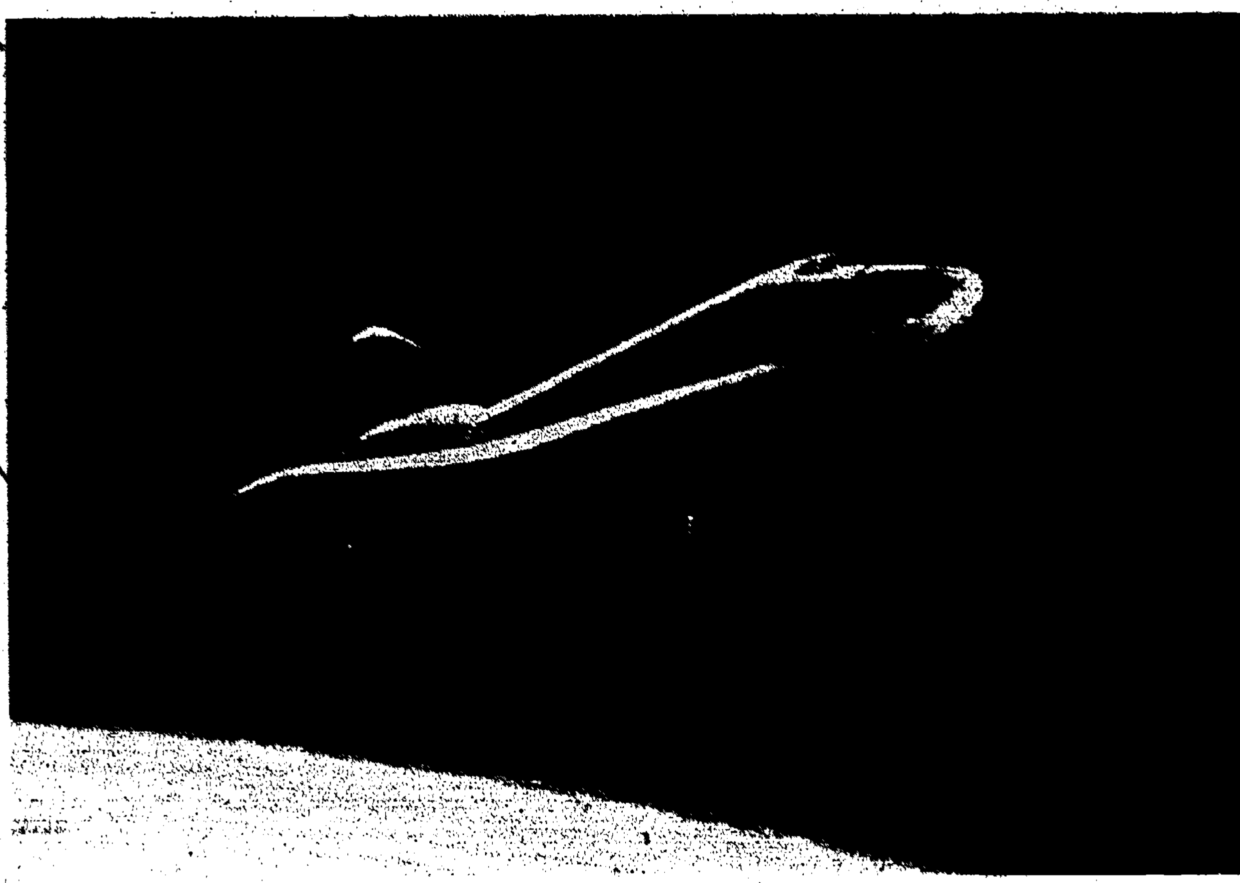
Designers of commercial communications satellites are studying concepts for future ones that would be four times heavier than today's and twice as bulky. The larger designs relieve many of the problems of packaging antennas and providing more area for solar cells for increased power. They should be more efficient and more reliable, and provide additional channels.

Frosch spoke also of a "global information system" based on remote sensing of the land, sea, and air from satellites launched and maintained by the Shuttle. "I think that rather than having individual satellites for individual purposes," he said, "we will more and more see ourselves as building a multipurpose system of satellites and sensors, with the means for broad-scale data transmission and archiving and processing data into information. This type of system would look at all features and characteristics of the entire surface of the Earth and its atmosphere that can be sensed from space. With this versatility, we would be able to provide a variety of data to different users."

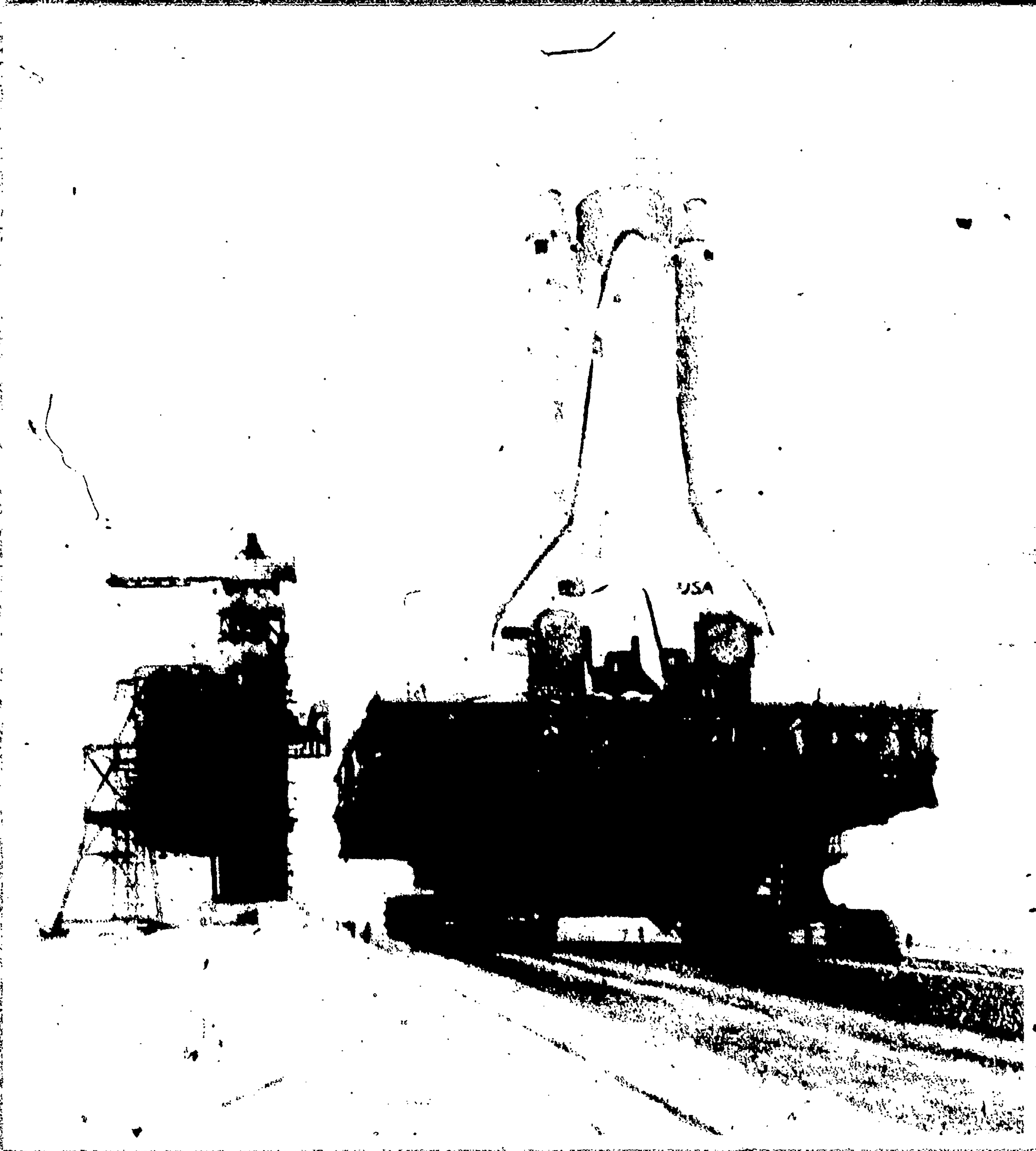
High-resolution remote sensing of natural resources from space will extend uses of such information that were demonstrated during the 1970s (Chapter 2). Instruments aboard Orbiters and a new generation of Earth-looking satellites will be able to detect crop and timber diseases and insect plagues, map ocean currents and temperatures that affect the movement of fish, maintain a worldwide watch on air pollution, provide information for experiments in weather modification and better understanding of climate, and forecast global production of several food crops.

The Shuttle also permits researchers to extend their investigations of how the unique conditions in space—virtually no gravity, near-perfect vacuum, very low vibration—might be used in manufacturing products that are difficult or impossible to make on Earth. Some ideas were tried out in Apollo, Skylab, and Apollo-Soyuz and in brief rocket flights with promising results. Government, university, and industrial scientists are planning both untended and hands-on experiments in Spacelab (Chapter 8). Most of these seek to take advantage of the lack of gravity. In the weightlessness of space, liquid mixtures of materials of different densities can be solidified without separating, as they would on Earth, by the heavier ones sinking to the bottom. Liquids may be floated freely during processing without being contaminated by reaction with containers. Large, flawless crystals can be grown without being distorted by their own weight as they form. Future possibilities for commercially valuable products include composite materials and metal alloys, electronic and optical crystals, new kinds of glass, and biological materials for medical research and treatment.

An entirely new activity seen as possible with the Shuttle is the building of large structures in space. Size and weight need no longer be limited to the payload of a single launch vehicle. A series of Shuttle flights could deliver structural members or modules to orbit for assembly there. An Orbiter could serve the construction crew as living quarters as well as provide electrical power, communications, and data processing. One or two electro-mechanical cargo-handling arms, attached to the Orbiter, could assist the space-suited builders in moving large pieces into place. Because there's no gravity, space structures could be very large yet relatively flimsy without collapsing of their own weight. Structures that might be assembled in space include large communication antennas, solar energy collectors and transmitters, manned laboratories, processing and manufacturing facilities, large spacecraft assembly plants, warehouses, and refueling and repair depots. One day a Shuttle may build an advance base for an expedition to the farther shores of the solar system.



Friction *with the thin air of the upper atmosphere will make parts of the Shuttle Orbiter glow for a few moments during critical reentry process.*


USA

4. What Shaped the Design

YEARS BEFORE EVEN THE FIRST SPUTNIK, scientists and aeronautical engineers recognized that economical, everyday use of space would require a transportation system employing vehicles that could make repeated voyages into space and return.

Newspapers in 1947 carried a series of imaginative stories describing "A Trip to the Moon and Back" that showed airplane-like rocket ships. In 1954 *Colliers* magazine published articles by Wernher von Braun and his associates popularizing the idea and economic advantages of Earth-to-orbit cargo carriers that would be recovered for repeated use. A paper given at the 1958 meeting of the American Rocket Society was entitled "Commercial Rocket Airplane: A Connecting Link to Manned Space Flight."

However, the technology needed for building returnable, reusable spacecraft was not yet in hand, particularly knowledge of how to design long lived, high-performance rocket engines and insulation that wouldn't burn away in a single fiery reentry into the atmosphere. The urgency of ballistic missiles and the perceived need to compete with the Russians in manned flight, moreover, kept American emphasis in the 1950s on conventional rocketry. One program to advance the technology—called Dynasoar, for dynamic soaring, using a vehicle that would bounce off the upper atmosphere, like a skipping stone—was begun by the Air Force but cancelled. NASA studied an idea called Head-End Steering. This involved putting a man-carrying, flatiron-shaped lifting body on the nose of a big rocket of very simple design. Expensive guidance and control equipment would be located in the lifting body, which could maneuver in the atmosphere after its reentry from orbit and be recovered for repeated trips—but the booster rocket still would have been expendable. This scheme was dropped because it didn't seem to offer much advantage over the simpler ballistic-capsule approach being worked out for the Mercury, Gemini, and Apollo programs.

By the early 1960s engineers studying the weight, propulsion, and thermal problems saw no practical way to design a single aircraft-spacecraft that would make the trip into orbit by itself with worthwhile loads and return. An economical system required two vehicles: a reusable cargo carrier plus some kind of booster to help it into orbit. Whether the booster also should be reusable was debated at length. Juxtaposed articles in the January 1963 issue of *Astronautics* magazine emphasized the greater operating economy but higher original development costs of "a winged, recoverable rocket-powered launch system."

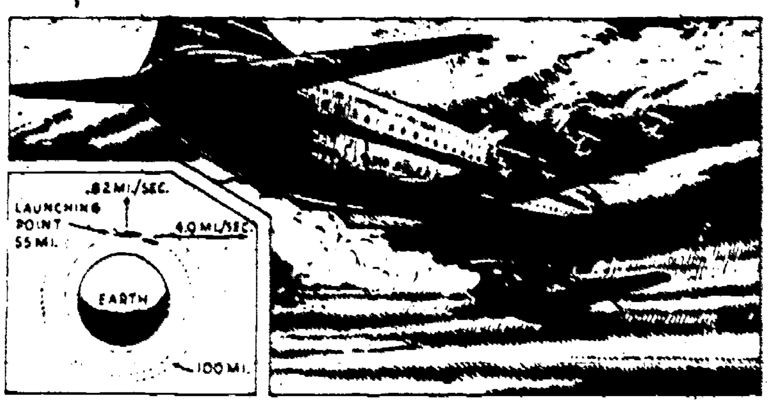
Through the decade uncounted engineers in Europe as well as the United States pondered various proposals for wholly or partly reusable Earth-to-orbit transportation concepts. The European Space Research Organization (ESRO)—now the European Space Agency—initiated studies involving industrial groups throughout western Europe. Titles of some of the papers given at a U.S.-European conference on Low Cost Space Transportation in 1967 indicate the wide variety of ideas explored: "French Concept for an Aerospace Transporter" . . . "A West German Approach to Reusable Launch Vehicles" . . . "A British Reusable Booster Concept" . . . "Air-Breathing Reusable Launchers" . . . "The Enigma of Booster Recovery—Ballistic or Winged?" . . . "A Comparison of Fixed Wing Reusable Booster Concepts."[4] Meantime, aerospace technology was being advanced by flight research with the X-15 rocket plane and lifting bodies, operational experience in Mercury, Gemini, and Apollo, and the development of supersonic military and transport aircraft. A series of studies for NASA, reported at a Space Shuttle conference in Washington in the fall of 1969, concluded that building a reusable

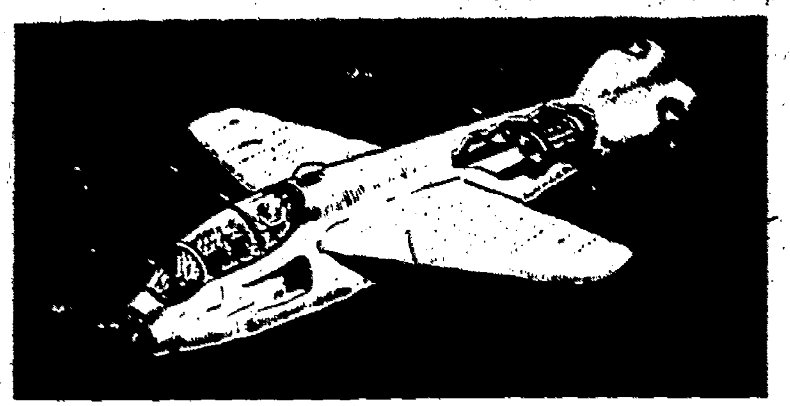
Concept of a reusable spaceship *that could land like a plane is far from new, as drawings from 1947* Sacramento Bee *below suggest. Many different engineering variations like the one at right, below, were examined, calculated, and wind-tunnel-tested. The Orbiter* Enterprise, *right, is the product of years of development work.*

THE SACRAMENTO BEE, THURSDAY, FEBRUARY 13, 1947

A Trip To The Moon And Back

No. 1: The Rocket Ship





Released By NEA Service

All aboard for the moon. The rocket ship will leave at midnight. Back to earth in time for a late breakfast. Round trip tickets only.

Scoffers kindly will remember they are the people who would have laughed at Columbus.

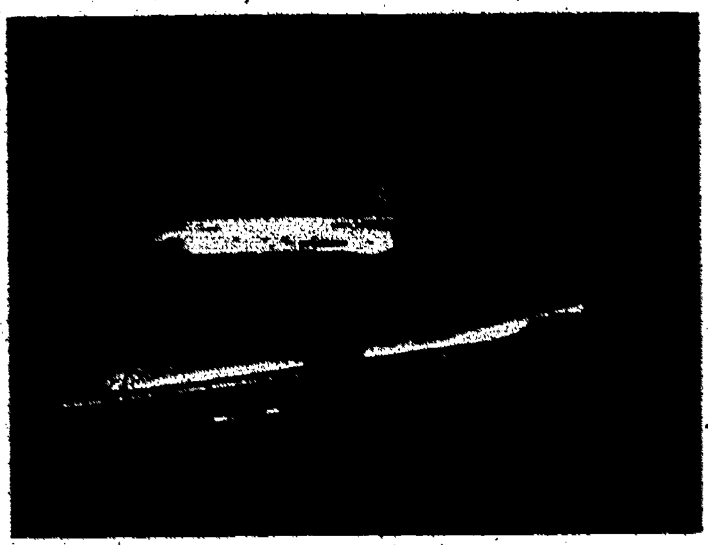
The moon is within reach. The trip will not be made tomorrow but many rocket experts believe it will not be long now.

A lot of problems remain and this is a semi-technical discussion of how they may be solved.

The following plan seems to the author the most feasible because of its minimum power requirement, simplicity of navigation and adaptability to the technique of modern aviation.

space transportation system was now becoming technically feasible and economically justified.

Before even the first Apollo flight, U.S. policy planners were shifting their sights to low-cost use of space for practical purposes. The President's Science Advisory Committee in February 1967 said: "For the longer range, studies should be made of more economical ferrying systems, presumably involving partial or total recovery and use." In September 1969, two months after the first Moon landing, in a report to a task group established by the President to outline the future of the U.S. space program, NASA recommended building ". . . a low unit-mission-cost transportation system that would make Earth-Moon space easily and economically accessible to man for his use for exploration, applications, science, and technology research." The head of the manned flight program, George E. Mueller, wrote: "No law says space must be expensive." In March 1970 the President announced that a major objective of the U.S. space program was to reduce substantially the cost of space operations. A reusable transportation system to shuttle between Earth and orbit was identified as a way of achieving this.



Two years of detailed feasibility, engineering, and economic studies by NASA, aerospace companies, and academic groups focused on a fully reusable two-stage, piggyback vehicle that would take off vertically and land horizontally. Each stage would carry its own fuel in internal tanks. When the first stage ran out, the second stage would continue its climb into orbit while the first returned to land on a runway. Since no tanks were to be dropped, the pair could take off without concern about passing over populated areas in the early part of the flight.

Each stage would have a crew of two. The second, orbital stage could carry, in addition, twelve passengers, since one of its main jobs would be to ferry replacement crews, as well as supplies, to a permanent space station. The cargo bay would be big enough to carry up modules from which the station could be assembled in orbit. Both stages would have new high-pressure hydrogen-oxygen rocket engines, two or three for the Orbiter and ten or twelve for the booster. The engines would be capable of repeated use and of being throttled back to half power to keep acceleration during ascent to less than three times normal gravity. This was important for crew and passenger comfort and would permit carrying less rugged, and therefore cheaper, payloads that would not be damaged by high acceleration and vibration. Engines were recognized as the pacing item in the Shuttle development, as they proved to be.

Two configurations for the Orbiter were considered. One had stubby, straight wings and was designed for reentry at a high angle of attack, which reduced extreme heating from air friction but also reduced maneuverability from side to side of the descent track that might be needed for an emergency landing. The second was a delta or triangular shape that could reenter at a lower angle of attack, permitting greater cross-range maneuvering but also causing greater heating of the nose, leading edges, and underside of the fuselage and thus complicating the problems of designing adequate thermal protection. The systems analysts, weighing advantages and disadvantages, chose the delta shape.

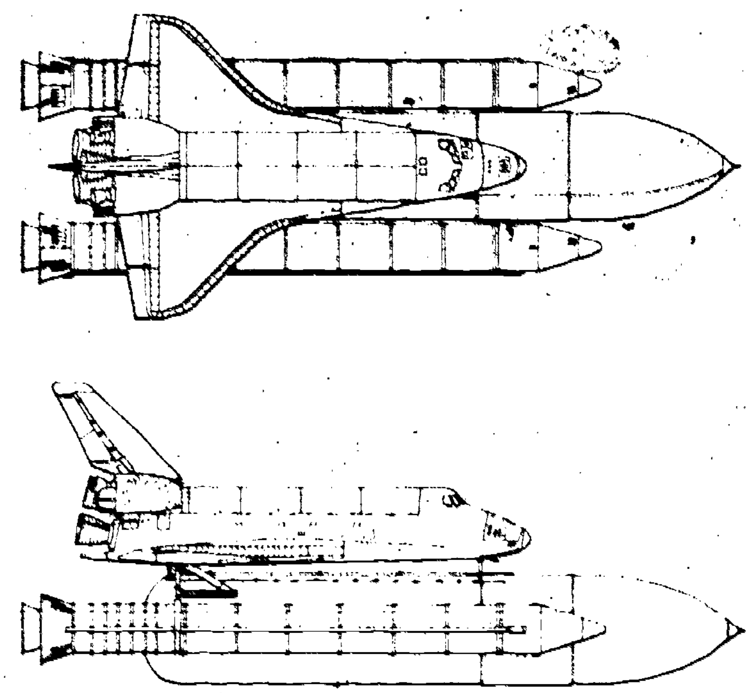
The very success of Apollo in beating the Russians to the Moon, and the subsequent trend toward reducing the annual cost of the U.S. space program, then forced a major change in the Shuttle design. The ultimate operating cost of a fully reusable vehicle would be lower than that of systems using some simpler, expendable elements; but the original development costs would probably have been more than $10 billion—1971 dollars—for two large piloted vehicles, both possessing features of a rocket launch vehicle and a supersonic aircraft. This seemed more than successive administrations and Congresses were likely to provide.

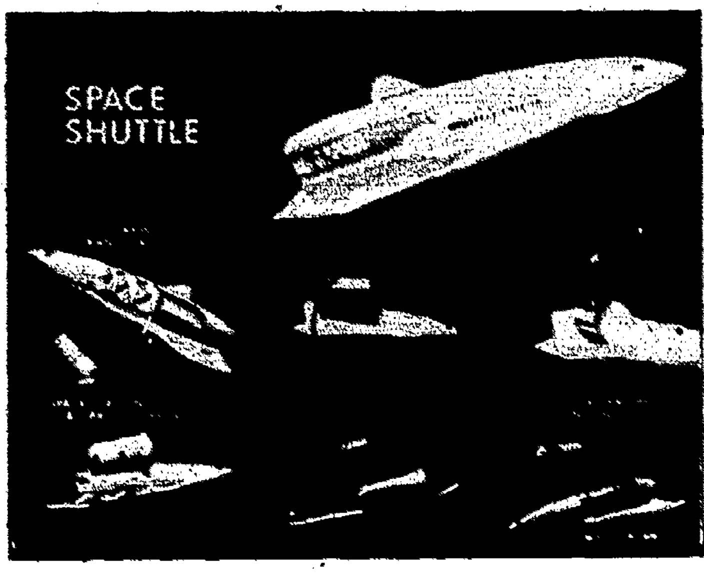
A search for ways to reduce the cost came up with a smaller, more efficient Orbiter with external, expendable hydrogen tanks; and the booster's top speed was lowered to permit the use of less expensive heat shielding. These changes cut the prospective price about 20 percent but not enough. So both the liquid oxygen and liquid hydrogen tanks were removed from the Orbiter in favor of a single expendable combined tank, divided to carry both propellants, further reducing the Orbiter's size and development cost but not its performance.

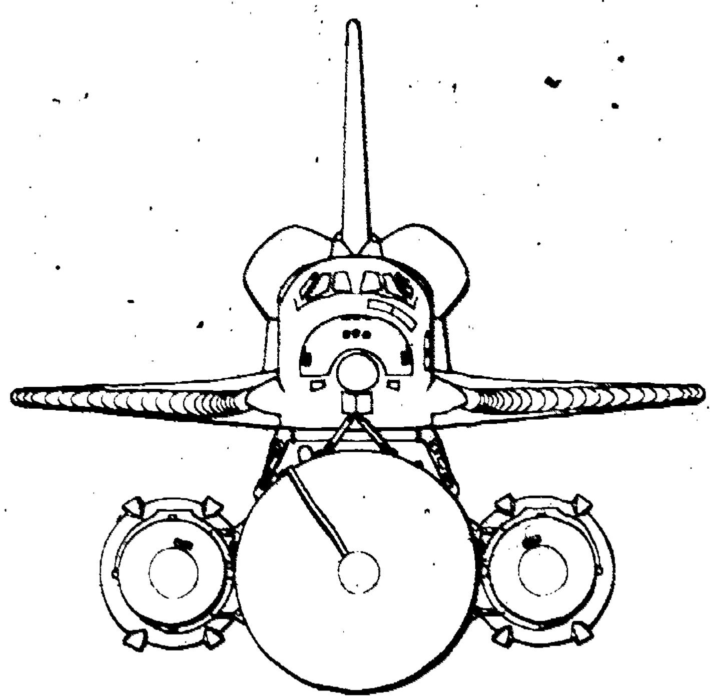
With the Orbiter configuration essentially settled, the final major decision was to resolve the booster issue. Charles J. Donlan, a leader in these studies, has described the interlocking engineering and economic tradeoffs and choices:

Partly to save money and partly because of worries about the safety of the booster crew in the event of a malfunction or aborted flight, the planners decided to give up the manned

One of dozens, ***the Orbiter design at right had some characteristics of the one chosen. Shown below are drawings of the complete launch vehicle now preparing.***







booster. An unmanned one then presented the choice of liquid-propellant or solid-fuel rocket motors. Liquid engines in a series-burn configuration, where the Orbiter engines would be ignited after the booster had shut down and separated, were compared with solid rockets that would be ignited simultaneously with the Orbiter engines at liftoff and burn in parallel during the initial ascent.

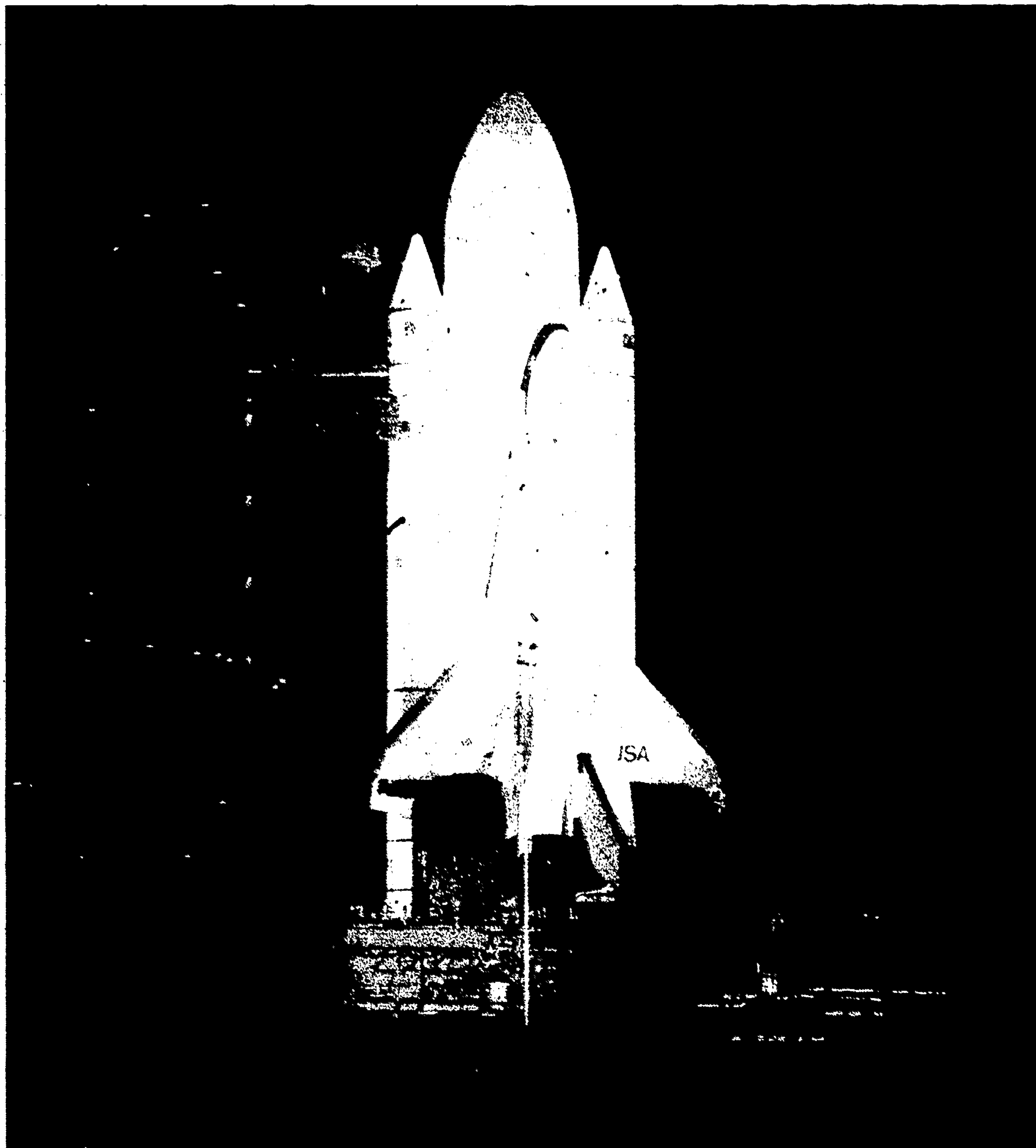
Because of the high price of a liquid-fuel booster, it would be important that each one be recovered, refurbished, and reused. This was not so critical for the cheaper solid-fuel rocket. In effect, the cost of discarding a liquid booster would be so much greater than discarding a solid that its use would impair the ability of the Shuttle to maintain the low cost of recurrent operations that was its major objective. Recovering a liquid booster would also be more complicated and expensive. Most of all, while the cost per flight would be higher with recoverable solid boosters and an expendable hydrogen-oxygen tank (fueling engines of a recoverable orbiter) than with the fully reusable vehicle originally favored, their choice would cut the program development cost almost in half. In the face of tight budgets, the decision seemed obvious.

On January 5, 1972, the President stated:

> The United States should proceed at once with the development of an entirely new type of space transportation system designed to help transform the space frontier of the 1970s into familiar territory, easily accessible for human endeavor in the 1980s and '90s. . . . It will revolutionize transportation into near space by routinizing it. . . . It will take the astronomical costs out of astronautics. . . . This is why commitment to the Space Shuttle's program is the right next step for America to take.

Separate solid-fuel rockets for abort from the launch pad and flyback jet engines for the Orbiter were later dropped to simplify the design and save weight, but other changes were minor through seven years of development, elaborate testing, and initial production.

The three-part configuration selected by NASA on March 15, 1972—reusable Orbiter, partly reusable Solid Rocket Boosters, and expendable External Tank—is essentially the Space Shuttle of today.



5. From Earth to Orbit

DESPITE THE FIRE AND THUNDER of liftoff and the enormous power required, getting into space is in some ways the easiest part of the Shuttle's journey. It follows a familiar pattern tested by earlier manned flights and hundreds of unmanned ones: simply dropping off parts of the vehicle, as they run out of fuel, while the rest continues into orbit.

The first to go are the Solid Rocket Boosters.

Standing 45.5 meters from nozzle to nose, and 3.7 meters in diameter (150 ft by 12 ft), the boosters are attached near their ends to the External Tank, slightly taller and twice as fat, which in turn is attached to the Orbiter. A Shuttle booster is the largest solid-fuel rocket ever flown, the first built for use on a manned spacecraft, and the first designed for reuse. It is assembled from seamless segments of half-inch steel, lined with heavy insulation, that are filled with propellant at the manufacturing site in Utah and shipped on railway flat cars to the Kennedy Space Center for assembly—or, for south-north flights, Vandenberg Air Force Base north of Los Angeles.

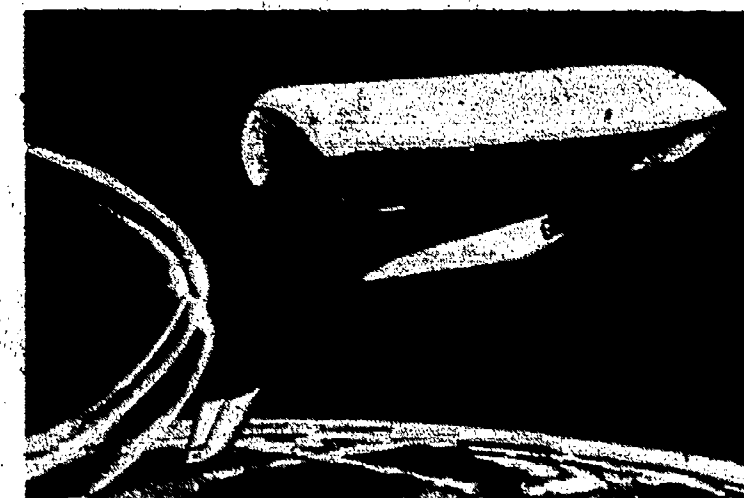
The propellant looks and feels like the hard rubber of a typewriter eraser. It is a mixture of aluminum powder as fuel, aluminum perchlorate powder as an oxidizer, a dash of iron oxide as a catalyst to speed the burning rate, and a polymer binder that also serves as a fuel. It is not sensitive to ignition by static, friction, or impact; and it will not detonate during storage. The case segments are loaded from a single lot of raw materials to minimize any thrust imbalance between the pair of boosters used for a given Shuttle flight.

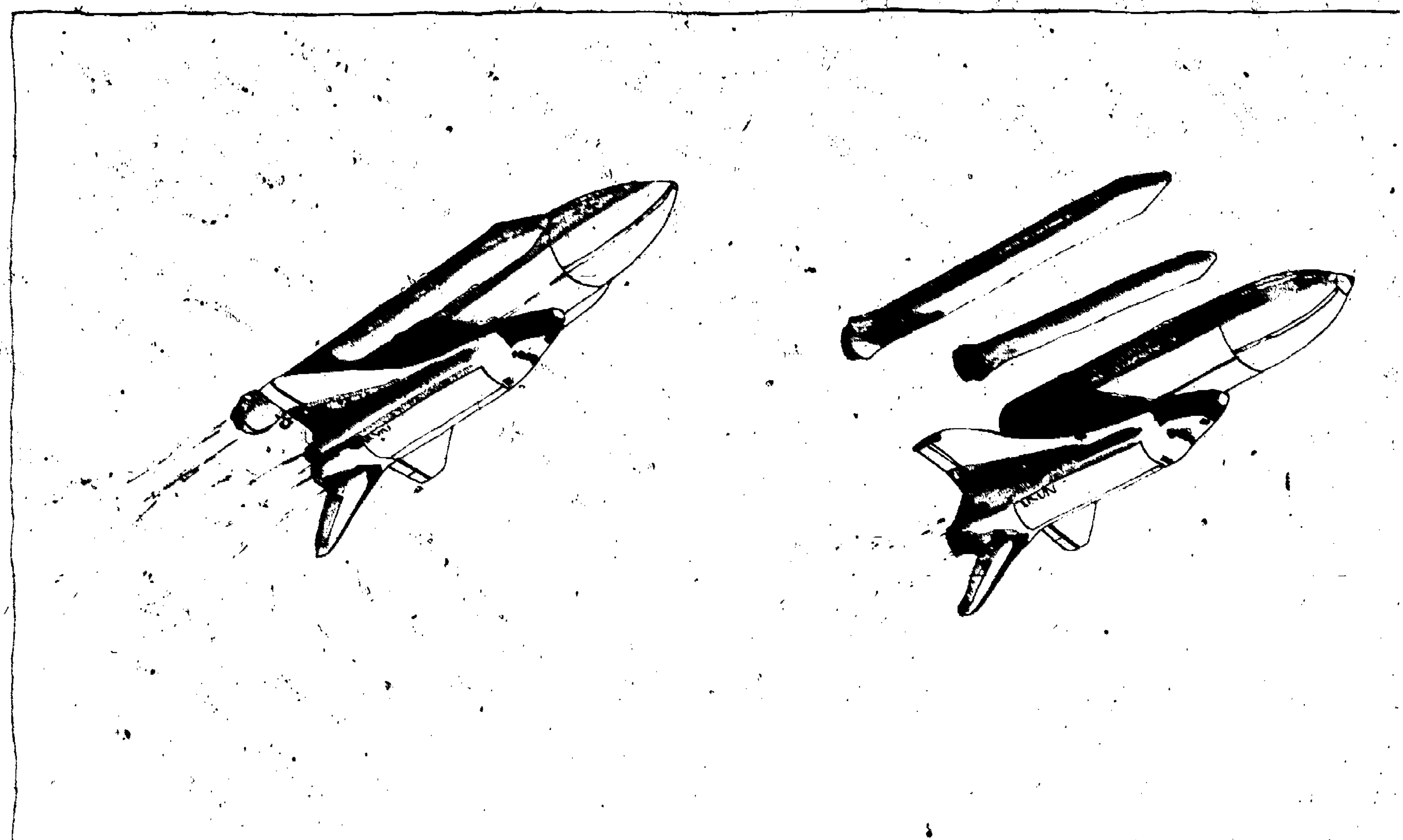
For launch, the propellant—500 000 kilograms (1 100 000 lb) in each booster—is ignited by a small rocket motor. Flame spreads over the exposed face of the propellant in about 0.15 second, and the motor is up to full operating pressure in less than half a second. As the propellant burns, at a temperature of about 3200° C, huge quantities of hot gases speed through the nozzle, which restricts their flow and increases the pressure, producing thrust as they spew from the exit cone. The two boosters' thrust of 5 200 000 pounds augments the 1 125 000-pound thrust of the Orbiter's three main engines through the first two minutes of ascent. The propellant is shaped to reduce the thrust briefly by about a third at 62 seconds into the flight, to prevent overstressing the Shuttle vehicle during the critical transonic period of maximum dynamic pressure.

The nozzles, each 3.76 meters (12 ft) in diameter at its opening, can be swiveled hydraulically up to 6.65 degrees on command by the Orbiter's guidance computer to control the direction of thrust. With similar swiveling of the Orbiter main engines, this steers the entire Shuttle vehicle. The outside of the boosters is insulated against the heat of air friction and the blast of the Orbiter engines at separation with an ablative material that burns away in temperatures that reach 1260° C.

After burning out, the Solid Rocket Boosters are cut loose from the External Tank by electrically fired explosive devices and are moved away by small rocket separation motors, four near the nose of each and four aft, fired by command from the Orbiter. The spent boosters coast upward and then fall Earthward for almost four minutes, reaching a speed of 4650 kilometers an hour (2900 mph) before being slowed by atmospheric drag. From about 4.7 kilometers (3 mi) each is

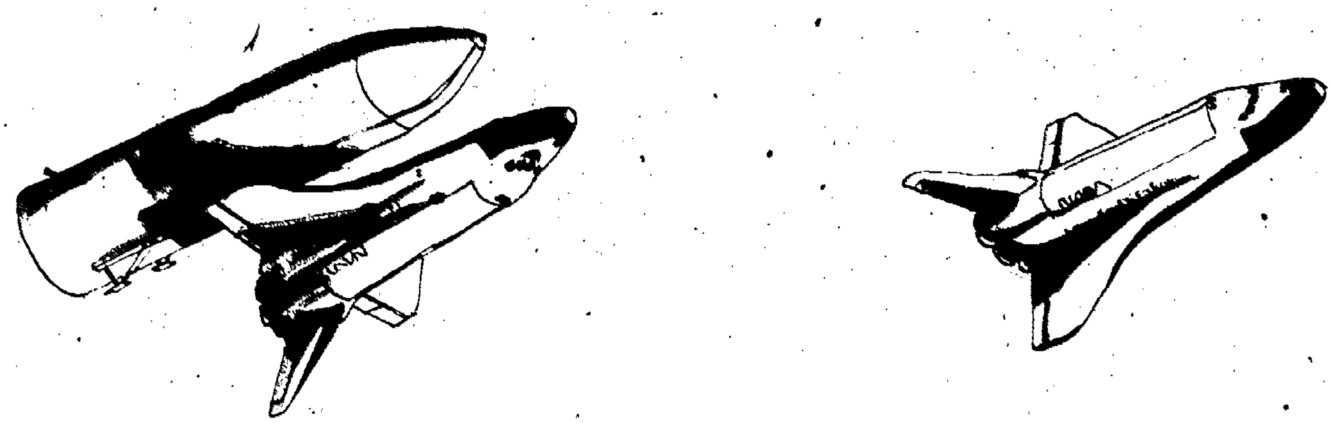
Huge External Tank *feeds fuel and oxidizer to the three engines until spacecraft is just shy of orbital velocity.*





lowered by a succession of parachutes, the three mains 35 meters in diameter (115 ft), deployed from the nose on signal from a barometric-pressure switch, to a splashdown of about 95 kilometers an hour (60 mph).

Since the empty rocket enters the water with the nozzle down, air is trapped in the upper end to float it upright until one of two recovery vessels, summoned by a radio beacon and flashing light, attaches lines to tow it back to the launch center. There the booster is taken apart and the rocket segments are shipped to the Utah factory, where they are cleaned out, inspected for cracks, pressure-tested, relined, reloaded, and reshipped to the site. When the rocket throat and nozzle also have been relined with ablative insulation, the parachutes washed and repacked, and other parts refurbished or replaced, the booster is reassembled to fly again. The main structure,



 directional controls, and electrical system are planned for twenty flights, the recovery system for ten.

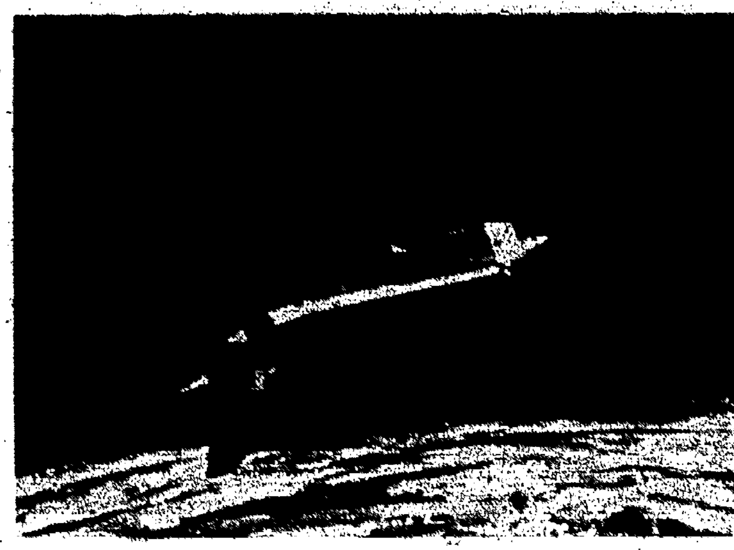
The second element of the Shuttle that is discarded during ascent to orbit, and the only major part not used again, is the External Tank. As tall (46.8 meters) as a fifteen-story building and as big (8.4 meters in diameter) as a farm silo, the tank contains the liquid hydrogen and liquid oxygen that fuel the Shuttle's three main engines in the stern of the Orbiter, and forms the backbone of the entire vehicle during launch. The tanks are built in a former Saturn plant near New Orleans and shipped by barge to the launch sites, those for the West Coast going through the Panama Canal.

Made of aluminum alloy up to 5.23 centimeters (2 in.) thick, the External Tank is actually two propellant tanks connected by a cylindrical collar that houses control equipment. The nose curves to a point tipped by a lightning rod. The forward tank is loaded with 529 900 liters (140 000 gallons) of liquid oxygen, chilled to minus 147.2° C, weighing 603 983 kilograms (1 330 000 lb). The one forming the aft section, two and half times larger, contains 1 438 300 liters (380 000 gallons) of liquid hydrogen at minus 251° C. This weighs only 101 503 kilograms (223 000 lb) because liquid hydrogen is sixteen times lighter.

The tank's outside skin is insulated with spray-on polyurethane foam that reduces heat transfer into the tanks that could cause excessive boiling of the propellants. It also helps prevent the buildup during launch preparations of ice that could shake loose in flight and damage the Orbiter. An ablating material that chars away protects the tank's bulges and projections from friction heating during ascent through the atmosphere.

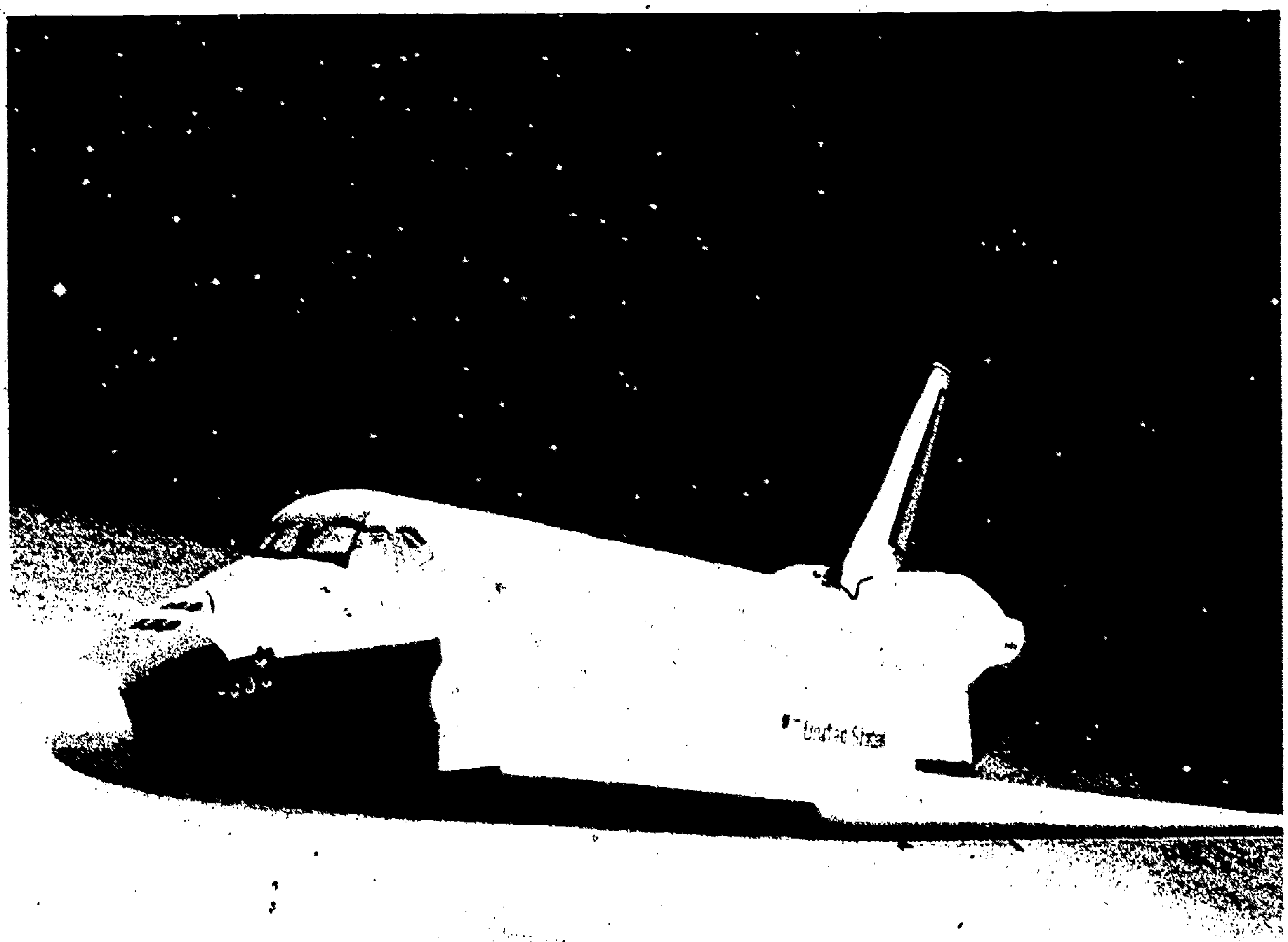
Horizontal baffles in the oxygen tank prevent sloshing that could throw the vehicle out of control, and anti-vortex baffles like fan blades in both tanks prevent the formation of whirlpools that could let gases, rather than liquid propellants, into the 43.18-centimeter (17-inch) pipes that carry 242 000 liters (64 000 gallons) a minute to the engines. Propellants are fed to the engine pumps by the pressure of gases formed by controlled boiling in the tanks and, during flight, by vaporized propellant gases routed back from the engines into the tanks. For cost saving, most of the fluid controls and valves are located in the reusable Orbiter rather than the expendable External Tank.

With the needed orbital velocity ***carefully computed, and the External Tank cut free, maneuvering engines now bring the Orbiter up to the exact speed needed for the mission.***



After the Solid Rocket Boosters separate at 50 kilometers (31 mi) altitude, the Orbiter, with the main engines still firing, carries the External Tank to near orbital velocity at about 113 kilometers (70 mi) above Earth. There, eight minutes after takeoff, the now-empty tank separates and falls in a planned trajectory into the Indian Ocean on missions from the Kennedy Space Center or the South Pacific on flights from Vandenberg Air Force Base in California. Venting of unused oxygen controls the tank's rate of tumbling to prevent skipping when it hits the upper atmosphere and to assure that it will break up and fall within the designated ocean areas far from busy shipping lanes. 39

Heavy, temperature-resistant windows give astronauts a view to the front.


United States

6. *The Amazing Orbiter*

THE ORBITER, which all other elements of the Space Transportation System support or depend on, looks like an airplane and acts like one during the last minutes of flight. But it is far more complex than the most sophisticated aircraft: forty-nine engines, twenty-three antennas, five computers, separate sets of controls for flying in space and in the air, electric-power generators that also produce drinking water.

The thick-bodied, delta-winged aerospace craft is 37 meters long, has a span of 24 meters (120 ft by 80 ft), and weighs about 75 000 kilograms empty (165 000 lb). Its cargo bay, 18.3 meters long and 4.6 meters in diameter (60 ft by 15 ft), can deliver single or mixed payloads of up to 29 500 kilograms (65 000 lb) to orbits of up to 370 kilometers altitude, or smaller loads up to 1110 kilometers (230 mi to 690 mi). It can bring payloads of 14 515 kilograms (32 000 lb) back to Earth; and it can carry out a variety of missions lasting seven to thirty days. It normally carries a crew of three astronauts and one to four scientists or technicians to manage the payloads.

The airframe is mostly aluminum protected by reusable surface insulation. The main sections are the forward fuselage, containing the air-tight crew module; the cargo-carrying mid-fuselage, with full-length overhead doors; the aft fuselage, including the engine thrust structure and the body flap that controls the craft's pitch in atmospheric flight and shields the main engines from the heat of air friction during reentry; the wings, which house the main landing gear; and the vertical tail.

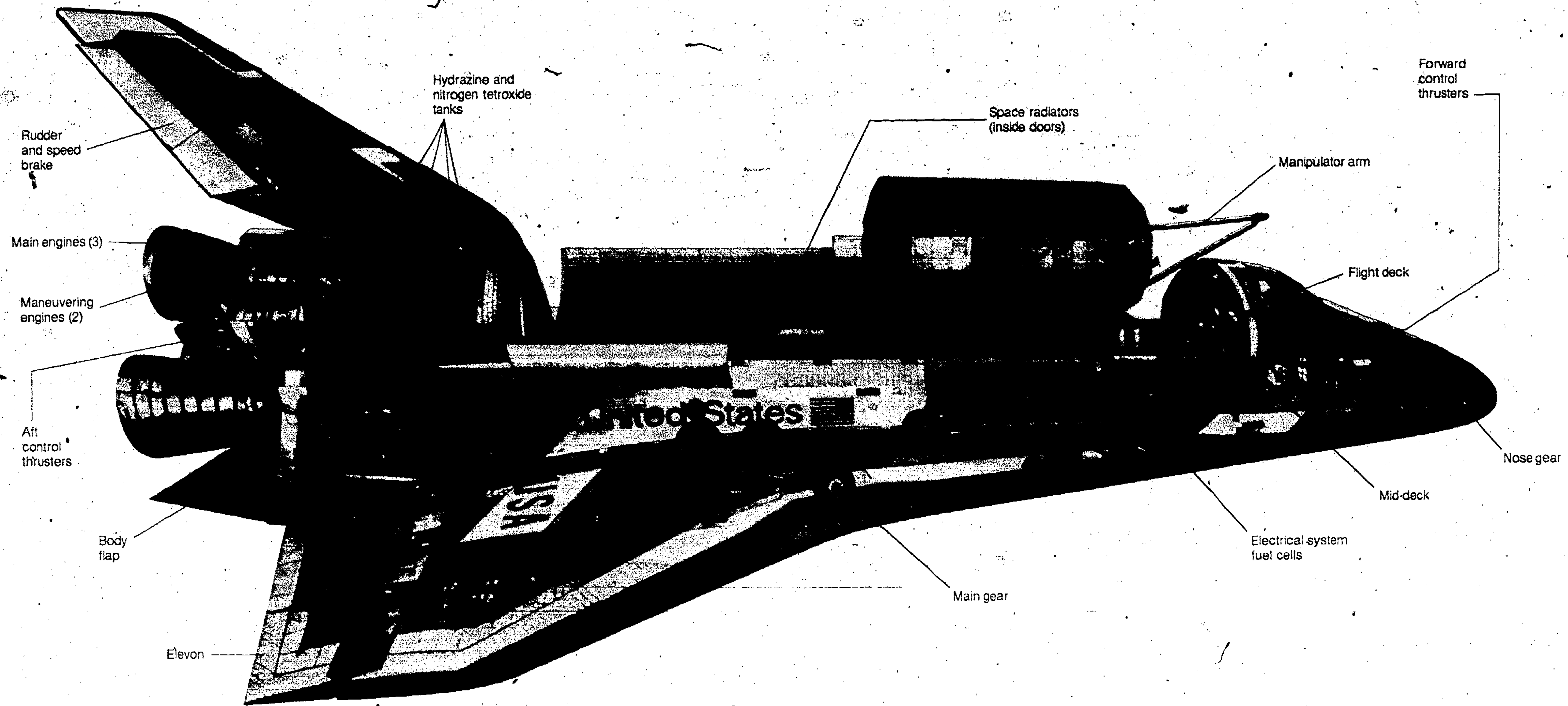
The forward fuselage is made of aluminum alloy panels, frames, and bulkheads, with window frames of machined parts attached to the structural panels and frames. The crew module, which will be described more fully in the next chapter, is machined aluminum alloy plate with integral stiffening stringers. It has a side hatch for normal entry and exit and an airlock from the crew living deck into the unpressurized cargo bay.

The mid-fuselage is the primary load-carrying structure between the forward and aft fuselages. The skin is machined and honeycomb-sandwich panels and the frames a combination of aluminum panels with riveted or machined integral stiffeners and a truss-structure center section. The upper half consists of the cargo hold doors, hinged along the sides and split at the top centerline. Made of graphite-epoxy composite frames and honeycomb panels, they incorporate radiators that are exposed to space when the doors are open to dissipate heat from electrical equipment in the Orbiter and payloads.

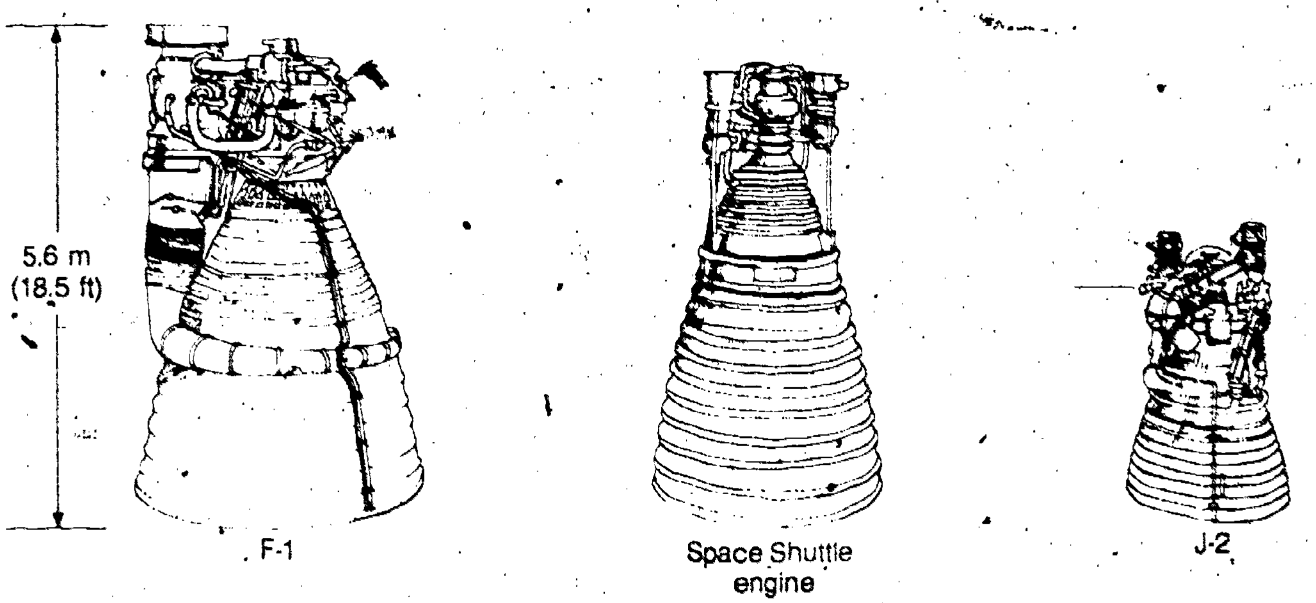
The aft fuselage structure, which carries the main-engine thrust loads to the mid-fuselage and, during ascent, to the External Tank, is a machined aluminum panel with a truss-type internal structure of titanium reinforced with boron epoxy. The wings are constructed with a corrugated spar and truss-type rib internal arrangement and skin-stringer stiffened aluminum alloy. The vertical tail is a two-spar, multi-rib, stiffened-skin box of aluminum alloy bolted to the aft fuselage at the two main spars. The rudder and speed brake assembly, divided into upper and lower sections, is aluminum honeycomb panels.

Insulation tough enough to protect the Orbiter and its crew from the searing heat of repeated reentries had to be invented. In earlier manned spacecraft, thermal buildup was controlled by shedding glowing bits of the heat shield itself. But NASA asked for materials that would last through 100 missions before replacement, and effective enough to protect the aluminum substructure beneath for 500 missions. The answer was a special tile-like insulation that reflects away heat so effectively that when one side is cool enough to hold in your bare hands, the other side can be red hot.

Two types of insulation cover the top and sides of the Orbiter: blocks of silica fiber with a glassy coating and flexible sheets of nylon felt coated with silicone. The tiles, around 2.5 centimeters thick and 20 centimeters square (1 in. by 7⅞ in. square), protect the aluminum surfaces up to 650° C, the flexible insulation up to 370° C. The coating gives the upper part of the craft a nearly white color and has optical properties that reflect solar radiation. Similar tiles with a different coating protect the bottom of the spacecraft and the leading edge of the tail up to 1260° C. The higher-temperature coating gives the underside a glossy black appearance. Top and bottom, there are more than 32 000 of the tiles, for which the Orbiter has been called "the flying brickyard." The nose and leading edge of the wings, which get hottest of all, are covered with a material called reinforced carbon-carbon (carbon cloth impregnated with additional carbon, then heat treated and coated with silicon carbide) that protects them up to 1650° C.


Hydrazine and nitrogen tetroxide tanks
Space radiators (inside doors)
Forward control thrusters
Manipulator arm
Rudder and speed brake
Main engines (3)
Maneuvering engines (2)
Flight deck
Aft control thrusters
United States
Nose gear
Mid-deck
Body flap
Electrical system fuel cells
Main gear
Elevon

The Orbiter's three main engines, developed by the Marshall Space Flight Center, which created the great Saturn V Moon rockets, are the most advanced rocket engines ever built and the first designed for repeated reuse. Their thrust for weight is the highest of any engine yet developed, and they can operate for up to seven and a half hours of accumulated firing time—fifty-five flights—before a major overhaul. Four and a third meters tall and 2.4 meters in diameter at the flare of the nozzle (14 ft by 8 ft), each produces 375 000 pounds of thrust—equivalent to about six and a half million horsepower—at the rated power level used for most launches and 470 000 pounds thrust in the vacuum of space. The thrust can be varied from 65 to 109 percent of rated power to tailor the performance to different loads and to keep acceleration within comfortable bounds.



Bulk alone *is a scant clue to differences in these three engines. The F-1 was in Saturn V's first stage, used kerosene, and had to work for minutes; the second- and third-stage J-2 used hydrogen, also had a short design life. Shuttle engines (SSME), vastly more efficient, last for 55 flights before overhaul.*

Mounted on the Orbiter aft fuselage in a triangular pattern, the three engines can swivel 10.5 degrees up and down and 8.5 degrees from side to side during flight to change the direction of their thrust and, with the two Solid Rocket Boosters that assist during the first two minutes, steer the Shuttle as well as push. They continue to burn for six minutes after the boosters are dropped off, each minute drawing about 47 000 gallons of liquid hydrogen and 17 000 gallons of liquid oxygen from the External Tank.

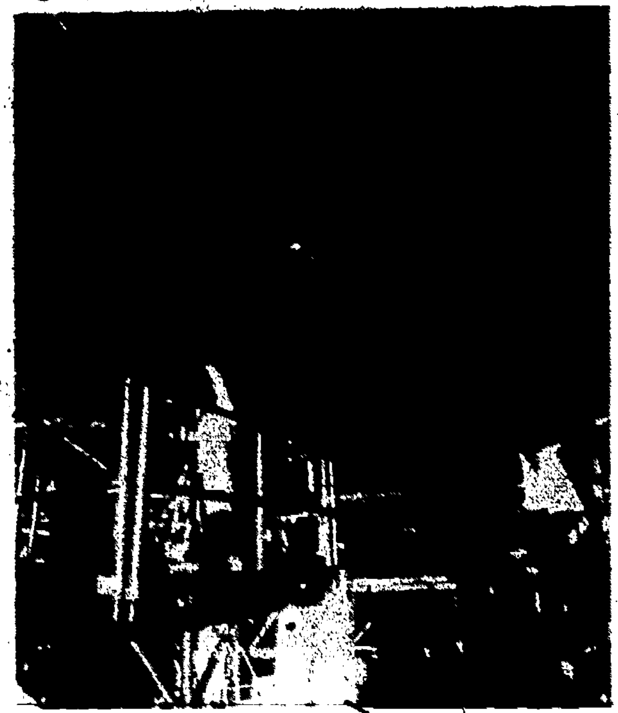
The propellants, ignited by devices similar to spark plugs, are burned in two stages, being partly combusted at relatively low temperature in preburners and then completely burned at high temperature in the main combustion chamber of each engine. Propellants are fed under high pressure by turbine pumps driven by hot gases from the preburners. Operating pressure in the main combustion chamber is 3000 pounds per square inch—four times that of previous rocket engines—as the fuel burns at 3515° C.

Each engine is controlled through a pair of computers (primary and backup) that monitor its operation. They compare actual with programmed performance fifty times a second; automatically correct any problems or safely shut down the engine; receive commands from the Orbiter's guidance and navigation computers for engine start, throttle changes, and shutdown; and keep a record of the engine's operating history for maintenance purposes.

Two orbital maneuvering engines in external pods to the left and right of the upper main engine each produce 6000 pounds of thrust to speed the Orbiter up to orbital velocity after the main engines shut down and the External Tank drops away. They also supply energy to change orbits, rendezvous with other spacecraft, and return to Earth. They burn monomethyl hydrazine as the fuel and nitrogen tetroxide as the oxidizer, which ignite on contact when mixed, requiring no starting spark. Propellants are force-fed to the engines from separate pairs of tanks in each pod by pressure from a tank of gaseous helium. The engines can be used separately or together and can be swiveled plus or minus 8 degrees to control the Orbiter's direction. They are designed to be reusable for 100 missions and are capable of 1000 starts and fifteen hours of continuous firing.

Batteries of small rocket engines, called reaction control thrusters, in the Orbiter's nose and near the tail provide attitude control in space and precision velocity changes for the final phases of rendezvous and docking or orbit corrections. Along with the ship's aerodynamic control surfaces, they also control its attitude during reentry into the atmosphere and at high altitude. In the nose are fourteen primary reaction control engines, each of 870 pounds thrust, and two vernier engines of 25 pounds thrust for fine tuning. Aft, twelve primaries and two verniers nestle in each pod beside the maneuvering engine. Their propellants are the same as for the maneuvering engines, and though the reaction control thrusters have their own tanks, they can also draw on those of the maneuvering engines. Each primary engine is designed for 100 missions, 50 000 starts, and 20 000 seconds of cumulative

Meticulous *installation of heat-resistant tiles is fussy. Almost no two tiles are alike; their backs are contour-machined. Closeness of fit with neighboring tiles is critical.*

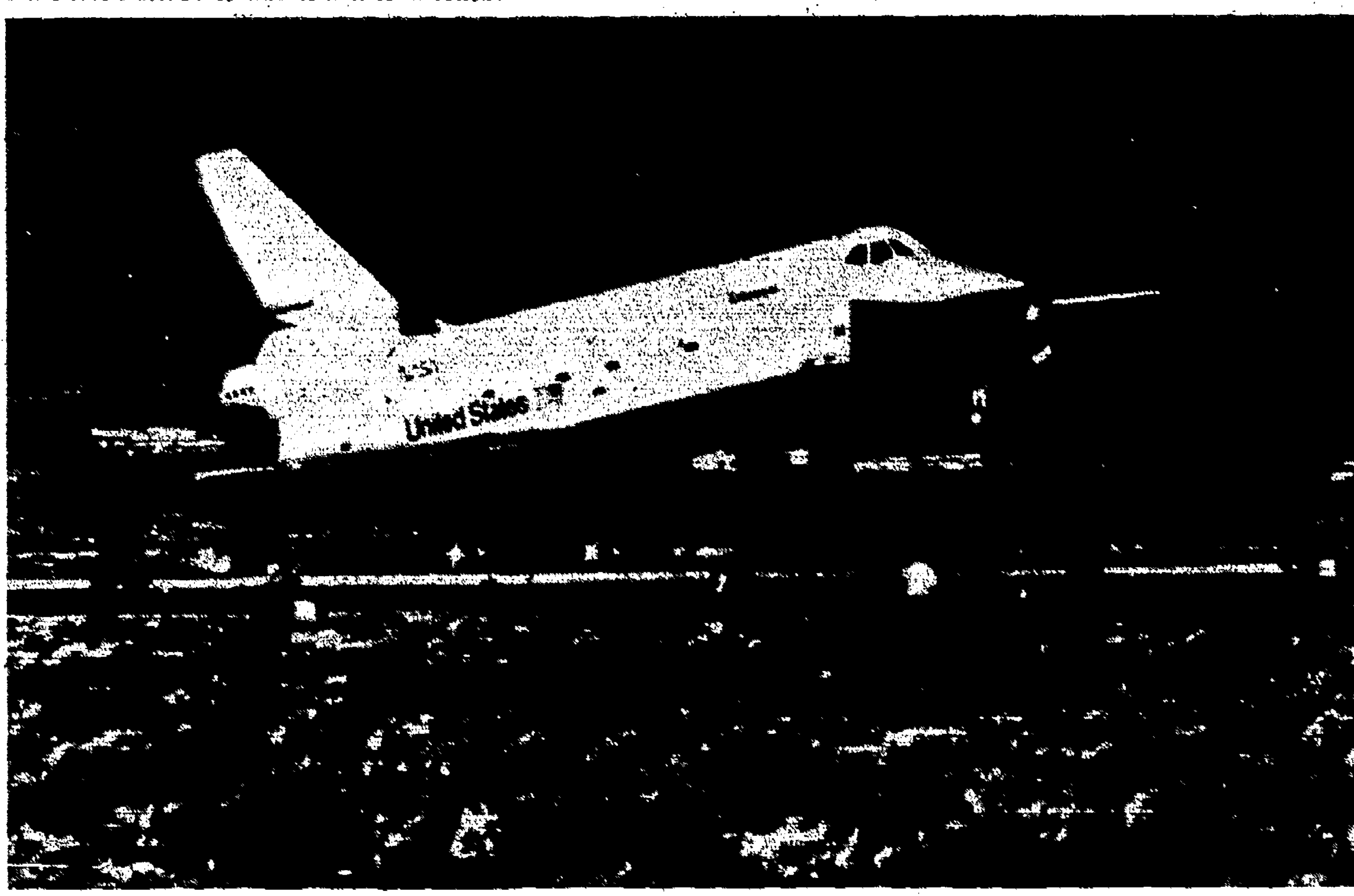


firing, each vernier engine for 100 missions, 500 000 starts, and 125 000 seconds of firing.

Internal power for the Orbiter is supplied by separate electrical and hydraulic systems. Hydraulic power is generated by three pumps geared to gas turbines driven at 74 160 revolutions per minute by the decomposition of hydrazine as it passes over a catalyst bed. Hydraulic actuators move the elevons (wing flaps), body flap, rudder/speed brake, main-engine valves and swiveling mechanisms, landing gear, wheel brakes, nose-wheel steering gear, and devices that disconnect the propellant lines from the External Tank to the Orbiter on separation.

Electricity for everything else, from computers to the payload-manipulating arm, is generated by three fuel-cell power plants. Developed in earlier manned flight programs, fuel cells generate direct current through the electrochemical reaction of hydrogen and oxygen. Electrical power needed may

Main gear touches *as the Enterprise comes in dead stick from an early landing test at Edwards Air Force Base. Nose wheels will soon touch.*



vary from 20 to 30 kilowatts during the ten-minute ascent to orbit and the half hour of reentry and landing, when most payload equipment is turned off or on standby, up to an average of 14 kilowatts and a peak of 36 kilowatts when the equipment is in operation in orbit. A valuable byproduct of the fuel cells is drinking water for the crew and passengers.

The Orbiter's cavernous cargo hold, with payload attachment points along its full length, is adaptable enough to accommodate as many as five unmanned spacecraft of various sizes and shapes on a single mission, instruments that view Earth or upper space from within the hold when the doors are open, small self-contained experiments for a variety of users, or a fully equipped manned scientific laboratory, Spacelab, described more fully in Chapter 8. The Orbiter supplies them with electrical power, fluid and gas utilities, heating and cooling, data transmission or storage and displays for the payload specialists aboard, and communications with ground stations. For instruments that make their observations from platforms in the payload bay, the Orbiter's computers fire the small vernier attitude-control thrusters to maintain pointing accuracy within half a degree.

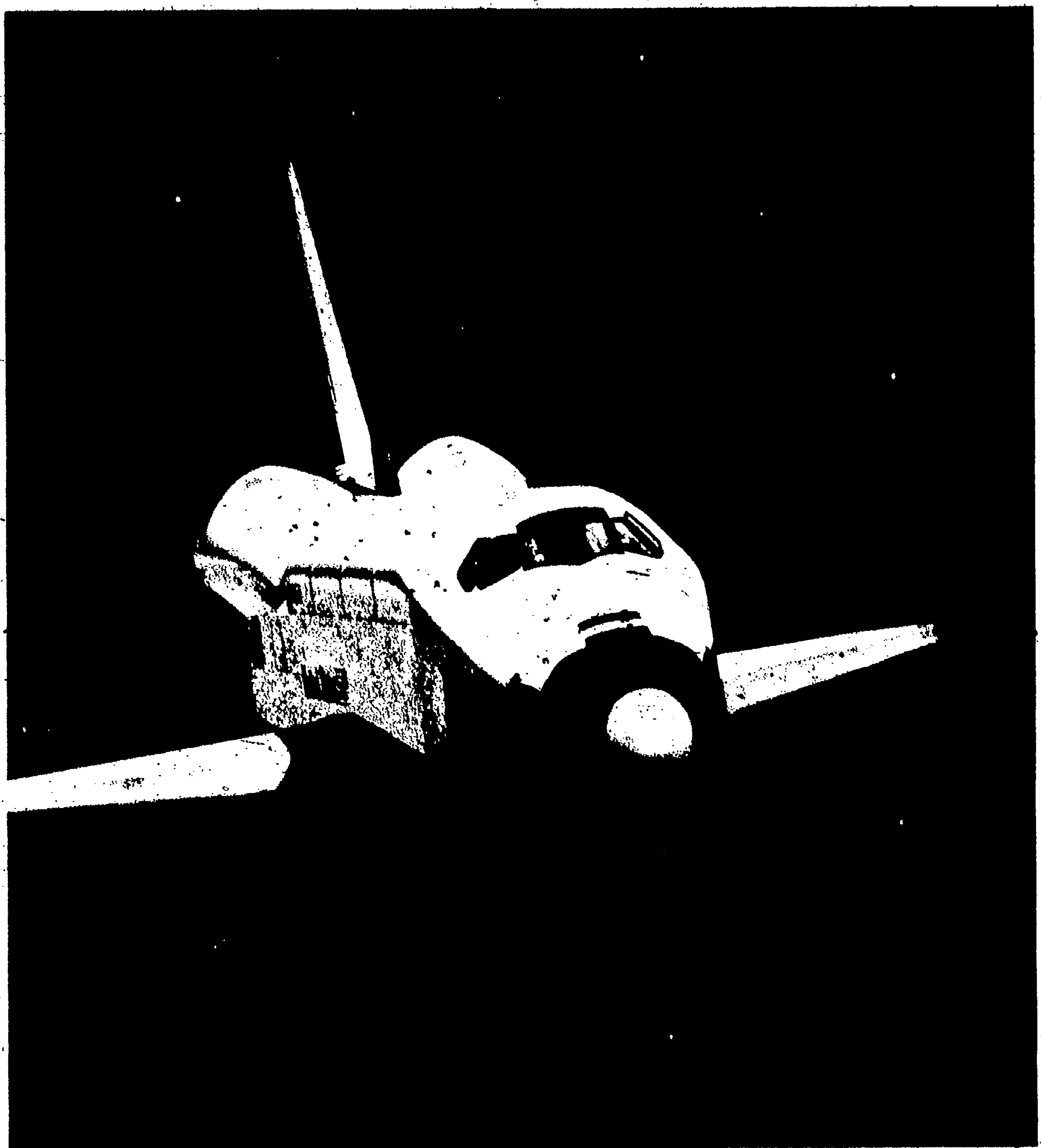
Using radar, the Orbiter can rendezvous from 560 kilometers away (350 mi) with a cooperative target, like the space telescope, or from about 20 kilometers (12 mi) with a passive one, like the Long Duration Exposure Facility, both described in Chapter 1. Voice communications, television signals, and scientific and engineering data are transmitted and received on five frequency bands through seventeen to twenty-three antennas, depending on the mission, to and from free-flying spacecraft being deployed, serviced, or retrieved; to astronauts working in open space in their pressure suits and maneuvering backpacks; to two tracking and data relay satellites, to be launched on early Shuttle operational flights; and directly to ground stations for use by controllers and experiment managers at the Johnson Space Center, the Goddard Space Flight Center in Maryland, and the Jet Propulsion Laboratory in California.

Satellites can be lifted out of or hauled into the cargo hold with a manipulating arm controlled remotely from the Orbiter flight deck. A second arm can be installed on the other side of the hold for missions on which very large or awkward payloads must be handled. Designed, developed, and built by Canadian industrial firms under the direction and funding of

Cargo bay is adaptable to an infinite variety of tasks. This is the load planned for second experimental orbital flight, a selection of test instruments.

the National Research Council of Canada, the manipulator is a robot human arm, 15 meters long (50 ft) with joints at the shoulder, elbow, and wrist, each operated by six electric motors. It ends in a device that engineers call the "end effector" that can take hold of a spacecraft to be deployed or grab one flying outside. Television cameras on the lower arm and lights in the cargo bay help the astronaut mission specialist guide the arm's movements from a station on the flight deck. The arm could be used to rescue the crew from a disabled Orbiter or to help assemble structures in space. There is no doubt that this ingenious electro-mechanical extension of men's brain and muscle will perform valuable service in years to come. What is vastly less certain is that we will actually call its hand an "end effector."

Multimission satellite *being deployed by the Orbiter is a new idea: a basic general-purpose satellite that can be tailored (and retailored) for many different jobs. It will reduce the high costs of satellites.*



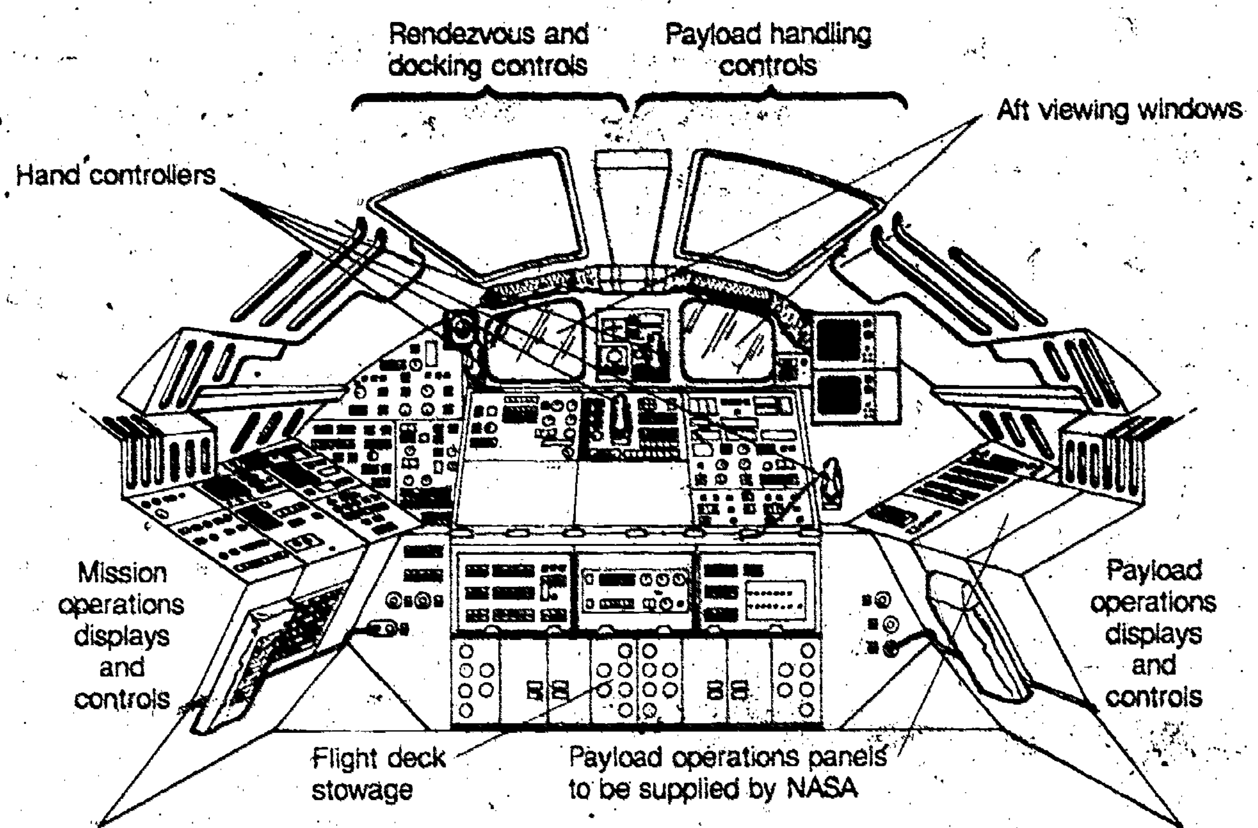
7. At Work Aloft

Once the Shuttle has completed its trial voyages, the list of those who may go into space will be greatly enlarged. No longer will travel beyond Earth's security blanket of atmosphere be restricted to a select population of physically perfect and intensively trained astronauts.

Acceleration stresses felt by the Orbiter's crew and passengers during launch and ascent to orbit are never more than three times normal gravity, only a third of the peaks hit on earlier manned flights and well within the physical limitations of non-astronaut scientists and technicians, who now can go into space for the first time to tend their own experiments there and observe the results. The spacious cabin (71.5 cubic meters: 2500 cu ft) provides separate working and living quarters supplied with ordinary air—22 percent oxygen, 78 percent nitrogen—at standard sea-level pressure of 14.7 pounds per square inch and comfortable temperatures of 11° C to 27° C. The humidity is controlled, and odors and carbon dioxide are continuously filtered out.

The upper section of the cabin is the flight deck, from which the Shuttle is controlled and most payloads are handled. It somewhat resembles the cockpit of a DC 10 jetliner. There is a conventional pilot-copilot arrangement of forward-facing seats for the ship commander (on the left) and pilot, TV-like displays, and duplicate sets of conventional-looking hand controllers, pedals, levers, and switches with which either astronaut can fly the craft alone. During ascent and return the mission specialist, who is also a NASA astronaut, and the non-astronaut payload specialist, if there's one along, sit behind the pilot and commander.

Behind and alongside the seats are four standup duty stations, two facing aft with windows and a windowless one along each side of the deck, where the crew and payload specialist work while in orbit. Looking aft on the left is the rendezvous and docking station, usually occupied by the commander, containing radar displays and controls for maneuvering the Orbiter close to another spacecraft. Alongside it, to the right, is the payload handling station, with displays and controls to manipulate, deploy, release, and capture payloads. The crew member at this station, usually the pilot, can open and close the payload doors; deploy the cooling radiators; deploy, operate, and stow the manipulator arm; and operate the lights and television cameras in the payload bay. Two TV screens display the pictures from the remote cameras.

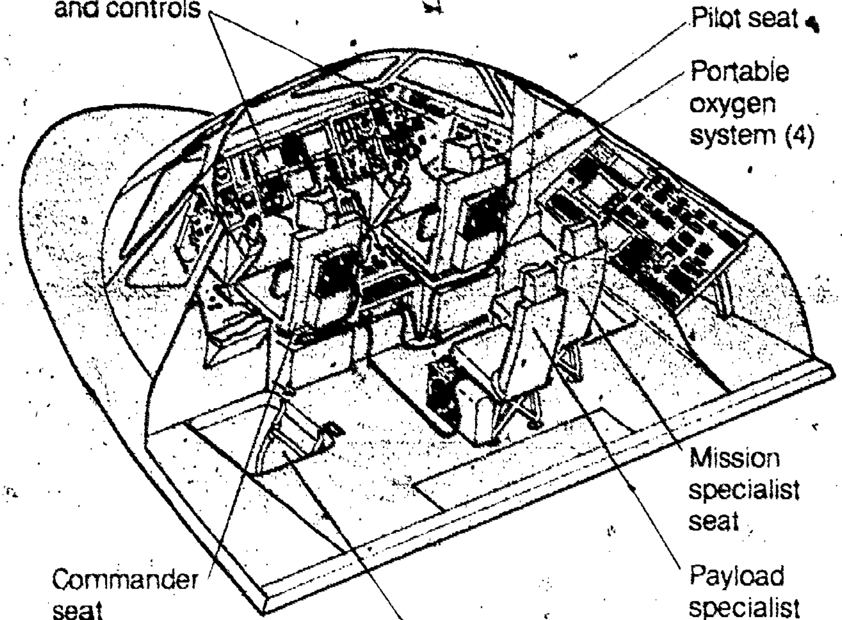


Flight deck *looking aft.*

The mission station, just behind and to the right of the pilot's seat and occupied by the mission specialist, contains controls to manage the Orbiter's interconnections with payloads and their equipment that is critical to the Orbiter's safety. The station is equipped to monitor, command, control, and communicate with payloads attached to the Orbiter or flying nearby; a caution and warning display alerts the crew members to malfunctions in payload components. Orbiter functions that are not immediately critical to the flight can also be managed from here.

On the opposite side of the flight deck, behind and to the left of the commander's seat, is the payload station, occupied by a payload specialist when the mission requires one. Payloads are checked out and managed from here, and the station includes a surface two meters square for removable displays and controls that can be changed for different payloads on different missions. A cathode-ray-tube display and keyboard for communicating with payloads through the Orbiter's data-processing system may be added. Electrical power and air-conditioning for payloads that need them are regulated from this station.

The Shuttle's flight is controlled by what aerospace engineers call fly-by-wire: there are no old-fashioned rods, cables, or hydraulic linkages. Movements of the pilots' hand controllers and pedals are converted into electronic signals and, like the programmed instructions for automatic flight, are routed through computers. The computers relay commands to the



Flight deck *looking forward.*

engines and attitude thrusters during launch, ascent, orbital operations, and reentry or to the hydraulic actuators that operate the elevon flaps, rudder, and speed brake during descent and landing. Data on the vehicle's performance, attitude, position, acceleration, velocity, and direction flow to cockpit displays and to the computers from rate gyros, accelerometers, star trackers, inertial measuring units, thrusters, thrust-direction controls, air-speed probes, radar altimeters, and air navigation and microwave landing systems. Four computers (there's also a backup one) process the same data simultaneously. Each compares its computations with those of the others and agreed-upon commands are sent to the appropriate control actuator. If and when there is disagreement, the computers in effect vote, and commands from the outvoted computer are ignored.

The cabin mid-deck, reached through an open hatch from the flight deck above, is the living area. (It also contains much of the Orbiter's electronics gear.) Here are three extra seats for additional payload specialists when the Shuttle is carrying the manned Spacelab. Along the left side of this deck are the galley and a washroom with a toilet. The galley includes an oven, hot and cold water dispensers for preparing freeze-dried foods, storage for seventy-four kinds of food and twenty beverages, places for drinking cups and eating utensils, a shelf for dining trays, a water tank, and trash bins. On the right, besides boxes for the crew's personal things, are three bunks and a "vertical sleep station." On a mission to rescue the crew of another Orbiter stranded in space, the bunks could be removed and three more seats installed. The total of ten seats, six here and four on the flight deck, then would accommodate the rescue flight crew of three and the maximum of seven from the disabled craft.

A lower section of the cabin module, beneath the living quarters and reached through removable floor panels, contains more storage space and the Orbiter's environmental-control equipment.

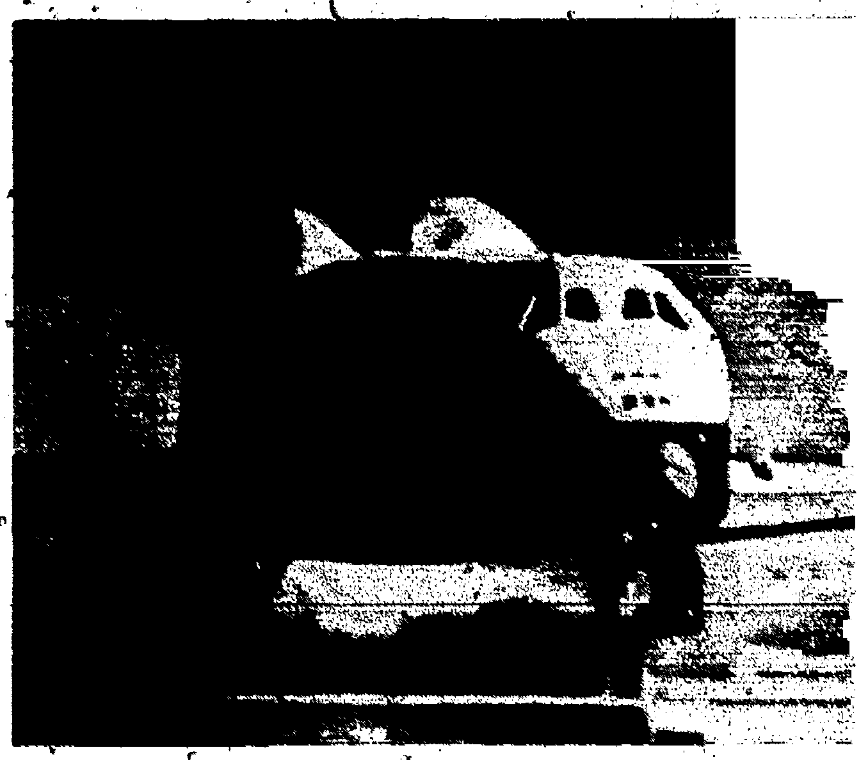
From the back of the mid-deck an airlock—a cylindrical compartment with air-tight hatches on opposite sides—leads into the cargo bay. Astronauts in space suits enter from the cabin and close the hatch on that side before opening the other one, thus preventing cabin air from escaping into the unpressurized bay and the vacuum of space. Handrails, hand holds, and foot restraints at various locations in the cabin, airlock, and payload bays help the weightless crew members, scientists, and technicians to move about and work as if neutrally buoyant underwater. They can go along a handrail on the load-manipulating mechanical arm to work on a payload at the far end of the bay; to reach a satellite held out in space by the arm during deployment, refurbishment, or retrieval; or to get at parts of the Orbiter itself that may need inspection or servicing.

Backpacks worn with the space suits provide oxygen and suit cooling for six hours, and the Orbiter carries supplies for two more six-hour periods of EVA—"extravehicular activity"—for two crew members. A space-suited astronaut can also wear on his back a personal rocket kit, called the manned maneuvering unit, to fly outside the cargo bay. With this hand-controlled propulsive device he can reach a nearby free-flying satellite, transport cargo of moderate size such as may be required for servicing a spacecraft, or retrieve small free-flyers that may be sensitive to perturbation or contamination by the Orbiter's attitude-control thrusters. The maneuvering unit's own low-thrust nitrogen propellant causes minimal disturbance and no contamination.

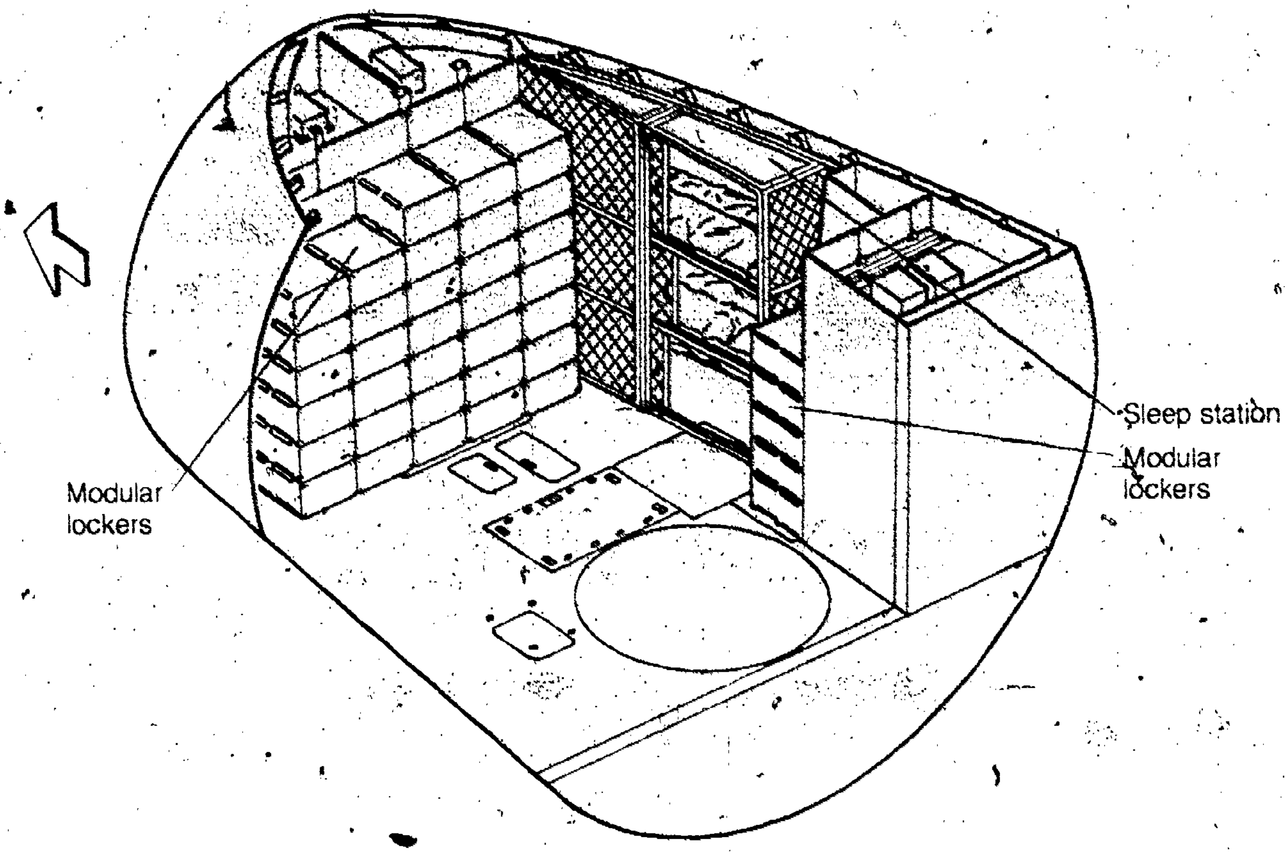
EVA tasks may include: inspecting and photographing payloads or their components; installing, removing, or transferring film cassettes, materials samples, protective covers, and instruments; operating equipment, tools, and cameras; cleaning optical surfaces; connecting, disconnecting, and stowing fluid and electrical lines; repairing, replacing, calibrating, and inspecting modular equipment and instruments; deploying, retracting, and positioning antennas, booms, and solar-power panels; transferring cargo; performing experiments in the cargo bay; and possibly repairing some damaged or malfunctioning Orbiter mechanism in orbit.

In case of serious trouble during ascent to orbit that made it impossible or unwise to continue the mission to its full duration, the Orbiter is expected to get back to Earth with its personnel safe and its payload intact.

If a decision to cut the flight short had to be made during the first four minutes of powered ascent on the main engines, they would if possible be kept firing until the vehicle reached an altitude of some 100 kilometers (60 mi). There the atmosphere would be thin enough so that the Orbiter, with the External Tank still attached, could flip over and point backward toward the launch site. Continued engine thrust



Landing runout *appears to pose no problems despite absence of reverse thrust. This was second drop test, with astronauts Engle and Truly.*

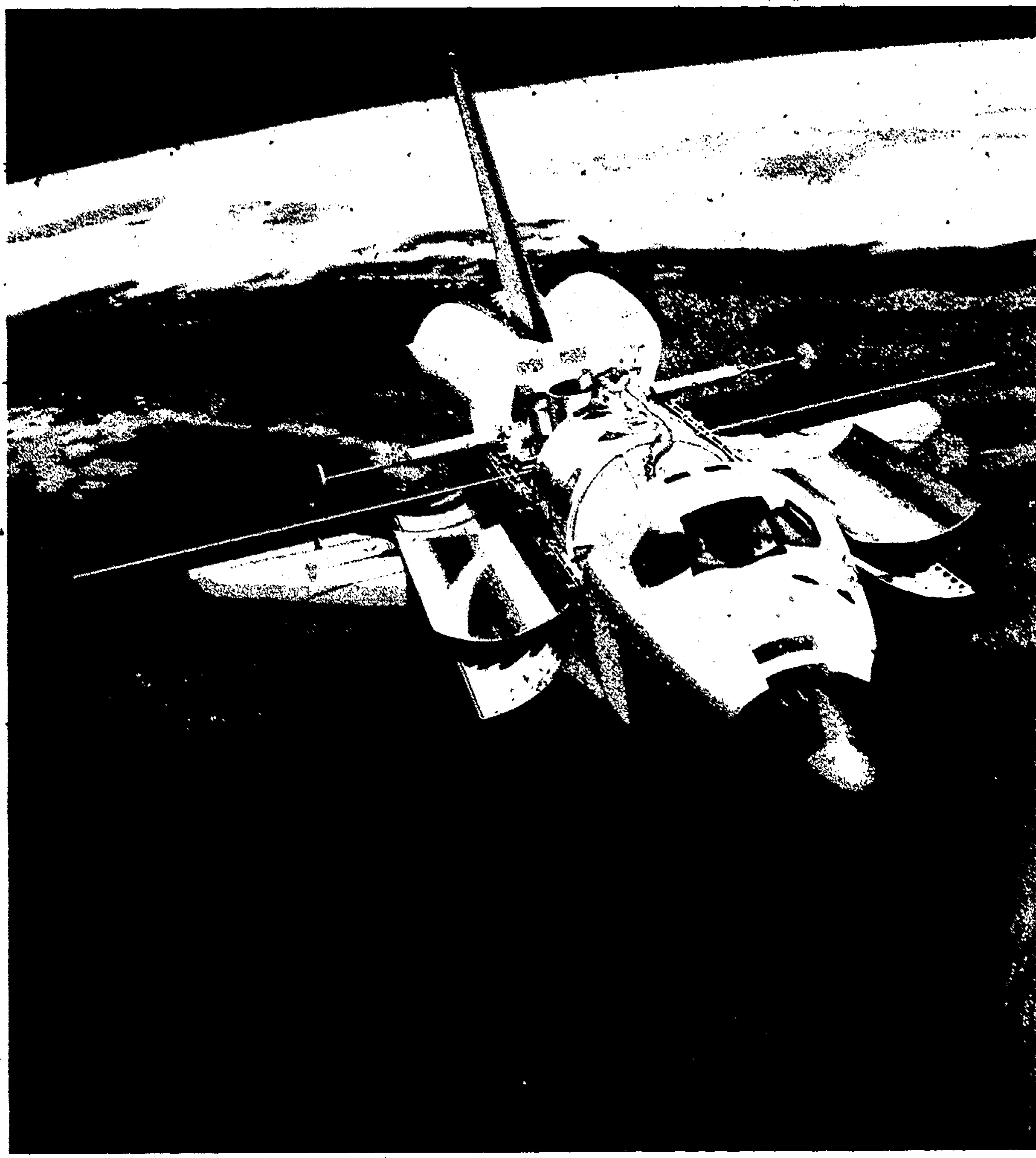


Mid deck *looking forward.*

would slow the tail-first velocity to zero and then accelerate the vehicle, nose first, back toward the launch site. When it reached the point where the Orbiter alone could glide home, the engines would be shut down and the tank jettisoned into a not-too-busy ocean area selected ahead of time. A computer guidance program for just such an emergency would control critical maneuvers until the Orbiter glided within range for the crew to make a manual landing on its usual base runway, about twenty minutes after liftoff.

In a mission aborted during the last half of the launch phase there would be enough thrust left to power the Shuttle to just short of orbital velocity. The External Tank would be dropped into the normal disposal area, and the Orbiter's trajectory would take it once around the globe for a nearly normal reentry and landing on the home runway about ninety minutes after takeoff. If the trouble came in the last few minutes of ascent, the tank would be discarded into the planned area and the Orbiter would make orbit, maybe at a lower altitude than planned, by firing its orbital maneuvering engines longer than usual. The mission, though probably shortened, might last several days and would conclude with a normal return to Earth.

If an emergency during orbital operations required urgent return, the crew could decelerate from orbit promptly but in the normal way and, if not within range of home base, come into one of several air fields with long, strong runways that NASA has lined up as emergency landing sites.



8. Airline to Space

THE SPACE TRANSPORTATION SYSTEM is, broadly, the Shuttle—Orbiter, fuel tank, and launch boosters—plus everything that goes with it:

- Spacelab, in which scientists and technicians of many nations can conduct their own experiments beyond Earth's gravity and atmosphere;
- Optional flight kits of special equipment and extra supplies, such as additional tanks of fuel for maneuvering, to enhance the Orbiter's performance, and extend its stay in space;
- The payload manipulating arm described in Chapter 6;
- A modular spacecraft that can be outfitted with different sets of instruments for a variety of missions;
- Rockets to propel Shuttle payloads to higher orbits or on their way to other planets;
- A complex communications network;
- Launch sites and service facilities;
- Ingenious cargo handling equipment to speed ground operations;
- Ground control centers;
- And the management structure to put them all together into a working system.

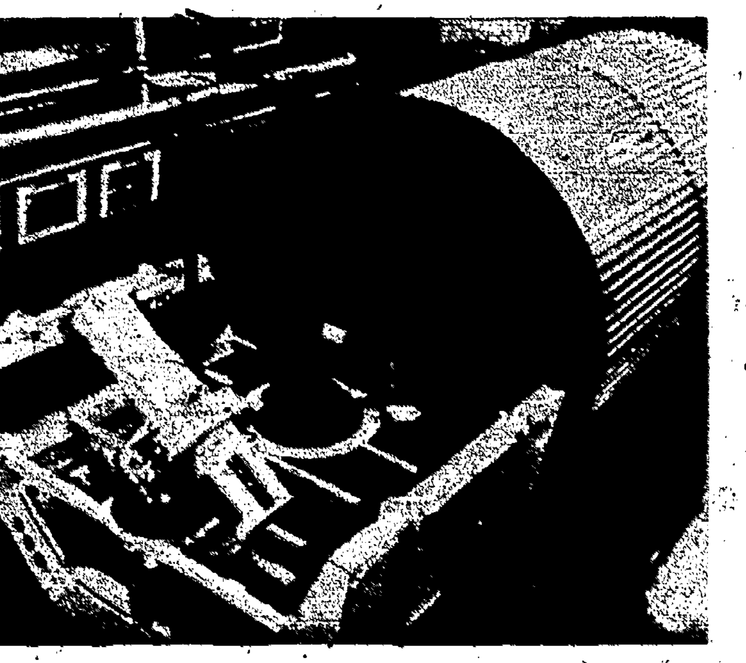
The head of NASA's Office of Space Transportation Systems, John F. Yardley, has compared the operation to running a scheduled airline with aspects of a charter service.

Twenty to thirty percent of all Shuttle missions will carry some parts of Spacelab, a versatile orbiting laboratory for manned and automated research in the low-gravity, high-vacuum environment of space. In its laboratory module men and women working without space suits in a comfortable, Earth-like atmosphere will conduct scientific and technical experiments in close cooperation with colleagues on the ground. Its development is financed by ten European nations under the European Space Agency. Agreements with the United States provide that ESA design and build one Spacelab as well as its test and ground equipment. Others that may be ordered later will be paid for by the U.S. NASA is in charge of operations. The European countries involved are Austria, Belgium, Denmark, West Germany, France, Italy, the Netherlands, Spain, Switzerland, and the United Kingdom.

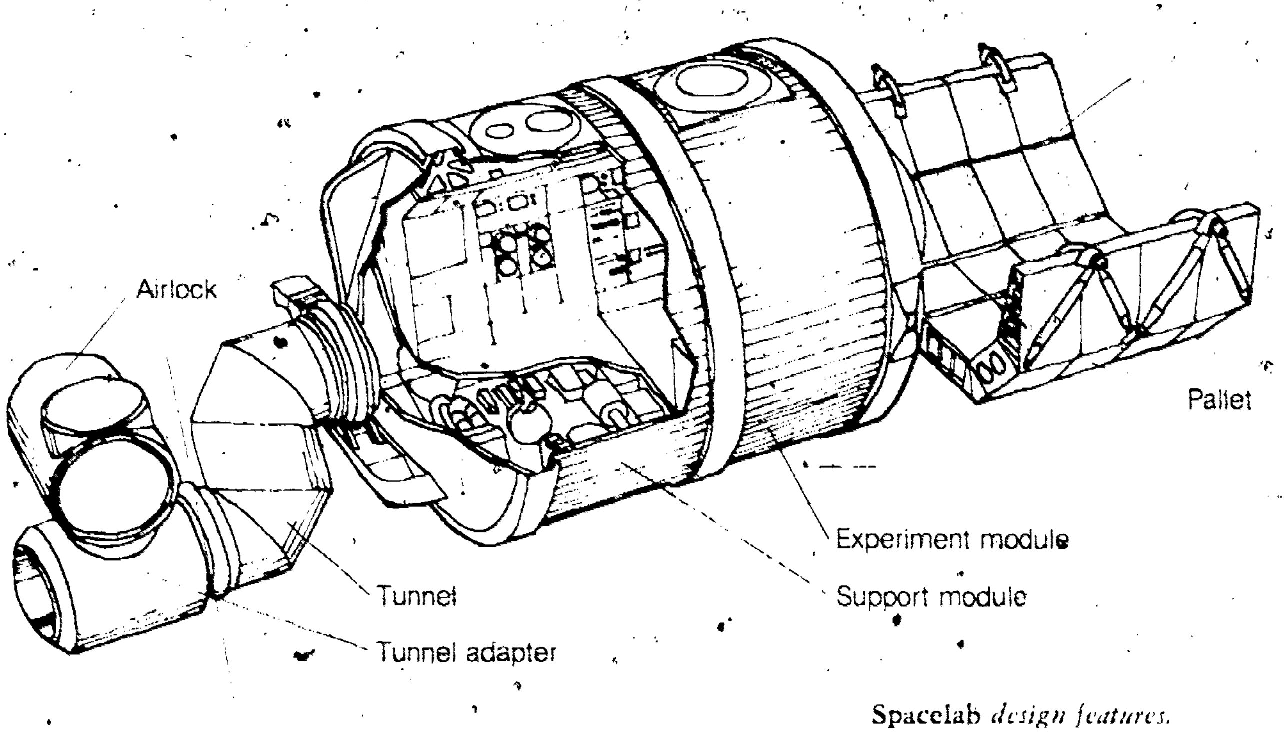
Like the Shuttle itself—but unlike Skylab—Spacelab is reusable, designed to be launched and returned with the Orbiter as many as fifty times over a life of ten years. It stays in the Orbiter throughout the flight, is exposed to space when the big cargo doors are open in orbit, and is removed on the ground for rearrangement of its elements and changes of instruments and equipment for different kinds of missions.

Spacelab's main elements are the pressurized laboratory, which affords shirtsleeve working conditions, and an instrument-carrying platform called the pallet, a sort of open back porch, that exposes materials and equipment directly to space. Each of these is segmented for mission flexibility; either can be flown alone or in more than half a dozen different combinations with the other.

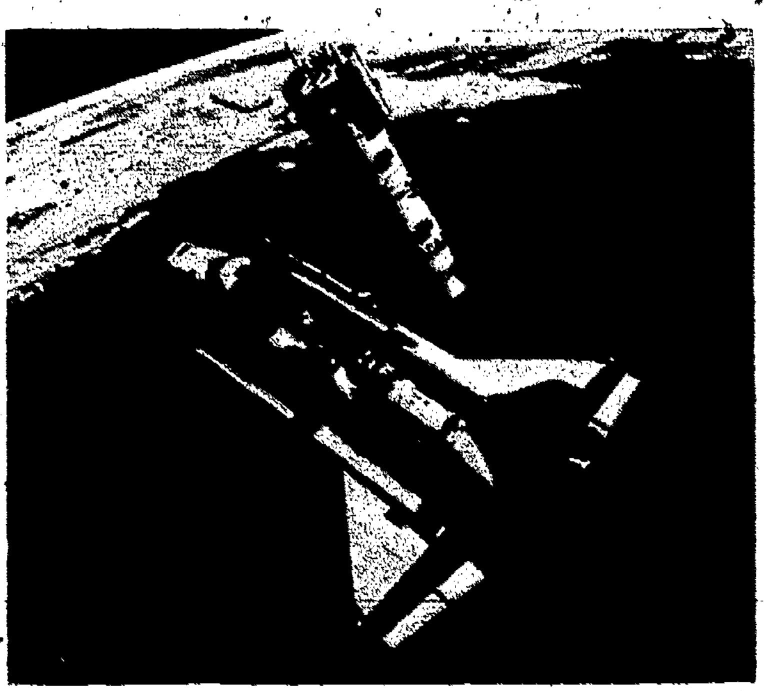
One segment of the laboratory module, called the core segment, houses data processing equipment and utilities for both the pressurized modules and the pallets when flown together. It also has usual laboratory fixtures—air-conditioned experiment racks, work benches, and so forth. The second, called the experiment segment, provides more pressurized working space, racks, and benches. Each pressurized segment is a cylinder 4.1 meters in diameter and 2.7 meters long (13 ft by 9 ft). When the two are assembled, with their cone-shaped end sections, the maximum outside length is 7 meters (23 ft).



Mockup of Spacelab *and drawing show one of many possible configurations.*



Spacelab *design features.*



Ability to combine *many tasks is a special virtue of the Orbiter. Here a Defense Department spacecraft is released, soon to ascend to its own orbit. Aboard for later deployment are other satellites, including an Advanced Radio Astronomy Explorer.*

As many as five pallet segments can be flown at one time, each three meters (10 ft) long. They serve not only as platforms for mounting instruments but also can cool equipment, provide electrical power (generated by one of the Orbiter's three fuel cells), and furnish connections for commanding experiments and acquiring data from them. When pallets alone are used, equipment for essential services for the experiments, such as a power distribution box and computers, are protected in a small pressurized, temperature-controlled housing called the igloo. Equipment and experiments can be serviced, if necessary, by astronauts in space suits. The pallets are used for large instruments—telescopes, antennas—and experiments that require direct exposure to space or need unobstructed or broad fields of view. An instrument-pointing system provides attitude control and stabilization for experiments that require more precise pointing than is possible with the Orbiter controls. Pallet experiments can be controlled from the laboratory module or the Orbiter flight deck or from the ground through the Orbiter's communications links.

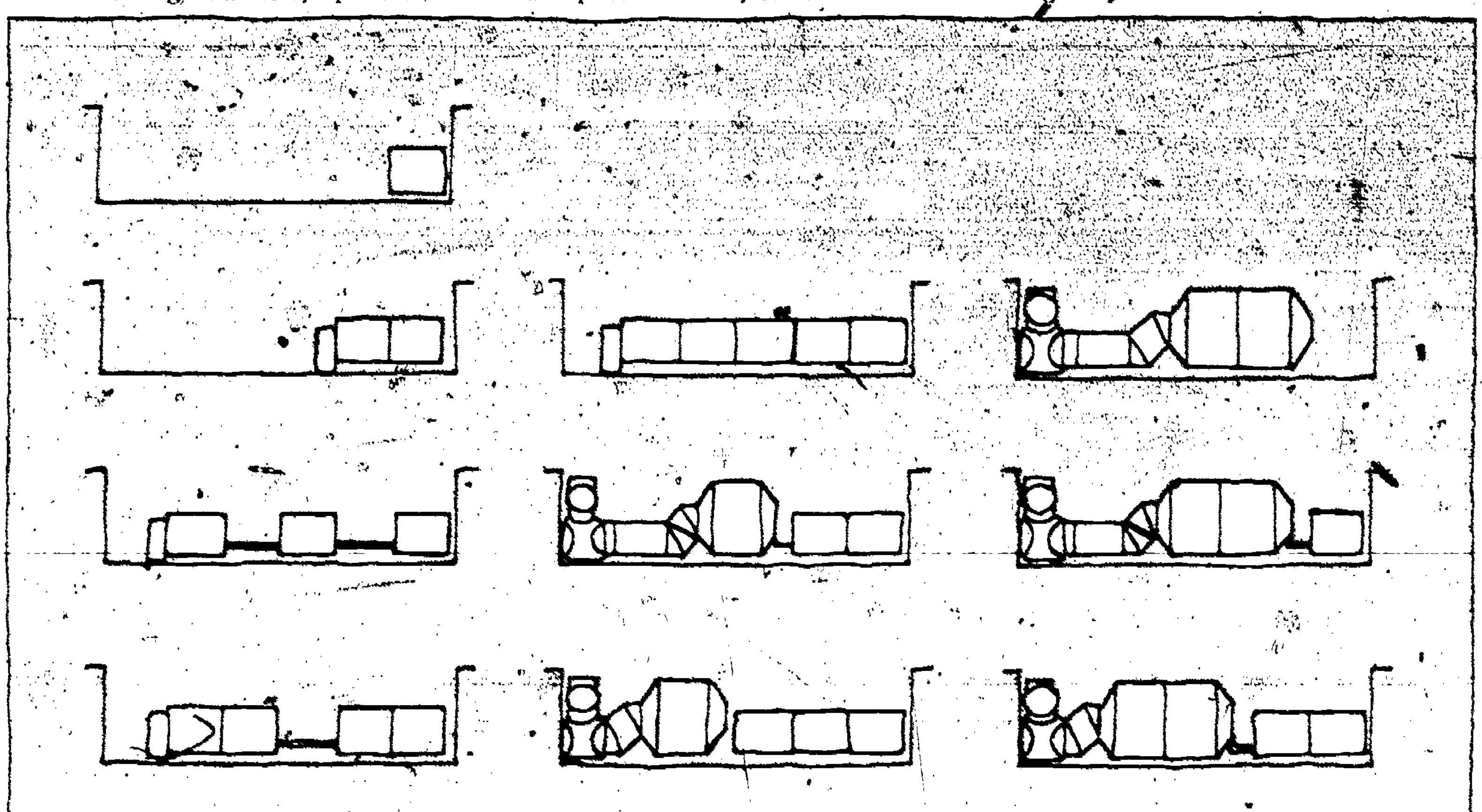
The laboratory module can accommodate three people regularly and a fourth for brief periods, such as a change of shifts. Handholds, handrails, and foot restraints help them work in the most convenient body position and move about safely. The overhead structure contains lights and air ducts. The air is at sea-level pressure, as in the Orbiter, and is kept at 18 to 27° C. At the work benches are electrical outlets, laboratory-wipe dispensers, writing instruments, paper, and storage compartments for equipment like microscopes, centrifuges, incubators, materials-processing furnaces, and photographic apparatus. There are view ports and, in the top, an optical window and an airlock, a meter in diameter, for extending materials and sensors into space and retracting them.

Spacelab missions will concentrate on intensive, relatively short investigations that complement long-term observation programs using free-flying satellites. Examples are studies of the Sun and solar wind, comets and novas, and high-energy radiation from distant regions of the universe; measurements of Earth's electromagnetic environment and upper atmosphere; experiments in space processing of industrial and biomedical products; studies of the effect conditions in space have on human beings, plants, animals, and cells; and—with the Orbiter flying upside down—testing and calibration of sensors that will be used later in Earth-survey satellites.

A pressurized tunnel leads from the laboratory module to the Orbiter cabin, where the experimenters, called payload specialists, will live when off duty. Unlike the basic Shuttle flight crew—commander, pilot, and mission specialist—payload specialists need not be career NASA astronauts. They are scientists or technicians in reasonably good health chosen, with NASA approval, by the designers and sponsors of the instruments and experiments to be flown. NASA gives them several weeks of classroom instruction and training in flight simulators to acquaint them with the Shuttle and its equipment, living and working conditions in space, safety and medical procedures, and their roles in cooperation with other members of the crew in carrying out the planned mission. The first five selected for training were two Americans and three Europeans: German, Swiss, and Dutch.

The Multimission Modular Spacecraft, although not classified by NASA as part of the Space Transportation System, is a versatile new unmanned workhorse to be carried into space in the cargo bay of the Shuttle. Designed to take advan-

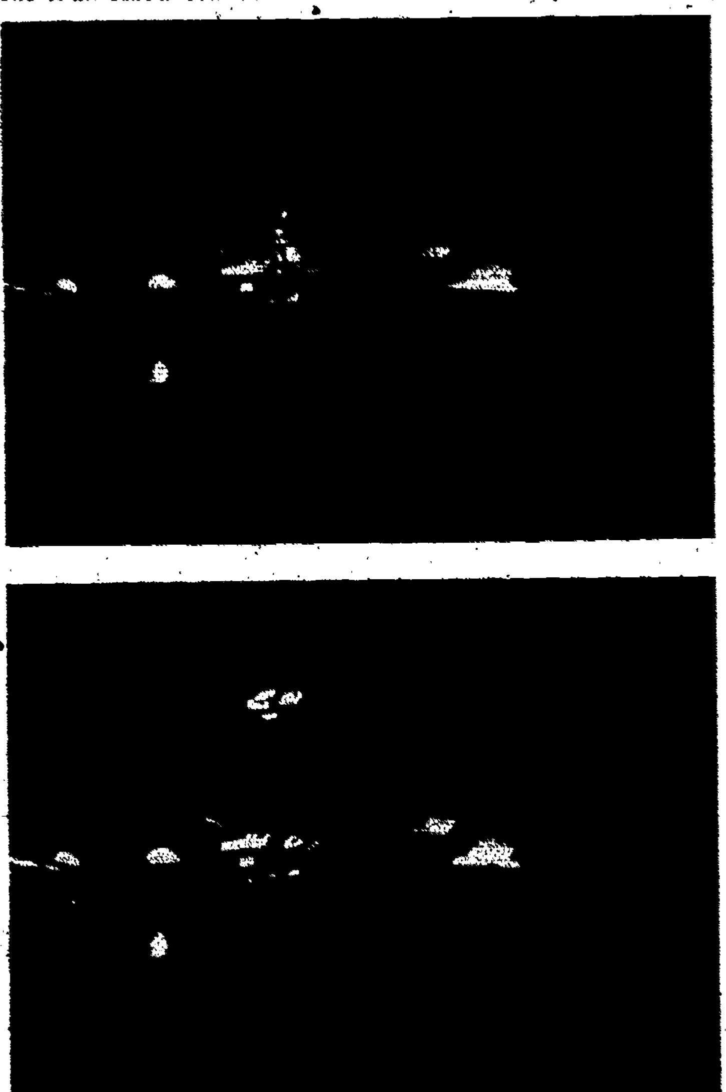
Various configurations *of Spacelab modules and pallets can be fitted into the Shuttle's cargo bay.*



tage of the Shuttle's unique capabilities, it will carry its own propulsion, stabilization, and guidance equipment. It can rendezvous with the Shuttle for servicing in orbit or for return to Earth for overhaul. Fitted with interchangeable instrumentation, the MMS can take on a variety of missions oriented toward Earth, the Sun, or stars. A considerable proportion of all automated satellite programs of the 1980s may use it.

The spacecraft is a load-carrying structure with modules attached for power, communications and data handling, and attitude control. Propulsion motors for changing orbits, solar-power arrays, and various kinds of antennas can be added. It is deployed from the Orbiter and recaptured for servicing or return by the mechanical cargo-handling arm. For servicing and updating in orbit, instruments can be removed and stowed and replacements inserted by mechanisms controlled from the Orbiter flight deck.

Satellites orbited by the Shuttle *begin life with a silver spoon: the orbit is exactly right; electronics get a last-minute test; solar panels and antennas are unfolded just right. This one is an Advanced Landsat.*



Two low-cost, expendable boosters are being produced to propel spacecraft deployed from the Orbiter to altitudes beyond its reach. They're called upper stages, since they do the work performed by the final, top stages of earlier launch vehicles. Both are solid-propellant rockets that come in different sizes and combinations for small to large payloads destined for missions near and far.

For a launch from the Shuttle, the upper stage and attached spacecraft are pointed in the right direction by the Orbiter's attitude-control thrusters, and are then gently ejected by springs. At the proper place in the circular orbit to achieve the desired destination (over the Equator, for example, to reach geosynchronous orbit), with the Orbiter maneuvered to a safe distance, the upper stage is ignited by radio command or a timer to increase velocity and raise the trajectory.

The simpler of these boosters, developed by industry as a commercial venture for sale to NASA and other users, is the Spinning Solid Upper Stage, so named because its stability and direction in flight are maintained simply by spinning, like a gyroscope. The rocket and spacecraft together are spun up mechanically as high as 100 revolutions per minute, depending on size, before being released from the Orbiter. Two sizes are designed to lift payloads of about 1100 kilograms or about 2000 kilograms (2400 lb or 4400 lb) to high transfer orbits, with the spacecraft then providing propulsion for final injection into geosynchronous orbit. Final weights on station will be about 550 and 1000 kilograms (1200 and 2200 lb) respectively. Four of the smaller spinning solid upper stage or two of the larger model, with their spacecraft, can be carried on a single Shuttle flight. One or two may also share a flight with other payloads.

A huskier booster, the Inertial Upper Stage, is being developed by the U.S. Air Force for use with both military and civilian spacecraft. As the name implies, it has a built-in guidance and propulsion system for stability and flight control. Using two or three solid rocket motors, it can place heavy loads—2270 kilograms (5000 lb) or more—in geosynchronous or other high-altitude orbits. It can also inject spacecraft into trajectories for the Moon or planets.

One of the first assignments for the Inertial Upper Stage will be to place in geosynchronous orbit Tracking and Data Relay Satellites to handle communications among all elements of the Space Transportation System. Space operations in the past have depended mainly on ground stations and tracking ships for communications, and there were large blind spots in their coverage. Crews of manned spacecraft were out of touch with Mission Control for part of every orbit, and satellites frequently had to record data on board and transmit them to Earth later when within range of a receiving station.

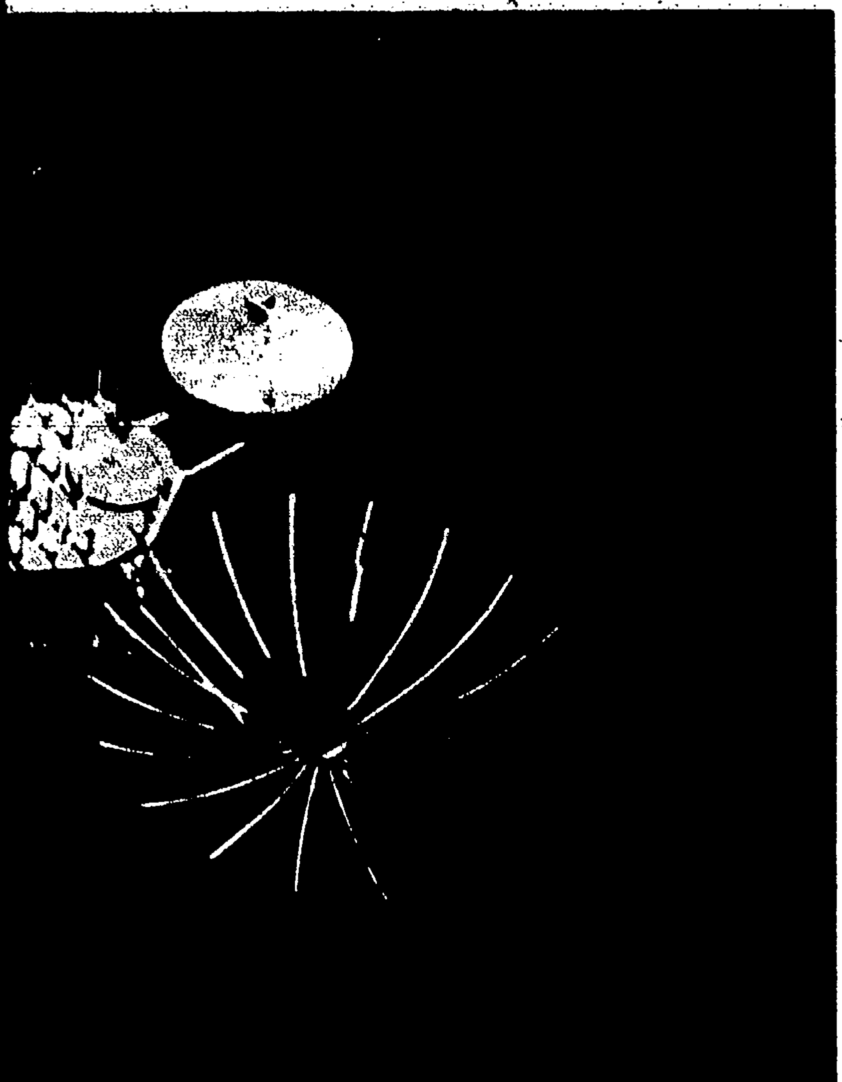
Two Tracking and Data Relay Satellites, one on the Equator off Brazil and one over the Pacific Ocean, and a single ground station at White Sands, New Mexico, make it possible to track and communicate with the Orbiter and most orbiting spacecraft for 85 to 98 percent of the time. Several tracking stations and tracking ships can be eliminated, and there will be less need for on-board tape recorders—often a trouble-prone part of a satellite.

The Tracking and Data Relay Satellites will be supplemented by the remaining stations of the older global space tracking and data network, and the NASA ground communications network, perhaps augmented by domestic communications satellites, will continue to link the tracking stations and control centers.

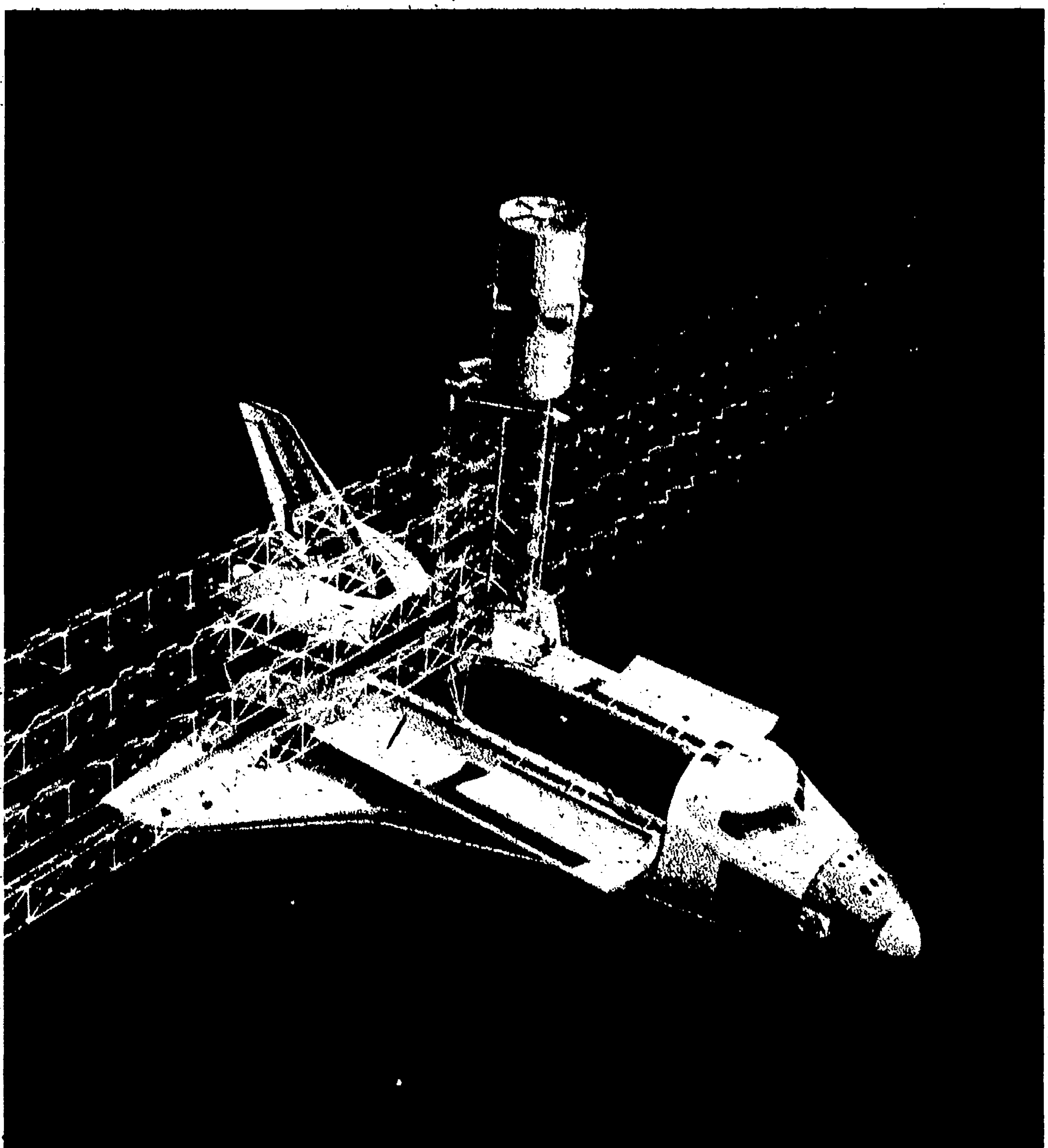
During operations in orbit, communications with the Orbiter are maintained, as in previous manned flights, by the Mission Control Center at the Johnson Space Center near Houston, Texas. Experiment ground controllers will communicate with payloads through the Orbiter as long as these are attached to it. After separation, communications with free-flying satellites in Earth orbit will go to and from a Payload Operations Control Center at the Goddard Space Flight Center, in Maryland, near Washington, D.C. One at the Jet Propulsion Laboratory in California, near Los Angeles, controls spacecraft headed for the Moon or planets through NASA's Deep Space Network. Payloads that remain attached to the Orbiter, including Spacelab, are monitored from a Payload Operations Control Center in the same building with Mission Control, which provides separate voice channels for science and Orbiter operations and television channels shared by the flight crew and payload specialists.

Launches of early Shuttle missions, both civilian and military, are from the Kennedy Space Center, Florida, out over the Atlantic Ocean to avoid flying over populated areas in the critical first minutes. This direction also gives spacebound vehicles an extra velocity assist from Earth's eastward rotation. The payloads from here include all communications satellites and others for geosynchronous orbit. Missions requiring north-south (polar) orbits, including many weather and Earth-survey satellites, are launched southward over the open Pacific from Vandenberg Air Force Base, on a point of the California coast.

Ground operations at the two bases are similar. Using procedures like those of commercial airlines, such as servicing the engines without removing them, ground crews working two shifts are expected to have an Orbiter ready for relaunch in as short a time as two weeks after return to Earth. The planned goal, when the Space Transportation System is fully operational and running smoothly, is 160 working hours: an hour at the landing runway for the crew to debark, for a quick safety inspection, and hooking up air-conditioning equipment and a tow tractor; 90 hours in the Orbiter Processing Facility for post-landing safety procedures; removing any returned payloads, inspecting and servicing of the spacecraft, and installing the new payload; 45 hours in the Vehicle Assembly Building for hoisting the Orbiter to a vertical position and mating it with a new External Tank and refurbished Solid Rocket Boosters; and 24 hours for moving the assembled space vehicle on the mobile launching platform to the launch pad, installing any hazardous or extra-sensitive payloads here rather than earlier, loading propellants, getting the new crew on board, and final checks during a two-hour countdown to liftoff.



This strange spidery satellite *will be one of two such key parts of the new Space Transportation System. They are Tracking and Data Relay satellites, and will link Orbiters and ground, with very few out-of-touch periods. They'll be up in geosynchronous orbit—one over the Atlantic and one over the Pacific.*



9. Plans, Possibilities, and Dreams

THE SHUTTLE IS PLANNED as the key element of American operations in space through the 1980s and into the '90s. What can we expect in growth of its abilities and extension of its uses? NASA is necessarily conservative in making firm plans, limited by budgets and expressed user needs, but is imaginative in the range of possibilities being examined. Some of the ideas discussed here may startle anyone but a reader of science fiction. All, in fact, have been looked at soberly by NASA planners or other hard-headed engineers, scientists, and economists in the Government, industrial companies, and universities.

NASA's advanced studies envisage an evolutionary buildup from longer Shuttle flights to free-flying Spacelabs, automated and then manned orbit-to-orbit freighters, Shuttle-tended and then continuously occupied space bases, demonstrations of solar power generation and other industrial applications of space, and wide personal use of space technology like electronic mail delivery and wrist telephones linked by satellite.

The first step is to extend the duration of the Orbiter's flight beyond the current capability with extra tanks of propellants for its attitude-control and maneuvering engines and of hydrogen and oxygen for its power-generating fuel cells. One solution planned is a utilities module that is carried to orbit in the payload bay and left in space. It will unfurl large winglike arrays of solar cells to collect sunlight for production of electricity, generating twenty-five kilowatts of power for the Orbiter and experiments on board. It will also contain extra payload-cooling radiators and a set of gyroscopes for attitude control of the Orbiter and attached payloads. The gyroscopes save maneuvering fuel by eliminating the need for frequent firing of the control thrusters.

A twenty-five-kilowatt module can supply power for a Spacelab or construction mission of sixty days or more. After sixty days the flight would be limited by such factors as food and drinking water. The module could also supply plug-in power for free-flying payloads that would dock with it, and it could be detached and parked in orbit between Shuttle missions. One version could itself fly free of the Orbiter with instruments for, say, studying the Sun or Earth. Another could be attached to a free-flying Spacelab for long-duration missions like observing the Sun continuously through two or more 28-day solar cycles or studying plants or animal specimens through several generations. A Spacelab with its own utilities

66 and attitude-control module could operate a long time—a step toward a permanent space station—if resupplied periodically by the Shuttle with food, water, and other consumables.

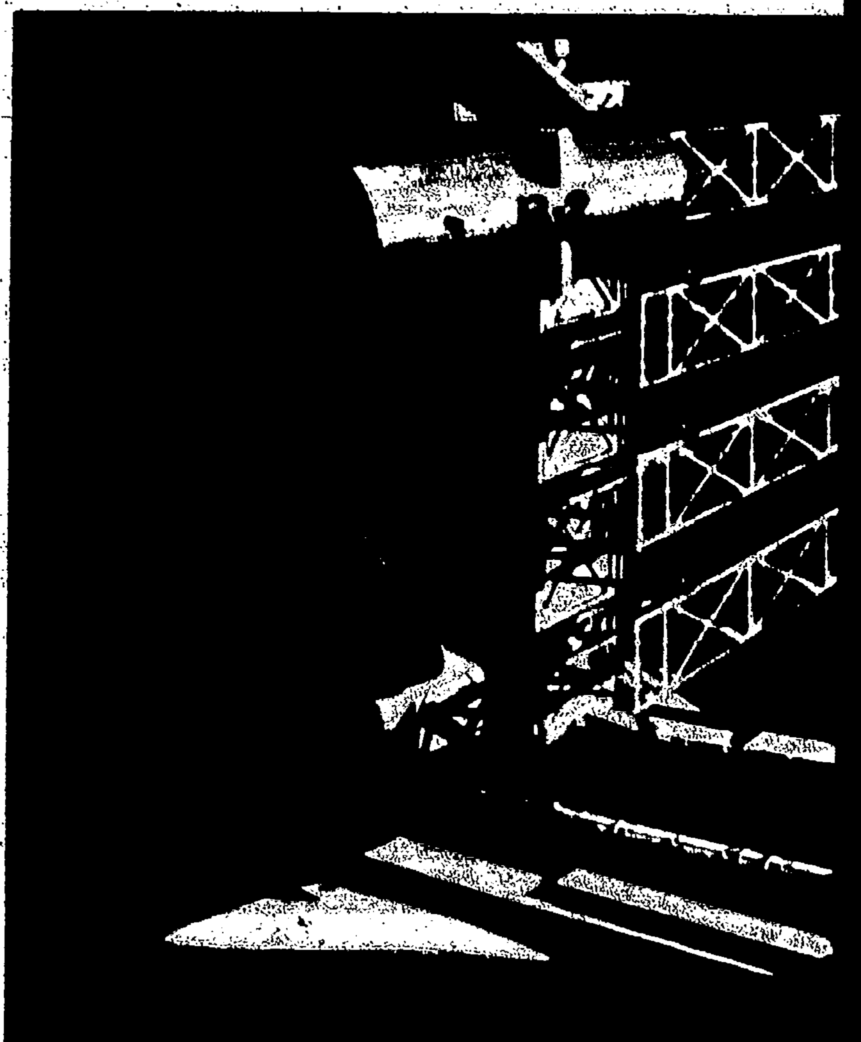
NASA planners foresee needs for considerably more than twenty-five kilowatts of power in space by the middle or later 1980s:

- About fifty kilowatts for a multibeam communications satellite serving hundreds of thousands of very small receivers on Earth—wrist telephones—or a prototype materials-processing laboratory if early Spacelab experiments prove promising;
- A hundred kilowatts for electronic mail—nearly instantaneous facsimile transmission of letters and other documents through satellites—and more for testing space-to-underwater communication;
- Two hundred and fifty kilowatts for a Shuttle-tended space base to construct a large precision antenna or for a low-orbit space-power test project. This could evaluate power transmission efficiency, pointing accuracy, possible heating of the atmosphere, and other factors to be considered before proceeding with a large-scale, high-orbit plant to collect solar energy and beam it to Earth;
- Several hundred kilowatts for solar electric propulsion for moving large objects from low to high orbits or for some of the exciting long-duration scientific missions like rendezvous with a comet or flybys of the outer planets.

This power could be generated by nuclear reactors or by the Sun. For both technical and environmental reasons, NASA so far prefers solar power. The Sun can be used to drive rotating generators; to convert solar heat directly into electricity with thermionic systems; or to convert the Sun's electromagnetic radiation into electric current with photovoltaic cells. These, commonly called solar cells, employ a semiconductor such as silicon that releases electrons when bombarded by photons from solar radiation. Because of its successful experience with solar cells for many years to power scores of satellites, NASA favors continuing with them; it has devised several configurations of an enormous 250-kilowatt photovoltaic power module.

Preparing to build and use a solar power generator of that size or larger, with dimensions in hundreds of meters, requires advances in a lot of other areas: transportation systems, cranes and remote manipulators, jigs and fasteners, so-called cherry

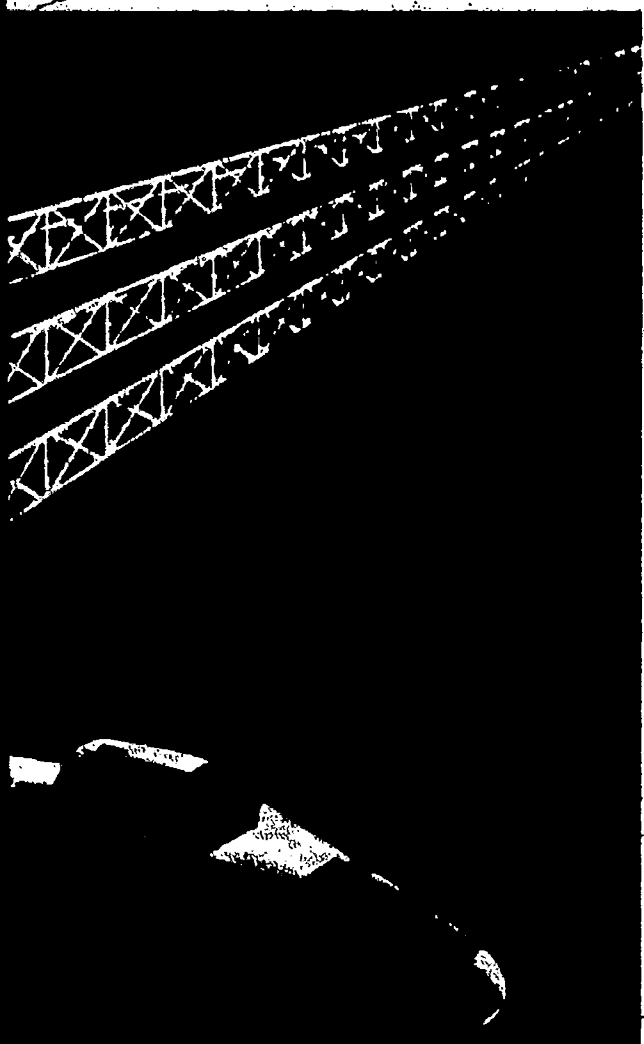
Automated beam builder *could roll-form and brace triangular section beams of the exact length needed for large orbiting structures. They'd be light but strong.*



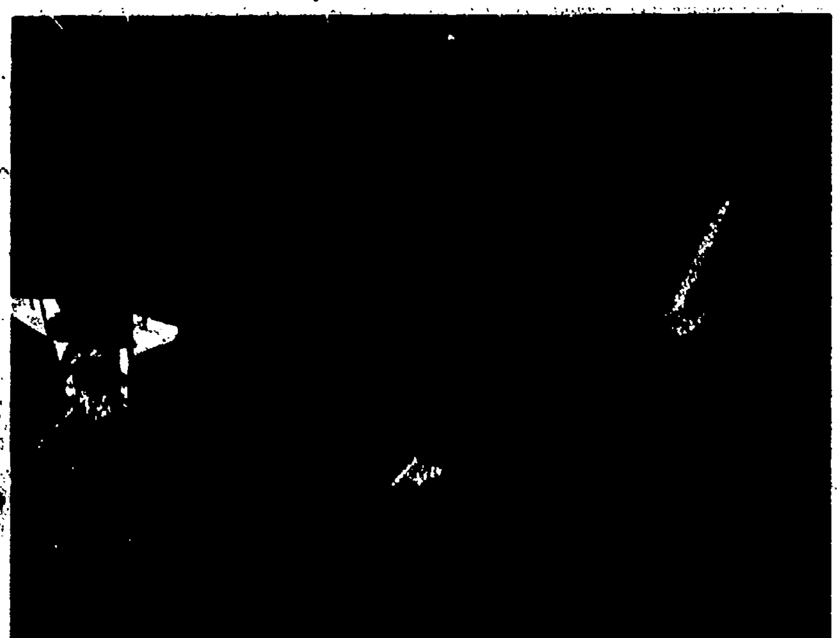
pickers like the ones that hoist powerline repairmen, power tools that can be handled by construction workers in space suits. A free-flying robot tractor designed in the 1970s for moving large objects around in space—NASA calls it a teleoperator—can be used not only to assemble space structures but also to place Shuttle payloads in medium-altitude orbits beyond the Orbiter's range and retrieve them for servicing.

For very large structures, it will make more sense to fabricate some sections in space rather than bringing up pieces in the Shuttle for assembly. An aerospace company has developed an automated beam builder to fit in the Orbiter that can extrude triangular girders from compact coils of ultralight metal plate. It's fed through rollers that shape it to the desired cross section in a manner similar to the on-site fabrication of aluminum rain gutters. The beams would be so light—less than a hundredth the weight of comparable ground construction—that a single Shuttle flight could bring up material for a structure approximately 300 by 100 by 15 meters (1000 by 325 by 50 ft).

A number of large space structures of the future, including multipurpose communications platforms, must operate in geosynchronous orbits in order to provide continuous coverage



Big antennas *will be needed in space for many high-data-rate applications; and an array may be easier than one huge one. Here two Orbiters double-team the job.*

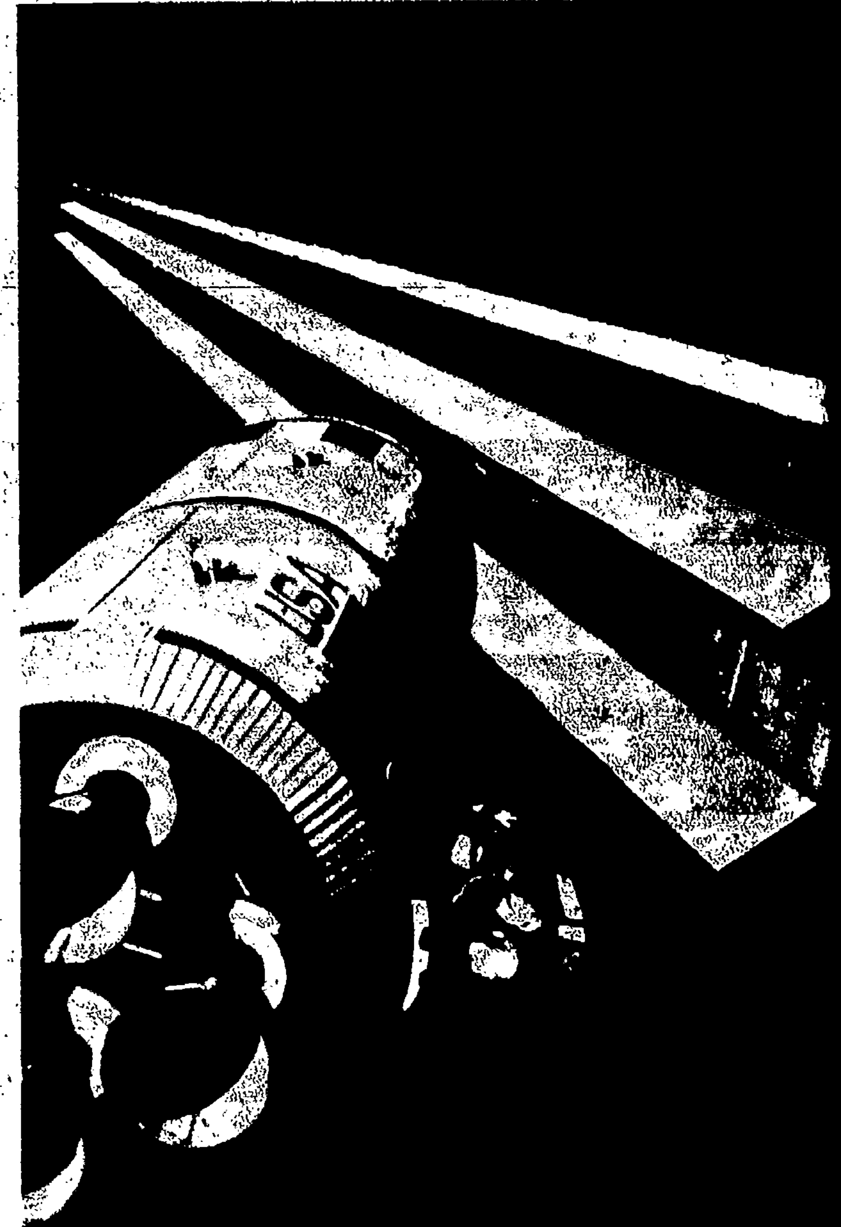


of their service areas. They not only will outgrow the size and weight capacity of the first-generation Shuttle-launched upper stages described in the previous chapter but also will require servicing in orbit to extend their working lives and spread their high original costs over many years. Some may be so large—solar power stations, for instance—that they can best be built at their operating sites. Hence a need for reusable, manned vehicles to carry both cargo and work crews between low and high orbits. A two-stage hydrogen-oxygen orbital transfer vehicle could be assembled in low orbit from separate stages carried by two Shuttle flights. Other Shuttle flights would bring up the propellants, cargo, and crews.

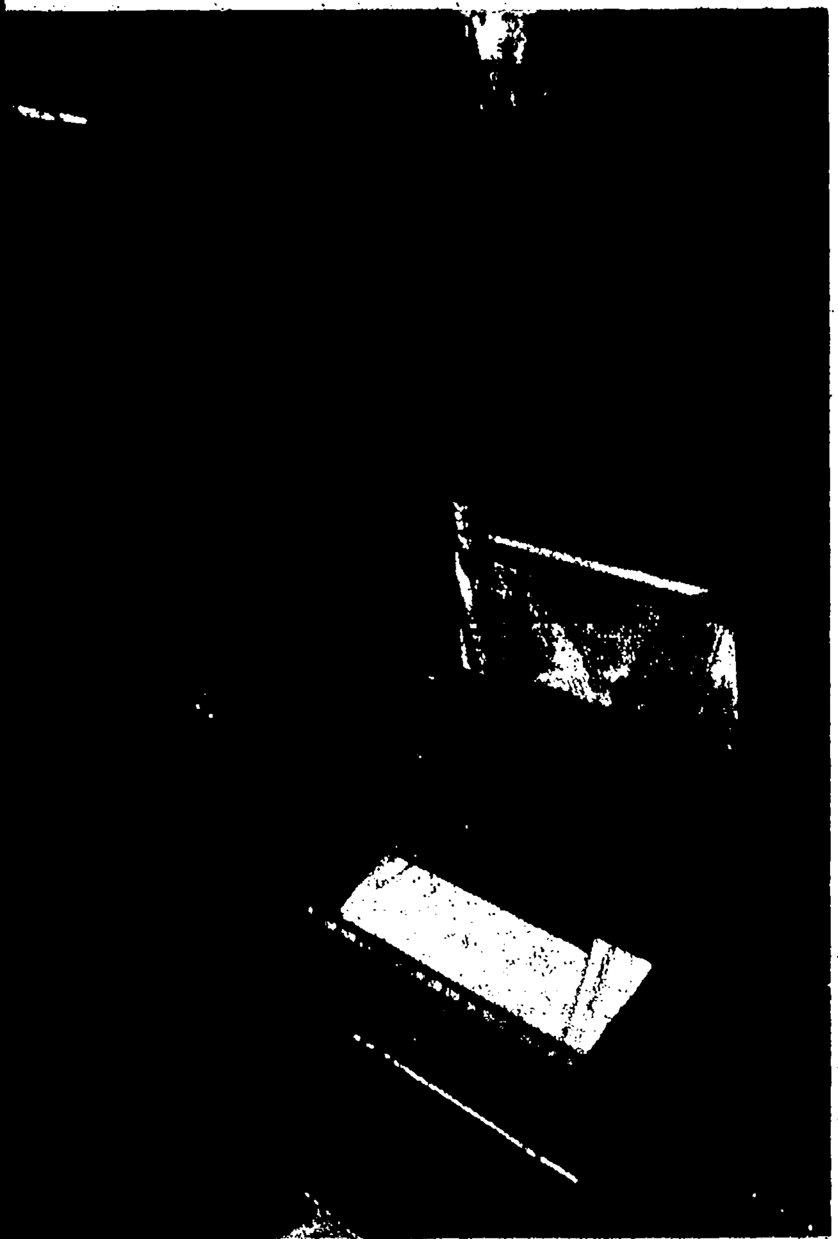
To avoid the complications of loading propellants in orbit, however, NASA planners are studying ways to increase the Shuttle's lift. A growth from the present limit of 29 500 kilograms (65 000 lb) to about 46 000 kilograms (100 000 lb) would allow two upper stages, already fueled, to be carried to low orbit by two Shuttle flights and linked there. One concept for a low-cost, heavy-lift launch vehicle uses the Shuttle's solid-propellant launch boosters and its three hydrogen-oxygen main engines, attached to the big fuel tank, but substitutes a large payload, covered only by a light protective metal shroud, in place of the more costly Orbiter. A single launch could then put more than three times the Shuttle's present maximum load in low Earth orbit. (Still mightier launch vehicles proposed by aerospace companies would team up sixteen or twenty-four engines to lift payloads of 225 000 or 275 000 kilograms (500 000 or 600 000 lb).)

Looking beyond NASA's recent studies of possible future space operations, the agency's director of Advanced Programs, John H. Disher, predicted in an article published as the Shuttle was being prepared for its first orbital test flights: ". . . the Shuttle and Spacelab, I believe, will energize space flight as the DC-3 and DC-4 did aviation—prompting greatly increased use of the unique features of space both for applications we understand today and for applications not yet conceived. Given this spur, I can see advances being made substantially more rapidly than provided for by our current quite conservative plans."

Energy shortages and pollution worries, and the prospect of worse to come, have focused special interest on the idea of converting space sunlight—unlimited, unfiltered by the atmosphere, uninterrupted by nightfall—into electricity for



Five-gigawatt solar power station *is conceived for geosynchronous orbit. Side reflector panels would increase efficiency of central solar-cell arrays. Microwave beam would transfer power to Earth. Energy for transfer of station up from low orbit might come from its own power.*



consumers on Earth. The respected American Institute of Aeronautics and Astronautics (AIAA) selected space power, along with materials processing (discussed in Chapter Three) and life sciences research (such as gravity-free bed rest for treatment of burns and fractures), as three particularly promising future ways to use the unique environment of space to help solve problems that are complicated by gravity and the atmosphere.

While noting that more research will be needed to establish the economic feasibility of space power, the AIAA study said, "There is little question of technical feasibility: all elements of prospective power plants have been established by either experimental tests or long periods of operation in space. . . ." The report listed a number of advantages besides ample free sunshine for locating power plants in orbit: isolation from populated places, no earthquake hazards, easy disposal of excess heat, savings of natural resources by lightweight construction, no corrosion of materials, no pollution, no need for energy storage or backup facilities.

The AIAA committee considered two ways of generating power: immense arrays of solar cells and large collectors of solar heat. The collectors would focus sunlight on a central receiver, heating a gaseous working fluid to drive a turbine, compressor, and generator. Either type of station would beam the energy to Earth as microwaves, which would be collected by large antennas and converted to alternating current for distribution by ground power grids. The generating plant, the study said, might be assembled in low orbit from components carried by future heavy-lift vehicles and then be moved to geosynchronous orbit by electrical thrusters using power generated by the plant itself on the way up.

(The report also mentioned as "extremely interesting" a proposal, originally suggested by proponents of space colonization, for building space power plants from materials mined on the Moon. The material would be refined and structures fabricated in solar-powered factories at neutral-gravity locations between Earth and the Moon. Cheaper transportation than from Earth, thanks to the Moon's low gravity, would offset the cost of the lunar mining base.)

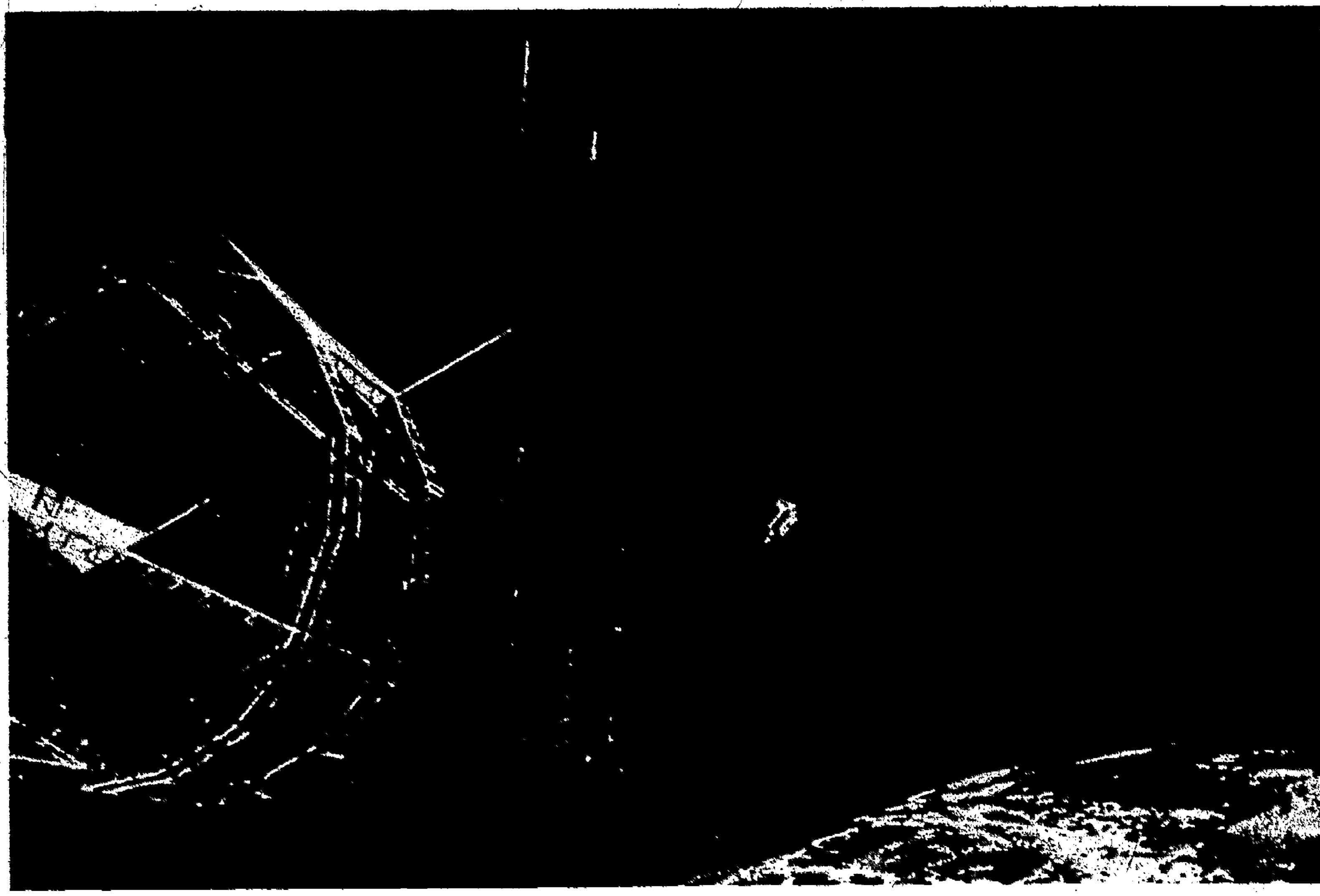
The AIAA study suggested that a solar power system of several generating stations, though it could cost tens of billions of dollars, might be paid for while being built up over several years from the sale of power at prices competitive with ground-based plants. "As a nonpolluting limitless source of energy," the report said, "space-based solar power stations could lead to a system capable of producing much of the United States' power requirements early in the 21st century, and in the very long term could conceivably develop into the world's primary source of electric power."

The Government's position is more cautious. "It is too early to make a commitment to the development of a satellite solar-power station or space manufacturing facility, due to the uncertainty of the technology and economic cost-benefits and environmental concerns," a White House statement said in 1978, then continued: "There are, however, very useful intermediate steps that will allow the development and testing of key technologies and experience in space industrial operations to be gained. The United States will pursue an evolutionary program that is directed toward assessing new options. . . ."

Aerospace company officials, understandably, see grander visions. One said his firm has identified 150 opportunities for profit-making space industrialization, including thirty-five for space manufacturing of new or improved products ranging from pharmaceuticals to high-strength permanent magnets. He envisages extremely large multibeam antennas in space making possible pocket telephones and also electronic telecommuting: "Rather than driving to work each day, the workers would operate from their homes or from a small satellite office where they could interact electronically with people and machinery in a central office building in a nearby city or in one located many hundreds of miles away. This . . . would help solve our energy problems and improve efficiency. It would also allow a life-style whereby people could live, work, and play in small communities, but still perform jobs that are essentially urban."

He cited a study which estimated that industrial uses of space could create 100 000 new direct jobs by the mid-1980s and nearly two million by the year 2010. Through the multiplier effects, the study forecast, this could lead to two or three times as many total jobs and an increase of hundreds of billions of dollars in the gross national product.

Others dream of space tourism: a NASA consultant sees a 100-room hotel by the year 2000 with rates—presumably not for the average family vacation—starting at $5000 for the round trip and a few days in orbit. And of permanent settlements in space. In an exercise in realistic imagining, a group



Another solar power *station might look like this. Unlimited pollution-free power is theoretically attainable. But effects of microwave or laser links are not fully known.*

of engineers, architects, physical and social scientists, and others met for ten weeks in the summer of 1975 at Stanford University and the nearby NASA Ames Research Center and designed a city in space for 10 000 inhabitants. The AIAA assessment of future practical applications of space, in discussing the potential of a life sciences laboratory, said: "It is almost certain that studies on plants will lead to being able to culture plants for space colonies and that these plants will be able to use human waste products to generate food and oxygen."

Dreams?

An economist who has done several cost-benefit studies for NASA on other subjects: "The establishment of space habitation will be an evolutionary outcome of the current United States space program. Mankind will achieve in the next 100 years the most significant accomplishment yet: true Earth-independent, self-support systems which will lead to the establishment of a multitude of new, different, and enterprising civilizations."

And John Dishe, in his article on NASA's own advanced studies: "No one can foretell when we may have permanent settlements of people in space or large-scale use of resources from the Moon or asteroids for space construction. The benefits, costs, and risks of such undertakings remain to be established. Fortunately, however, the nearer-term developments discussed here will proceed on their own merits and constitute necessary developmental steps toward the longer-term possibilities. . . ."

Possibilities . . .?

Dreams . . .?

Or goals?

Time will tell. Decades from now some of these ideas may seem innocently unrealistic, based on ignorance of hard reality. But it's also possible that some will seem astonishingly timid, cautious forays by limited imaginations. (One remembers those 19th Century visions of future air travel in ship staterooms aboard sail-driven balloons.) There may be as much chance that we will undershoot as overshoot in predicting the topography of the future.

What we are concerned with are not solely engineering measurements like mass and specific thrust. Fully as important is another kind of thrust: the questing human spirit.

Acknowledgments

Material for this publication was supplied by John L. Hammersmith, Fred R. Steven, Mary Fitzpatrick, David W. Garrett, Shirley Keehn, Richard McCormack, Nicholas Panagakos, and Margaret Ware, of NASA Headquarters; Robert V. Gordon and Anthony A. Verrengia, Johnson Space Center; Amos Crisp, Marshall Space Flight Center; and Darleen Hunt, Kennedy Space Center. The reproductions on pages 20 and 28 are taken from paintings by Arthur Shilstone.

About the Author

Howard Allaway is a journalist living in Canton, Mass. He has worked for the Associated Press, *PM*, the *New York Times*, *Popular Science Monthly*, *Consumer Reports*, and NASA, where he served for more than a dozen years before his retirement in 1976, receiving an Exceptional Service Medal for his part in the Apollo Program. A previous NASA publication of his was *"Houston, We've Got a Problem,"* an account of the Apollo 13 incident.

About the Fold-out Drawing

The painting on pages 42 and 43, which in full size measures 43¼ in. by 80¼ in., was made by Barron Storey. It presently hangs in the Administrator's office in NASA Headquarters. In modified form it also appears in a 29-in. by 40-in. wall chart prepared by the NASA Public Affairs Division, and is offered for sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. Price is $1.60 and stock number is 033-000-00743-4.

Index