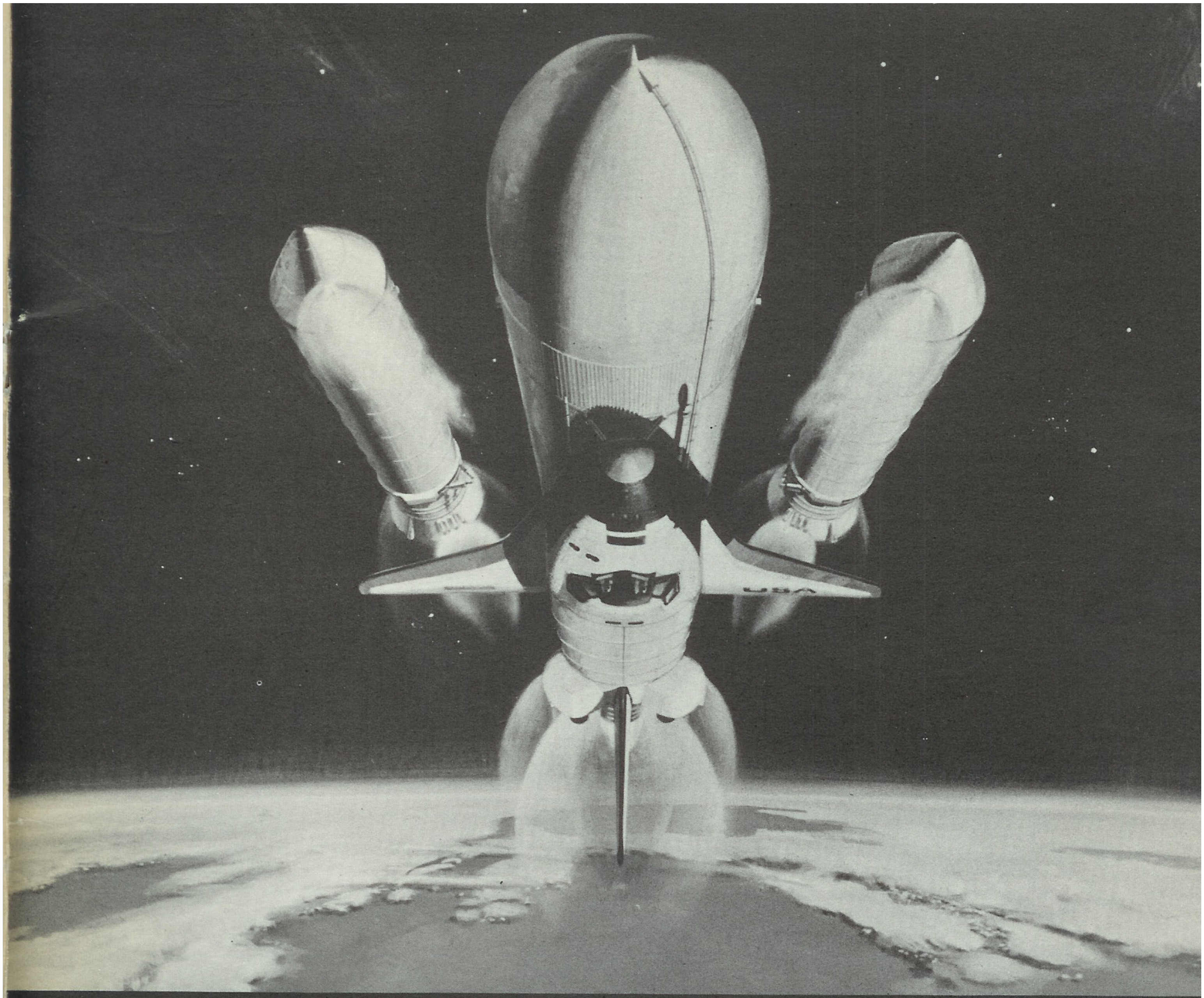

The Space Shuttle Design and Construction

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INTRODUCTION

Major astronautical endeavors represent a culmination of much of the total body of current scientific, engineering, and technological knowledge and art. They also demand skillful application of most of today's sophisticated administrative, economic, and political systems.

This article is concerned with the scope of scientific and engineering disciplines associated with the design and construction of the Space Shuttle Vehicle, the world's first reusable space transportation system, which is now approaching flight readiness. The men who lead the design and development effort on this program are the beneficiaries of an evolutionary growth in interdisciplinary engineering capabilities that enabled the development of high-performance aircraft, missiles, and manned spacecraft.

During the first half of this century, the range of scientific disciplines encompassed by aeronautical engineering was perhaps broadest of all recognized engineering specialties. The engineer was expected to be trained and competent in mathematics, basic physics and chemistry, mechanics, aerodynamics, thermodynamics, fluid mechanics, stability and control, structures, dynamic materials, propulsion and fuel systems, radio communications, electronics, electrical and hydraulic systems, air conditioning and pressurization, human engineering, armament, ground support equipment, flight test instrumentation, and operations analysis. By the 1950's, individual engineers began to specialize in one or two of these disciplines as the body of information in each area increased and the applied methodology in each functional specialty became increasingly esoteric. During these times, a project engineer with a staff of perhaps a half-dozen broadly trained and experienced engineers planned, directed, coordinated, and integrated the efforts of the diversified disciplines.

Program technical complexity continued to increase with the development of intercontinental-range missiles. New engineering specialties were introduced in areas such as inertial and radio guidance and navigation, digital data processing, active and passive sensing systems, chemical auxiliary power systems, ablative heat shield design, atmospheric physics, pyrotechnic devices, automatic checkout equipment, and trajectory analysis.

As the aeronautical industry entered the space age, the number of required scientific and engineering specialties continued to grow. Space-oriented specialties entered into such diverse disciplines as space medicine, mass conservation, environmental control and life support systems, celestial mechanics, lunar and planetary astronomy, solar and nuclear auxiliary power systems, landing and recovery systems, thermal protection and control systems, exobiology, and prevention of back-contamination.

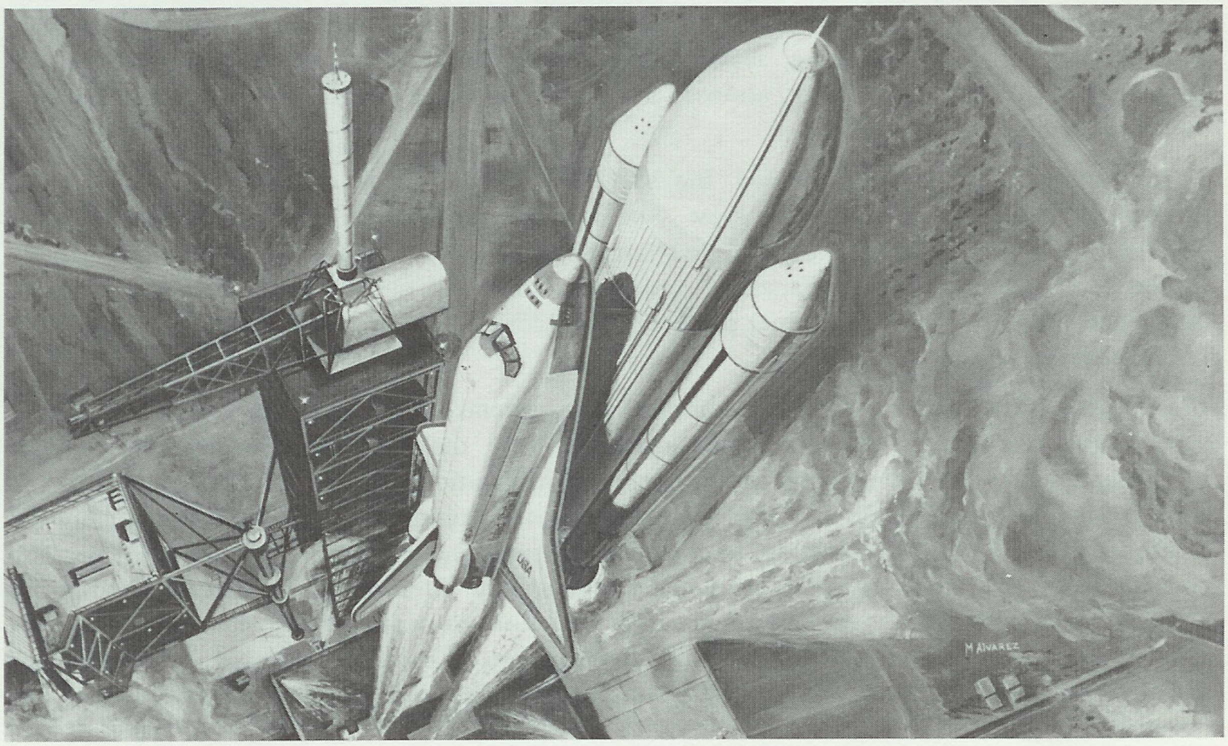
This constant growth in the technical complexity of systems ultimately overwhelmed the project engineer and his small staff, who could no longer use the old project engineering tools to comprehend subsystem interactions and integrated configuration alternatives. The solution to this problem was the development of more formalized system definition and integration technology, sometimes called systems engineering, to augment the traditional project engineering function. This function was staffed with engineers who had demonstrated interdisciplinary interests and strong analytical capabilities. The systems engineering function contained major elements of all the technical disciplines involved in the project. Today, the systems engineering activity synthesizes and evaluates integrated configuration options, studies interface requirements and sensitivities, and allocates system functions and specifications to specialized engineering groups. A major part of preliminary system design is established through this systems engineering process. The function is also used to solve interdisciplinary problems as they arise during a development program.

The development of the Space Shuttle Vehicle system provides an excellent example of the systems engineering process at work and of the broad scope and interaction of separate technical disciplines focused on the solution of a design problem. The development of Shuttle has raised many multidisciplinary issues: some involved several disciplines and others required a host of disciplines.

While the Shuttle is but a waystation on the road to full utilization of space and interplanetary industrialization, it represents the culmination of years of learning how to develop systems that are beyond the capability of any single individual or single group, regardless of talent or dedication. It illustrates the coordination, cooperation, and communication of thousands of individuals and groups with myriad capabilities and interests.

To illustrate the modern systems engineering process in a system as complex and broadly scoped as the Space Shuttle system, one must select from a multitude of examples a few that offer insight into the function. Certainly, no one area can be said to dominate the overall development of the Shuttle; but were such a distinction to exist, it might lie outside of the technical and scientific arena. For instance, during the initial stages of Shuttle's development, cost analyses led to the conclusion that the high peak annual funding to develop a fully reusable system would be significantly reduced by designing a partially reusable system. This new concept resulted in increased cost per flight but did not affect the total cost of the program planned by NASA. Such were the considerations that led to the Shuttle configuration as we know it today.

The examples of the interdisciplinary design process (applied during the Space Shuttle Vehicle development program) selected for discussion here do not present a comprehensive review of the detailed design and development of the Shuttle; instead, they focus on specific design and development tasks. These discussions, however, are brought into perspective in this article by descriptions of how the Space Shuttle Program began and evolved, its progress today on the eve of the first manned orbital flight, and some growth concepts and derivatives to support future space programs.



Lift-Off From Cape Kennedy

THE EVOLUTION OF THE SPACE SHUTTLE— GENESIS TO DECISION

Space Shuttle is the culmination of the successes and failures of many dedicated people. Concepts for vehicles to fly man into space and return to earth have been generated by scientists and engineers in the last four decades. A review of the different directions some of the ideas and developments have followed lends a context to the history-making Space Shuttle. The technology advancements in rocketry, guidance and flight control, and thermal protection (among others) made during the last few decades were the basis for developing a reusable orbital transportation system with minimum technical risks.

Shuttle's background comprises the separate histories of rocketry, aircraft, and space flight. The concepts for orbital transportation systems that have been developed at intervals over the last four decades have brought together the best available technologies of each. Early concepts of the 1930's and 1940's were concerned with two driving questions: Can it be done? Is it technically feasible? In later years, the primary concern was choosing the best concept. At this time, a corollary question (Best concept to do what?) expanded the concepts in all directions. Both the direction manned space flight was to take and mission needs were vague.

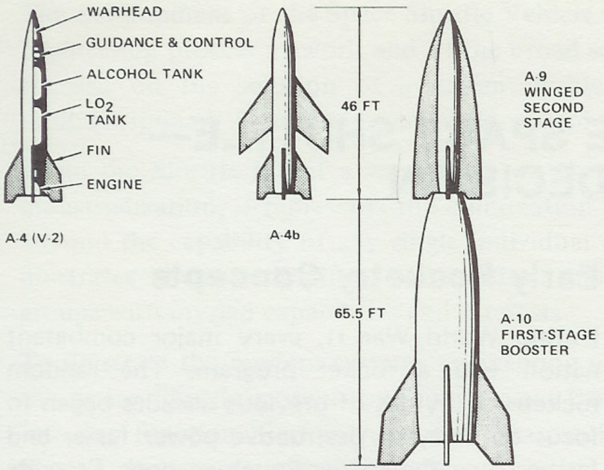
As the usefulness of space was recognized, the need arose for a system that could make use of past technological advancements and permit routine access to space. Along with the technical issues of delivering crews and large payloads to orbit and returning them to earth were the realities of development and operating costs to challenge the conceptual designer. Minimizing development risk and cost and extending existing technology and equipment to increasingly higher levels of performance became major goals. The resulting blend of new and old is reflected in Shuttle, whose lightweight, reusable materials and new high-performance engines are combined with conventional aircraft structure and spacecraft boosters.

Early Rocketry Concepts

During World War II, every major combatant nation had a rocket program. The random rocketry activities of previous decades began to focus on carrying destructive power faster and farther than the conventional weapons. Progress became evident only when the rockets were used in battle, e.g., the largest and most advanced—the German V-2. Thousands of these missiles were produced and fired at distances up to 306 kilometers (190 miles) in southern England and on the Continent. However, much of the technological progress, shrouded by wartime secrecy, surfaced after the war. Many of the more advanced concepts never left the drawing board, and only a few reached the stage at which prototype hardware could be tested.

One of the advanced concepts under development by the Germans was a winged missile, designed to achieve a longer range. The idea was to use the aerodynamic lift, caused by the short wings during descent from the peak altitude, to extend the glide. The team at Peenemunde, under the direction of General Walter Dornberger and Dr. Wernher von Braun, conceived a V-2-size rocket (called the A-9) whose wings would give it a much greater range than that of the V-2. Another aspect of their plan was to carry the A-9 to high altitude with a larger rocket (designated A-10), which would give the A-9/A-10 a range of 4828 kilometers (3000 miles).

Although the missile was never built, this concept of supersonic glide to extend range was applied to the A-4 rocket (the development version of the V-2). Since the V-2 had to be fired near the coast to reach targets in England, an experimental program to extend range was initiated in which short wings were added to the A-4. The range of the resulting A-4b was estimated at about 595 kilometers (370 miles) compared with 306 kilometers (190 miles) for the original A-4 (or V-2). Apparently, only two

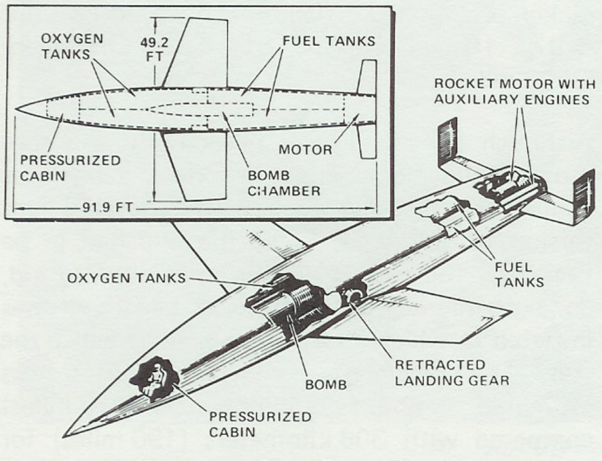


German Long-Range Missiles

A-4b's were constructed and fired (with only partial success) before the war's end.

In Germany during the late 1930's and early 1940's, Dr. E. Sanger and his wife, Dr. I. Bredt, promoted the concept of an advanced hypersonic, long-range, rocket-powered bomber. The concept consisted of boosting the bomber out of the atmosphere at a low angle on a ballistic path. Upon reentering the atmosphere, the bomber would be pulled up, skipping out of the denser air. After repeated skips of decreasing length, it would end the flight in a normal glide.

Dr. Sanger's bomber configuration had an aircraft-life appearance that would not be too unconventional today but was quite unconventional in the 1930's. The body was a slender, flat-bottomed ogive about 28 meters (92 feet) long. It had small swept wings (approximately a 15-meter, or 49-foot, wingspan) and stabilizers on a wedge-shaped airfoil section. Recognizing the performance advantage of high chamber pressure, Dr. Sanger selected an engine design that used liquid oxygen and hydrocarbon fuel as propellants and operated at a chamber pressure of 1.01325×10^7 Pa (100 atmospheres). (The Space Shuttle main engines will be the first operational rocket engines to have a higher chamber pressure.)



Hypersonic Long-Range Bomber

Dr. Sanger's concept for launching the bomber was quite different from the vertical ascent used for the A-4b and A-9/A-10 vehicles. The bomber was to be launched by a rocket sled on a horizontal launch rail. A booster attached to the sled would accelerate the bomber along a 3-kilometer (1.8-mile) monorail track to a velocity of about 488 meters per second (1600 feet per second). Rocket-propelled, the bomber was to climb until the propellants were depleted, then continue on a ballistic trajectory to high altitude. (This approach is used to this day in a number of reusable space transportation system concepts.)

Manned Orbital System Concepts

Popular interest in space travel was stimulated by Wernher von Braun's concept of a three-stage rocket ship and a space station, which appeared in *Collier's* magazine in 1952. The concept presented in the article (and in some detail in the book *Across the Space Frontier*) caught the imagination of many people. It was a fascinating preview of how man could reach space, establish a space station, and peaceably utilize the new frontier of space. The three-stage rocket ship was about 81 meters (265 feet) high and weighed 6.35×10^7 kilograms (14 million pounds) at lift-off. The crew and 32,659 kilograms (72,000 pounds) of payload were housed in the winged reentry vehicle, which also contained the third-stage propulsion. The multi-engine first and second stages contained parachutes for recovery, while the winged third stage glided to a landing strip like a conventional airplane.

Although possibilities for utilization of the space frontier were becoming evident and the capability for exploiting it was within reach, direction and decisions came slowly. Launch of Sputnik 1 in 1957 focused attention on space and greatly stimulated interest in exploring this new frontier. In this period, various preliminary concepts for manned space missions were developed. Missions were conceived for intercontinental or global transportation, orbital transportation to space stations, and manned exploration of the moon and planets. These missions produced a wide range of potential requirements for the conceptual designer and resulted in a large number of concepts, each directed toward a different goal.

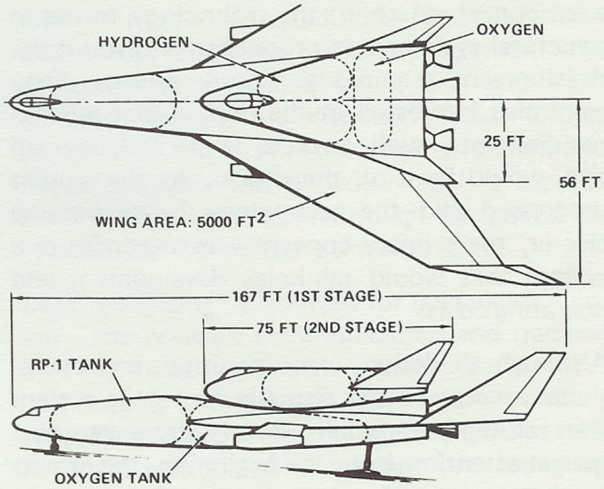
As the usefulness of space was recognized and the need for economical, routine access to space became clearer, the conceptual designer concentrated on effective ways to build and operate reusable orbital delivery systems.

Reusable Transport Concepts of the Early 1960's

Studies of reusable transportation systems were generally devoted to design approaches for reusable launch vehicles that could place very large payloads in orbit or for reusable orbital carriers for passengers and limited cargo. Investigators conducted comprehensive studies of design approaches for a generation of launch vehicles capable of delivering a large payload, up to 453,600 kilograms (1 million pounds), into orbit at minimum cost. A large recoverable single-stage-to-orbit booster would satisfy these objectives, if it could be developed. To enhance the feasibility of different concepts, designs of such vehicles incorporated conceptual technology advances in high-performance rocket engines and high-strength, lightweight structural materials.

Concepts of reusable transportation systems that could carry passengers and a limited cargo to earth orbit (instead of very large cargoes) were also developed. On returning, these vehicles would land like conventional aircraft. Logistic support of a space station in the mid-1970's was the primary mission for these systems. Many of the concepts were two-stage-to-orbit systems with payload provisions integrated into the second stage.

One concept of a ten-passenger reusable orbital transport, developed under NASA contract, had a crew of two to control each stage. The passenger-carrying vehicle (second stage) was mounted piggyback on the winged launch vehicle. A track-mounted rocket sled (a la Sanger) was used to accelerate the combined vehicles for horizontal take-off. The first stage was a rocket airplane that used aerodynamic surfaces for lift and control during boost. After the first stage separated from the second stage, turbofan engines returned the first stage to the landing site; the second stage completed the boost, coasted to orbit, and, after deorbiting, reentered the atmosphere and maneuvered to a conventional airplane-type landing.



Reusable Transport

Reentry vehicle (second stage) designs included many concepts of lifting bodies with hypersonic lift-to-drag ratio (L/D) of 1.2 and winged bodies with L/D of 2.6 that used liquid oxygen/liquid hydrogen propellants, engines of varying chamber and nozzle designs, and thrust vector control methods. Material problems continued to be major obstacles to the development of these advanced systems. There were serious deficiencies in applying superalloys and refractory metals to high-temperature structures, heat shields, and engines. Material and design problems also emerged with cryogenic insulation and the structure. To achieve a workable system, high-performance, long-life, low-refurbishment-cost rocket engines were needed for both the first and second stages; and long-life, high-thrust-to-weight-ratio air-breathing engines were needed for the first stage. The technology of the early 1960's was not advanced enough to develop a viable reusable orbital transportation system. Moreover, fully reusable systems necessitated an operational plan for a large number of launches per year to be economically feasible.

Space Shuttle Concept Definition

The detailed definition of Space Shuttle began with NASA's July 1970 award of contracts to McDonnell Douglas and North American Rockwell (now Rockwell International) for the study of a fully reusable two-stage configuration. The studies, conducted in 1970 and early 1971, involved primarily the technical issues of design, fabrication, and performance. Designers were concerned about the technology to use in structural systems and propulsion and about the development required to ensure success. They were also interested in the impact that mission requirements, such as cross range and payload size, would have on the design. As the studies progressed and the technology issues became clearer, the primary concern was to configure a system that would minimize development and operating costs.

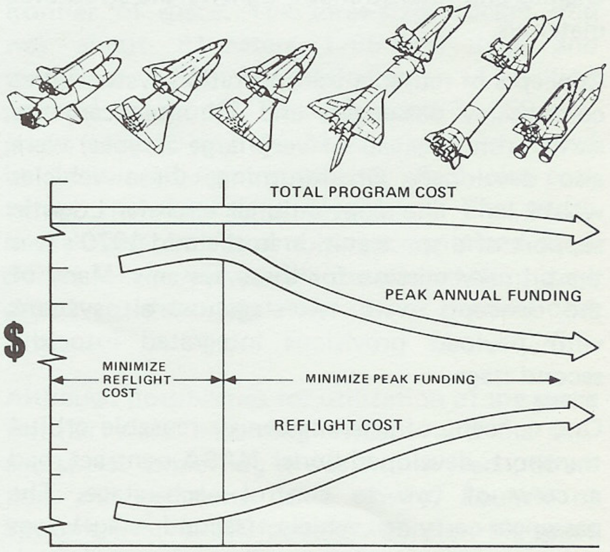
Although all design, manufacturing, and operational aspects of the reusable two-stage system were studied in detail, several areas received special attention from the beginning: the effects on the program of various degrees of technology advancement in structures, propulsion, and subsystems were of major interest, and the development of suitable reusable thermal protection for both the booster and orbiter was of particular importance to the reusability and life of the system. Each of the several candidate protection and structural subsystems involved materials and methods that transcended the current technology of that time.

System cross-range requirements and capabilities were also important issues. While the booster was expected to remain essentially unaffected by either long or short orbiter cross range, distinctly different orbiter configurations were involved, with attendant variations in design, development, and cost. Preliminary designs of a straight-wing orbiter had a 370-kilometer (200-nautical-mile) cross range, and an alternative delta-wing configuration had a cross range of 2778 kilometers (1500 nautical miles). Both designs were powered by advanced high-chamber-pressure rocket engines that used liquid oxygen/liquid hydrogen propellants, contained in internal tanks. Hydrogen-fuel turbofan engines were to be used for landing and ferry operations.

NASA officials met in mid-January 1971 to establish a single set of design characteristics for Shuttle. They selected a high-cross-range system with a payload capacity of 29,484 kilograms (65,000 pounds) to be launched due east into a 185-kilometer (100-nautical-mile) orbit. Efforts were then concentrated on a delta-wing vehicle with a 2037-kilometer (1100-nautical-mile) cross range.

Early in 1972, results of the detailed studies of alternative configurations were reviewed by NASA. These data and the results of economic analyses conducted by Mathematica, Inc., underscored the desirability of proceeding with the established design. They also showed the series-burn or parallel-burn pressure-fed booster or the solid-propellant parallel-burn booster to be the most effective in meeting funding constraints. Cost per flight was predicted to be lower with the pressure-fed booster, but development cost was estimated to be lower for the solid-propellant parallel-burn system.

As previously discussed, funding trends showed that the high peak annual funding for the system was significantly reduced as the configuration shifted from fully reusable concepts toward partially reusable designs that cost less to develop. Although the partially reusable systems resulted in increased cost per flight, NASA examined the technical and programmatic issues of the alternatives and, in March 1972, selected the parallel-burn, solid-propellant recoverable booster concept for Shuttle. Two days after



Cost/Funding Trends

making the decision, NASA issued a Request for Proposal (RFP) for design, development, and fabrication of the Space Shuttle. In August 1972, the Space Division of Rockwell International was authorized by NASA to proceed with design and development of the Space Shuttle; the history-making program was underway.

The Technical Challenge of the Space Shuttle

In concept, the Space Shuttle was to be as close to a "state-of-the-art" system as possible. Developing the system on schedule and achieving the desired reliability left no margin for technology breakthroughs to achieve goals. The technology of manned space flight was established: hours and days of actual flight experience had been accrued, and the development and management teams were essentially intact from the Apollo and Skylab programs. The Shuttle, then, was conceived to be an extension of proven technology into the everyday world of routine operations: i.e., the trucking system for foreseeable and, indeed, unforeseeable space missions. The time had come to use that knowledge—to reap the fruits of years of investment—by establishing an operational Space Transportation System.

Inevitably, challenges arose that could be met only by major extensions in technology. Significant advances were achieved in several areas: some derived from the new requirements of the Shuttle system and others developed because of the very size of the system and subsystems. The common impetus for all these innovations and, for that matter, nearly all of the Shuttle design considerations, was the need for multiple reuse—not just once or twice, but for a total of 100 orbiter flights. Amortization of the system cost was to be spread over as large a number of flights as possible to minimize the cost to the potential users and reduce the cost of space flight to a level at which commercial utilization of space could become a reality.

Reusability demanded that the thermal protection system utilize new materials that would not be consumed by the heat and stresses of reentry during each flight. The successful development and testing of fused silica ceramic material, blocks of which cover most of the orbiter's heated surface area, were major efforts, for the material had to satisfy its primary function of maintaining the airframe outer-skin temperature at an acceptable level while meeting stringent requirements for ease of maintenance and flexibility of ground and flight operations. It is a passive system, requiring no active control or monitoring.

Shuttle system performance required a highly efficient ascent propulsion system. Therefore, a new rocket engine was developed—one that would deliver substantially higher performance than its predecessors, could be throttled over a wide thrust range, and could be used many times without major malfunction or overhaul. Three of these engines are installed in each orbiter along with the associated control subsystems. Liquid oxygen and hydrogen fuel is supplied from the external tank through automatic disconnects on the orbiter's lower surface.

Data processing capabilities for guidance, navigation, and control; communication and tracking; displays and controls; system performance monitoring; payload management and handling; subsystem sequencing; and selected ground functions are centralized in the data processing and software subsystem. The equipment for this subsystem is organized around a computer complex consisting of five interconnected general-purpose computers than can be operated in redundant groups for critical services. The development of this system represents a great advance in avionic software, not only because of its complexity but also because of its accuracy and reliability.

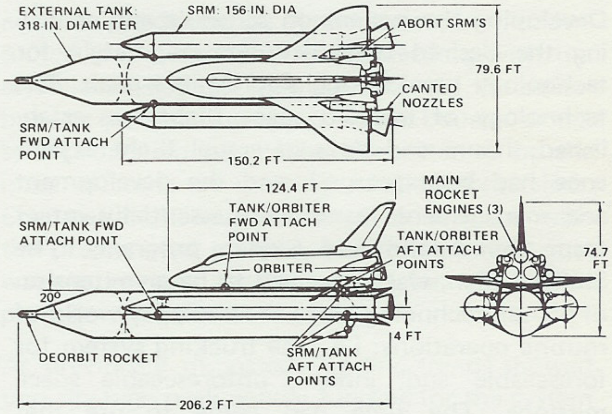
The payload bay doors—perhaps a lesser technology advancement than those just cited—constitute a significant advance in the use of composite materials. The four door panels that make up most of the fuselage upper surface are the largest composite unit structures built to date. The primary structure is a honeycomb and frame construction, employing graphite/epoxy tape and fabric with a Nomex honeycomb core.

Of course, these were not the only challenges: they are merely some of the most prominant ones. Others too numerous to list here were met during the development of the Space Shuttle. Through the interactive design process, employed to its fullest, the initial Shuttle configuration evolved to its present arrangement and capability.

Space Shuttle Design and Development

The Shuttle system was to be used for at least ten years and capable of 60 flights per year. To ensure that it could carry out a wide variety of missions, the system was designed to deliver 29,484 kilograms (65,000 pounds) into a 185-kilometer (100-nautical-mile) orbit on a due-east launch, carry 18,144 kilograms (40,000 pounds) into a polar orbit, and land with 18,144 kilograms (40,000 pounds) of payload. The orbiter had to accommodate large payloads, up to 5 meters (15 feet) in diameter and 18 meters (60 feet) long, and be capable of deploying and retrieving them. It also had to be capable of returning to the launch site in one orbit, which required a 2009-kilometer (1085-nautical-mile) cross-range capability.

The proposed Shuttle vehicle underwent a rigorous analysis, and many improvements were made in the configuration and design during the first several months of the program. Thrust from the three main rocket engines would be augmented during the initial phases of launch by two 396-centimeter-diameter (156-inch) fixed-nozzle solid rocket motors (SRM's), which were equipped with systems for thrust termination and parachute recovery. The proposed fixed nozzles were replaced with gimbaled nozzles to improve stability and control during ascent under a wide range of conditions. As analysis of nominal and abort profiles progressed, it was found that the SRM thrust-termination system, the orbiter solid-propellant abort motors, and the deorbit motor on the external tank could be deleted. Additional Shuttle vehicle changes resulted from improvement in orbiter design.



Proposed Shuttle System

THE SPACE SHUTTLE TODAY — WHAT IT IS AND WHAT IT CAN DO

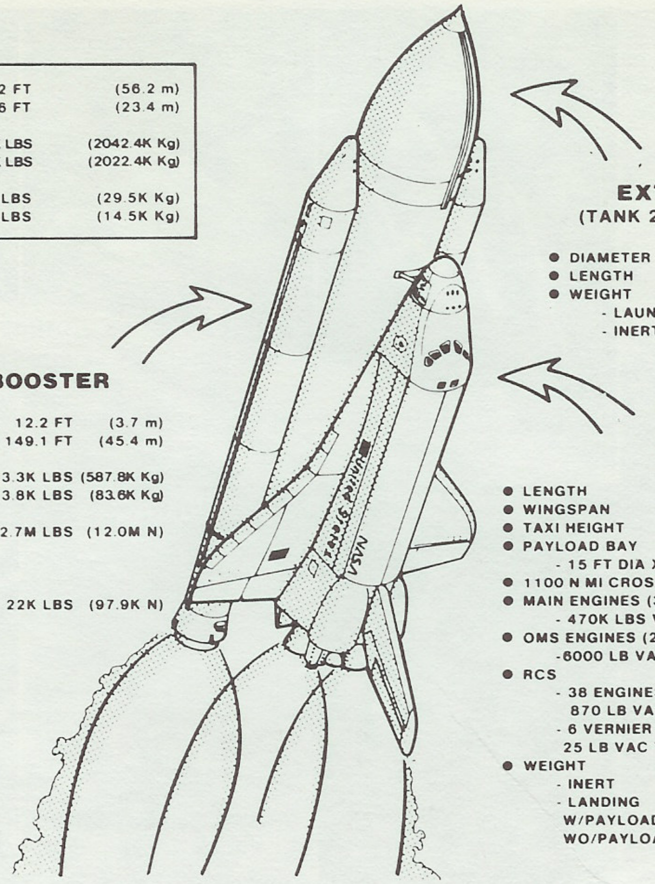
The total Space Transportation System (STS) will consist of the Space Shuttle, a variety of standard payload carriers, ground integration and launch facilities, and ground-based payload operations control centers. The STS will perform all services formerly accomplished by a variety of unmanned launch vehicles at considerably less cost. It will also routinely perform tasks not possible or practical in the past, such as manned flight operations, in-space servicing and maintenance, payload retrieval, and intact mission aborts.

The flight plan and operation of the Space Shuttle will differ markedly from that of the now-familiar launch procedure and splash-down of the Apollo missions, which utilized the expendable Saturn-V launch vehicle. The Space Shuttle Vehicle will provide a relatively comfortable environment for its crew and accommodations for additional passengers. Thus, experienced scientists and technicians can accompany their payloads into space. The environmental improvement is a result of the lower levels of launch and entry accelerations and a crew cabin that provides an air environment at shirt-sleeve temperature, pressure, and humidity.

How the Shuttle Operates

The Space Shuttle flight system consists of an orbiter, an external tank, and a booster made up of two solid rocket motors. The orbiter and solid rocket booster are reusable elements; an external tank is expended on each launch.

The orbiter normally carries into orbit its payloads and a crew of three, with provisions for up to four additional scientists and technicians. It can remain in orbit nominally for 7 days (up to 30 days with special payloads), return to



● OVERALL LENGTH	184.2 FT	(56.2 m)
● HEIGHT	76.6 FT	(23.4 m)
● SYSTEM WEIGHT		
- DUE EAST	4493.3K LBS	(2042.4K Kg)
- 104°	4451.6K LBS	(2022.4K Kg)
● PAYLOAD WEIGHT		
- DUE EAST	65K LBS	(29.5K Kg)
- 104°	32K LBS	(14.5K Kg)

SOLID ROCKET BOOSTER

● DIAMETER	12.2 FT	(3.7 m)
● LENGTH	149.1 FT	(45.4 m)
● WEIGHT (EACH)		
- LAUNCH	1293.3K LBS	(587.8K Kg)
- INERT	183.8K LBS	(83.6K Kg)
● THRUST (EACH)		
- LAUNCH	2.7M LBS	(12.0M N)
● SEPARATION MOTORS (EACH SRB)		
- 4 AFT 4 FWD		
- THRUST (EACH)	22K LBS	(97.9K N)

EXTERNAL TANK
(TANK 26 AND SUBSEQUENT)

● DIAMETER	27.8 FT	(8.5 m)
● LENGTH	154.4 FT	(47.1 m)
● WEIGHT		
- LAUNCH	1649.3K LBS	(749.7K Kg)
- INERT	72.0K LBS	(32.73K Kg)

ORBITER

● LENGTH	122.3 FT	(37.1 m)
● WINGSPAN	78.0 FT	(23.8 m)
● TAXI HEIGHT	~57 FT	(17.4 m)
● PAYLOAD BAY		
- 15 FT DIA X 60 FT LG		(4.8 m DIA X 18.3 m LG)
● 1100 N MI CROSS RANGE		(2038 Km)
● MAIN ENGINES (3)		
- 470K LBS VAC THRUST EA		(2090.7K N EA)
● OMS ENGINES (2)		
-6000 LB VAC THRUST EA		(26.7K N EA)
● RCS		
- 38 ENGINES 870 LB VAC THRUST EA		(3869.8 N EA)
- 6 VERNIER 25 LB VAC THRUST EA		(111.2 N EA)
● WEIGHT		
- INERT	152.7K LBS	(69.4K Kg)
- LANDING		
W/PAYLOAD	~194.4K LBS	(88.4K Kg)
WO/PAYLOAD	~164.0K LBS	(74.55K Kg)

Space Shuttle System Configuration

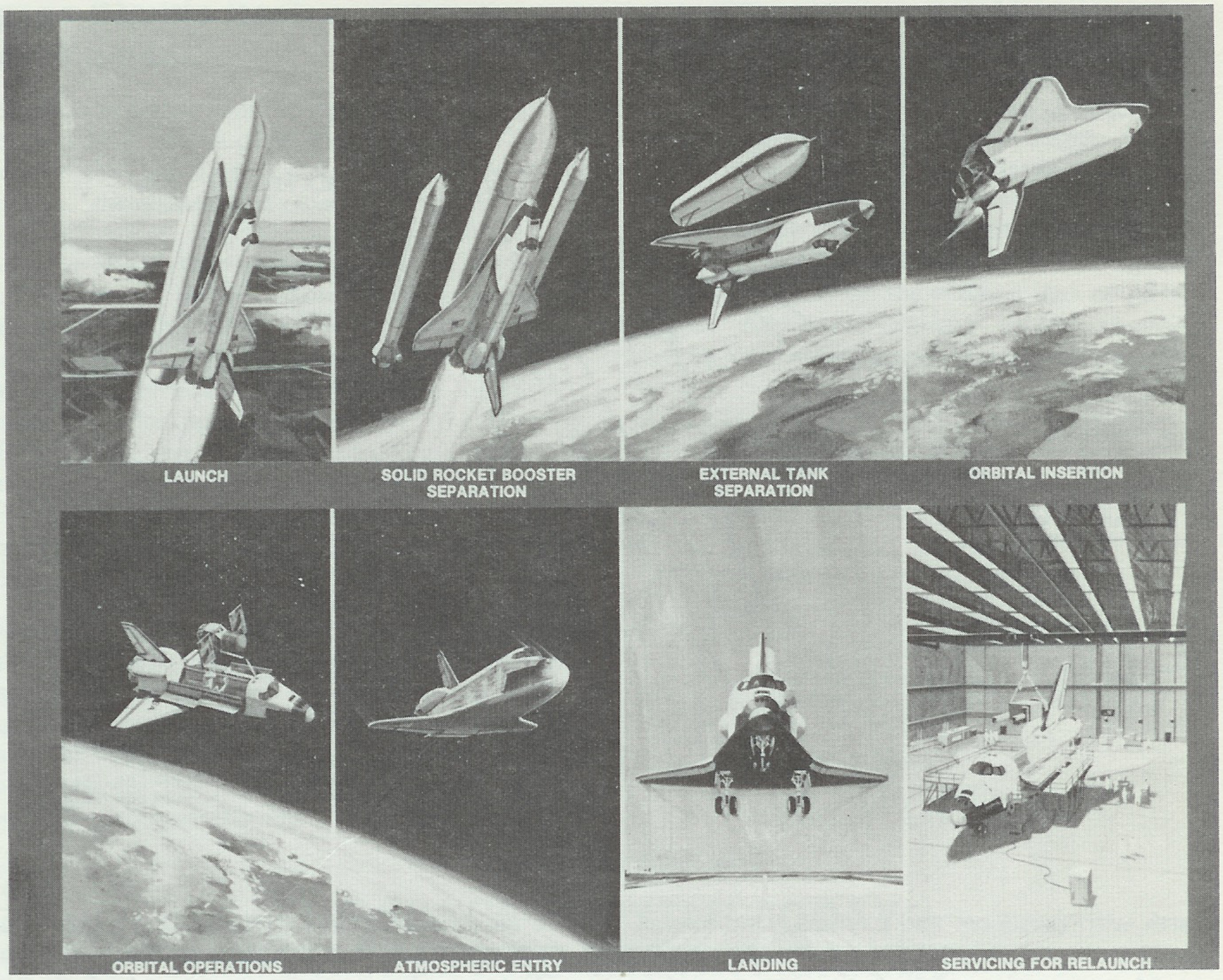
earth with personnel and payload, land like an airplane, be refurbished for a subsequent flight in 14 days, and provide for a rescue mission launch within 24 hours after notification (from standby status).

The three-person crew and a payload specialist occupy a two-level cabin at the forward end of the vehicle. From the upper level flight deck, the crew controls the launch, orbital maneuvering, atmospheric entry, and landing phases of the mission. Seating for up to three additional payload specialists and habitability provisions are located on the mid deck. The mid deck can be reconfigured to provide an additional three seats in the event of a rescue mission. The load factors experienced by the crew during any mission is 3 g's or less.

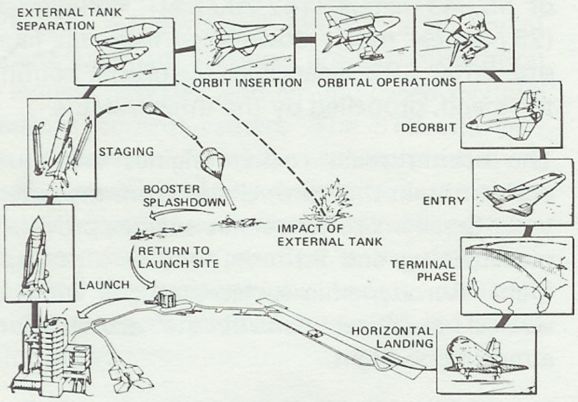
The system is launched with the three orbiter Space Shuttle main engines (SSME's) and the two solid rocket boosters (SRB's) burning in parallel. A maximum dynamic pressure (q) of 3174 kilograms per square meter (650 pounds per square foot) is experienced 62.5 seconds after launch at an altitude of 11,308 meters (37,100 feet). At 108 seconds, the X-axis load factor reaches a maximum value of 2.6 g's. SRB separation occurs at 122.3 seconds at an altitude of 43,343 meters (142,200 feet), 46 kilometers (25 nautical miles) downrange from the launch site. After SRB separation, the orbiter continues to ascend, propelled by the three SSME's.

The orbiter main rocket engines used during ascent obtain their propellants from the external tank. Smaller orbiter rocket engines provide for maneuvering and attitude control during space flight. Aerodynamic surfaces on the wings and vertical stabilizer control the orbiter during atmospheric flight.

The SRB's burn in parallel with the orbiter main propulsion system and are separated from the orbiter/external tank at approximately 45,720 meters (150,000 feet). The SRB's descend on parachutes and land in the ocean about 278 kilometers (150 nautical miles) from the launch site. They are recovered by ships, returned to land, refurbished, and reused.



How the Shuttle Operates



Typical Mission Profile

After SRB separation, the orbiter main propulsion system continues to burn until the orbiter achieves the required ascent trajectory. The external tank then separates and falls into the little-used areas of the Indian Ocean or the South Pacific Ocean, depending on the launch site and mission. The orbital maneuvering system completes insertion of the orbiter into the final desired orbit.

Main engine cutoff (MECO) takes place 479 seconds after lift-off, when the orbiter has reached an altitude of 115,745 meters (379,740 feet). The external tank (ET) separation occurs at MECO. The orbital maneuvering system (OMS) engines provide the additional velocity needed to insert the orbiter into an elliptical orbit with a minimum apogee of 278 kilometers (150 nautical miles). The OMS engine cutoff occurs 600 seconds after launch at an altitude of 127,604 meters (418,650 feet) when the orbiter is 2645 kilometers (1428.2 nautical miles) from the launch site. At first apogee, the orbiter initiates the first of two maneuvers to circularize the orbit at 278 kilometers (150 nautical miles).

Following the completion of orbital operations, the orbiter is oriented to a tail-first attitude. After the OMS provides the deceleration thrust necessary for deorbiting, the orbiter is reoriented nose-forward to the proper attitude for entry. The orientation of the orbiter is established and maintained by the reaction control system (RCS) until the altitude is reached where the atmospheric density is sufficient for the pitch and roll aerodynamic control surfaces to be effective—about 76,200 meters (250,000 feet) altitude and 7925 meters (26,000 feet) per second velocity. The yaw RCS remains active until the vehicle reaches an angle of attack of about 10 degrees—about 24,384 meters (80,000 feet) altitude.

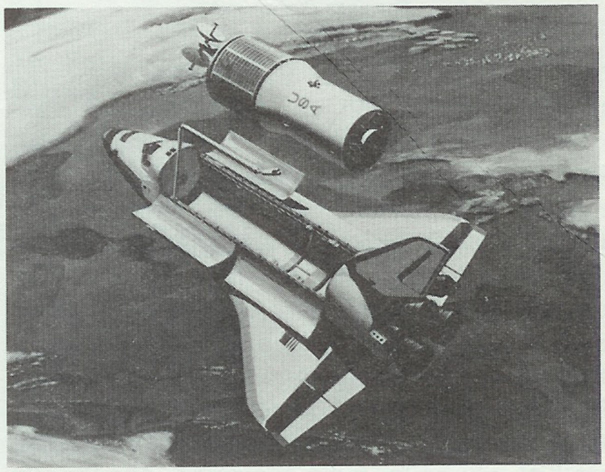
The orbiter entry trajectory provides lateral flight range to the landing site and energy management for an unpowered landing. The trajectory, lateral range, and heating are controlled through the attitude of the vehicle by angle of attack and bank angle. The angle of attack is established at 38 degrees for the theoretical entry interface altitude of 2591 meters (8500 feet). The entry flight path angle is -1.19 degrees. The 39-degree attitude is held until the speed is reduced to 6462 meters (21,200 feet) per second (about 67,056 meters, or 220,000 feet, altitude); it is then reduced gradually to 28 degrees at 5243 meters (17,200 feet) per second (about 57,912 meters, or 190,000 feet, altitude); it is held at 28 degrees until speed is reduced to 2591 meters (8500 feet) per second (about 45,720 meters, or 150,000 feet, altitude) and then reduced gradually to 6 degrees when the speed is about 457 meters (1500 feet) per second (about 21,336 meters, or 70,000 feet, altitude) at the beginning of terminal area energy management (TAEM).

During the final phases of descent, flight path control is maintained by using the aerodynamic surfaces. TAEM is initiated to provide the proper vehicle approach to the runway with respect to position, energy, and heading. Final touchdown occurs at an angle of attack of about 16 degrees. The maximum landing speed for a 14,515-kilogram (32,000-pound) payload, including dispersions for hot-day effects and tailwinds, is about 106 meters per second (207 knots).

Shuttle Capabilities

The Space Shuttle has been designed to support a wide variety of current and planned space missions. This is implicit in the vehicle's capability to orbit 29,484 kilograms (65,000 pounds) of payload compared to the current expendable launch vehicle capability of about 13,608 kilograms (30,000 pounds). But the Space Shuttle is more than a launch vehicle; it can support new missions and operations that will enable higher productivity for the space program and greater utilization of space resources.

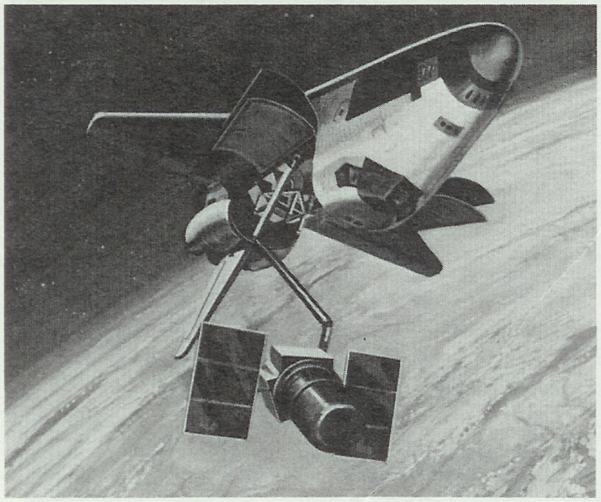
In addition to its ability to provide more cost-effective launch services, the Shuttle has been designed to service and refurbish low-earth-orbit satellites, retrieve and return to earth payloads weighing up to 14,515 kilograms (32,000 pounds), perform dedicated experimentation and technology development missions, carry passengers in relative comfort, and, with suitable upper stage propulsion, launch from orbit satellites and spacecraft whose missions require the attainment of superorbital velocities.



Spacecraft Delivery

These capabilities can be used in many ways. Some of these applications have already evolved into vital programs; others await the special operational capabilities of the Space Shuttle to enable their initiation. With its capabilities, economy, and operational flexibility, the Space Shuttle provides the United States and its partners in space ventures the means to develop space resources for everyone's benefit.

Space Shuttle missions will primarily place satellites in earth orbit. However, during many of these placement missions, a satellite launched on a previous mission can be retrieved and returned to earth for refurbishment and reuse. In some cases, the orbiter will be launched empty to rendezvous with, recover, and return a satellite to earth for refurbishment and reuse. In a typical placement mission, the satellite or satellites are serviced, checked out, and loaded into the Shuttle.



Satellite Placement

The crew that boards the Shuttle from the launch platform will consist of Shuttle commander, pilot, and mission and payload specialists. Upon arriving at the desired orbit, the mission and payload specialists will conduct predeployment checks and operations. After determining that the satellite is ready for deployment, the crew will operate the payload deployment system, which lifts the satellite from the cargo bay retention structure, extends it about 15 meters (50 feet) from the orbiter, and releases it. The final activation of the satellite will be by radio command. The Shuttle will stand by until the satellite is performing satisfactorily before proceeding with the remainder of this mission. Satellites that fail to check out or activate will be returned to earth for repair and subsequent relaunch.

To recover a satellite, the orbiter will rendezvous with it, maneuver close, and attach the payload handling/manipulator arms to the satellite. After the satellite is deactivated by radio command, it will be moved into the cargo bay and structurally locked into place. Once the payload bay doors are closed, the orbiter will perform deorbit maneuvers, enter the atmosphere, and land, returning the satellite for reuse. This recovery capability offers a new dimension to satellite designers that will substantially reduce the development and production costs of the payloads (satellites).

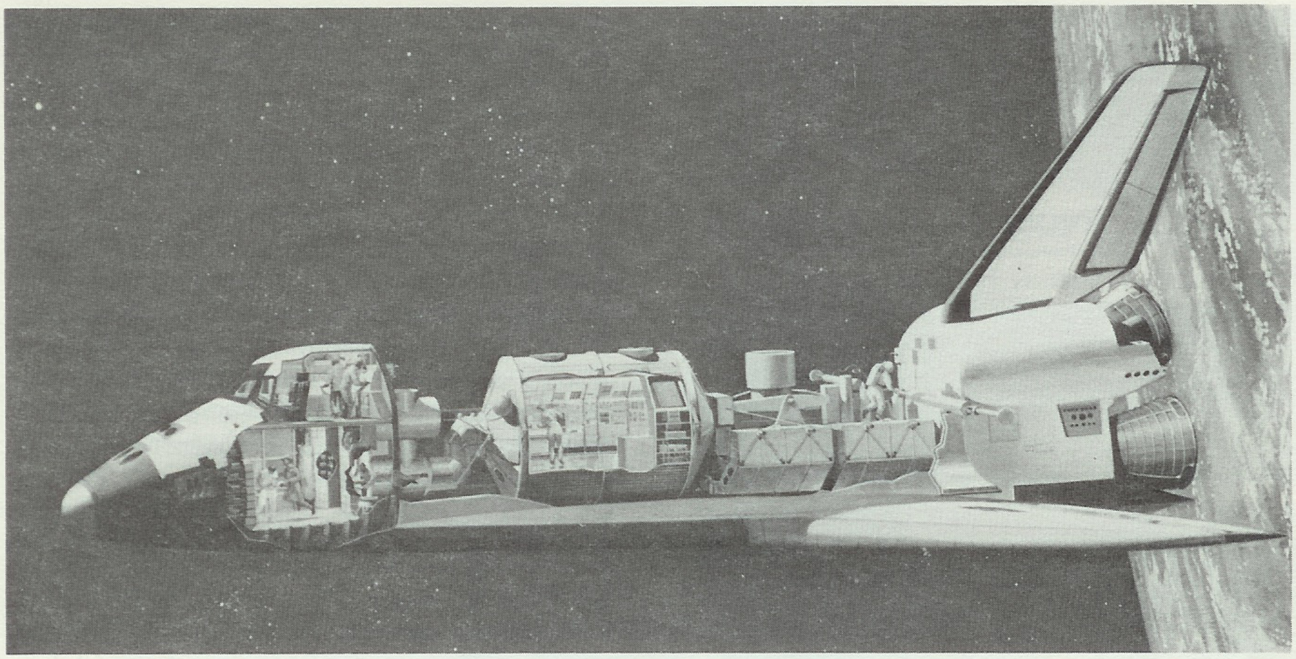
The Shuttle orbiter can be extended to conduct on-orbit research with Spacelab payloads (being developed by the European Space Agency, ESA, whose members are listed below). It can supplement the experimenter's ground-based laboratories with the unique conditions that only space flight can provide, such as a long-term gravity-free environment, space vacuum, vantage point for observing and examining the earth, and an environment in which the celestial sphere can be studied without atmospheric interference.

ESA Member States

Belgium
Denmark
France
Ireland
Italy
Netherlands
Spain
Sweden
Switzerland
United Kingdom
West Germany

Several Spacelab system configurations will be flown. The basic configuration includes a pressurized module where scientists can work in a shirt-sleeve environment. A tunnel gives access to the cabin area of the Shuttle. Instruments or experiments that require exposure to the space vacuum, are oversized, or require observation are mounted on a pallet aft of the pressurized module. The Shuttle can be flown in an inverted flight attitude to orient the instruments toward earth to survey resources or to investigate geophysical and environmental parameters.

Spacelab is an international program. In addition to the manufacture of the Spacelab, European scientists will also participate in Spacelab operations. Other nations have also indicated an interest in Spacelab operations. The Shuttle—carrying Spacelabs to orbit, operating them, and returning them to earth—provides an entirely new capability for manned space studies that will increase the effectiveness of space research as well as reduce the cost of applying space technology.



Spacelab

The Space Shuttle will not always carry just a single payload into orbit. Payload bay volume permitting, excess area can be used to add payloads to the cargo manifest, allowing flight costs to be shared. Pooling of payloads can provide economic advantages when mission and schedule constraints are compatible.

Rockwell International studies of the prospects for mixing payloads show that, in numerous instances, the payloads of different agencies (NASA and other U.S. Government agencies, commercial organizations, and other nations) can be combined into efficient cargoes for Shuttle flights. For instance, a payload going to geosynchronous orbit could share launch costs with two navigation satellites; or the navigation satellites could be launched from Vandenberg Air Force Base, sharing launch costs with a weather satellite.

THE INTERDISCIPLINARY CHARACTER OF SHUTTLE'S DEVELOPMENT

Reviewing the genesis, development, and current state of the Shuttle system as it awaits its first orbital flight provides a context for the examples of systems engineering discussed in this section. The current Shuttle program has the singular and distinct advantage over other major new programs in that it inherited almost intact the complex but proven managerial techniques that were polished to a fine edge during the Apollo lunar exploration program. Indeed, Apollo not only provided this fine managerial legacy, but the administrative organization and most of its key personnel also remained almost the same for this new effort. Thus, the lessons of Apollo did not have to be relearned but merely applied to the next program, namely, the Shuttle. The basic tools necessary to develop the next major step in mankind's development and application of the potential of space were available: 12 years of space flight experience, 70 years of aircraft experience, and over 40 years of management experience in large-scale technological endeavors.

The following discussions demonstrate how a range of technical and scientific disciplines came together to solve individual and collective problems and establish "the era of space transportation." Just as a broad range of disciplines is required to develop a surface-bound transportation system, so must an infinitely broader range be assembled for a space-rated transportation system. As noted previously, these examples do not attempt to form a comprehensive review of the Shuttle's development, but serve to highlight the interdisciplinary character of the scientific and technical aspects of the program.

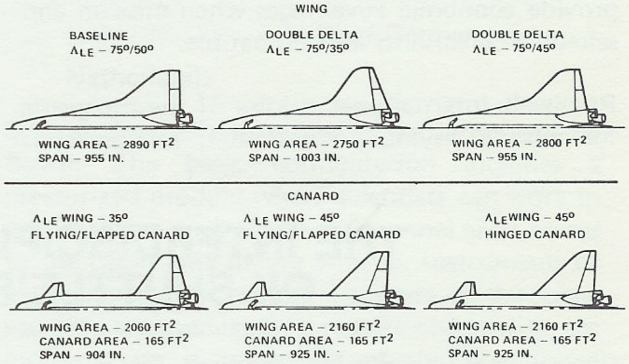
Wing Development and Analysis

The Shuttle orbiter is both an aircraft and a spacecraft: its external features have been carefully configured to provide the protection and versatility required for orbital and atmospheric flight, as well as the aerodynamic performance and control necessary for unpowered descent and landing. The aerodynamic lines ensure performance that is acceptable over the entire hypersonic/subsonic speed range while providing the required cross-range capability and touchdown velocity. One primary design factor that strongly influenced the aerodynamic wing shape was the need to sweep the wing planform properly to minimize aerothermodynamic heating on the leading edges without compromising the aerodynamic flight performance. The pair of control surfaces on the trailing edge of each wing provides the primary pitch and roll control forces during the aerodynamic portion of the entry flight profile. (The body flap on the fuselage base is mainly a trimming surface.)

The structural design reflects the need to minimize weight in the face of ascent aerodynamic and dynamic loads and, unlike most conventional aircraft, loads on the heated structure induced during entry. All of these conflicting requirements have been met through the participation of design and analysis teams from many diverse disciplines. The design of the orbiter wing is a microcosm of the integrated design process for the entire Shuttle vehicle. The following discussion outlines some of the significant reiterative development and analysis studies conducted to bring the Shuttle to its present state of readiness for orbital flight tests.

AERODYNAMICS. There were three major objectives in the aerodynamic development plan for the Shuttle integrated system. The first was to support development of the overall system arrangement by establishing the aerodynamic and aeroload impacts of various arrangement candidates. Another important objective was to provide continuing and maturing evaluation of the basic stability and control aerodynamic characteristics of the following configurations: (1) the total launch vehicle, (2) the orbiter/external tank (ET) and the SRB's independently just before SRB separation, then in various attitudes after separation, (3) the orbiter and ET just before ET separation and again in postseparation attitudes. The third important task was the development of air loads data to support structural flight load analysis. The challenge was formidable, since the complexity of the configuration renders conventional analytical methods of only superficial use. Wind tunnel tests of very detailed models were used extensively (more so than on most previous programs) but with modest program funding.

Major considerations in the refinement of the baseline Shuttle configuration were the interrelationships of center-of-gravity travel, structural load paths, element weight impact, and the resulting influence on the orbiter design. A key aerodynamic issue in these arrangement trade studies was the influence of each configuration option on aerodynamic performance in terms of stability, control, lift, drag, aeroloads, and aerodynamic heating.

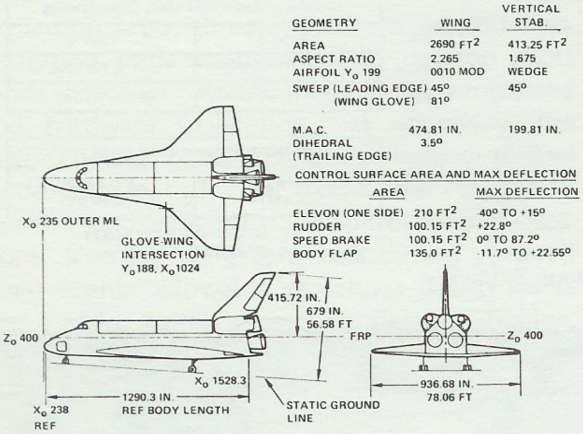


Assessed Configurations

Trade studies that used the orbiter configuration at the start of the contract as a baseline were initiated to decrease orbiter dry weight and increase deliverable payload weight. Configurations assessed included a varied leading edge sweep, double delta wing (selected), and canard concepts.

A 5- to 8-percent improvement in trimmed lift and up to a 907-kilogram (2000-pound) saving in wing weight were effected by optimizing wing twist and camber. The overall studies included effects of fuselage bending, fuselage forebody corner radius, airfoil twist, camber, incidence, glove size, and wing size. Further refinements, such as glove leading edge radius, wing glove fillet, planform geometry, and optimal wing camber, resulted in an additional increase in trimmed lift.

Later refinements produced the current orbiter configuration with a down payload of 14,515 kilograms (32,000 pounds), design landing velocity of 87 meters per second (169 knots) at an angle of attack of 15 degrees, and a design center-of-gravity range of 2.5-percent body length with -2-percent static margin at the aft center-of-gravity limit (acceptable with stability augmentation). The SRB's were moved circumferentially around the external tank from zero degree above the horizontal, thus relieving orbiter wing aeroloads.



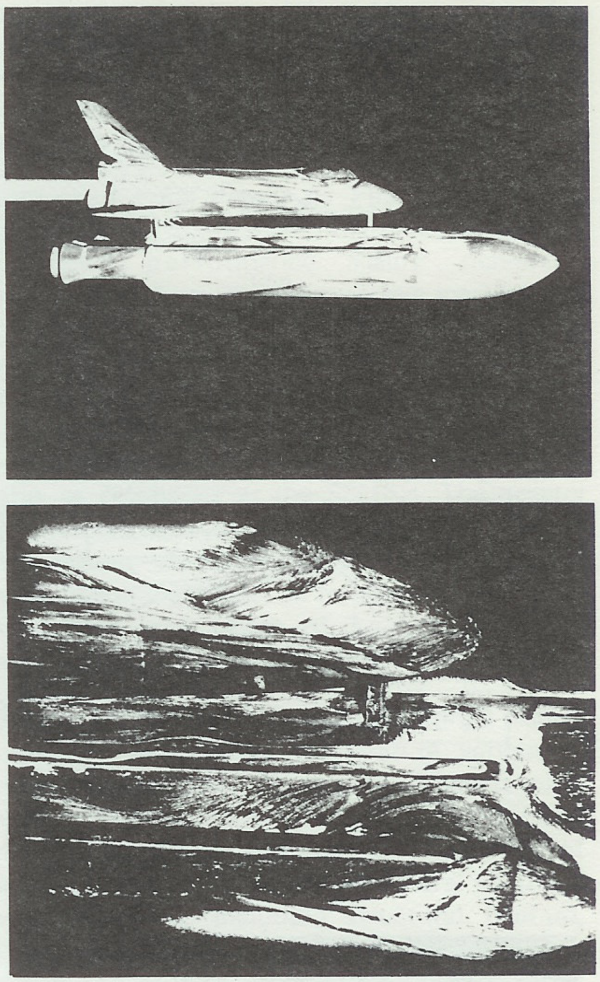
GEOMETRY	WING	VERTICAL STAB.
AREA	2690 FT^2	413.25 FT^2
ASPECT RATIO	2.265	1.675
AIRFOIL Y_0 199	0010 MOD	WEDGE
SWEEP (LEADING EDGE)	45°	45°
(WING GLOVE)	81°	
M.A.C.	474.81 IN.	199.81 IN.
DIHEDRAL (TRAILING EDGE)	3.5°	

CONTROL SURFACE AREA AND MAX DEFLECTION

	AREA	MAX DEFLECTION
ELEVON (ONE SIDE)	210 FT^2	-40° TO +15°
RUDDER	100.15 FT^2	+22.8°
SPEED BRAKE	100.15 FT^2	0° TO 87.2°
BODY FLAP	135.0 FT^2	-11.7° TO +22.55°

Operational Orbiter

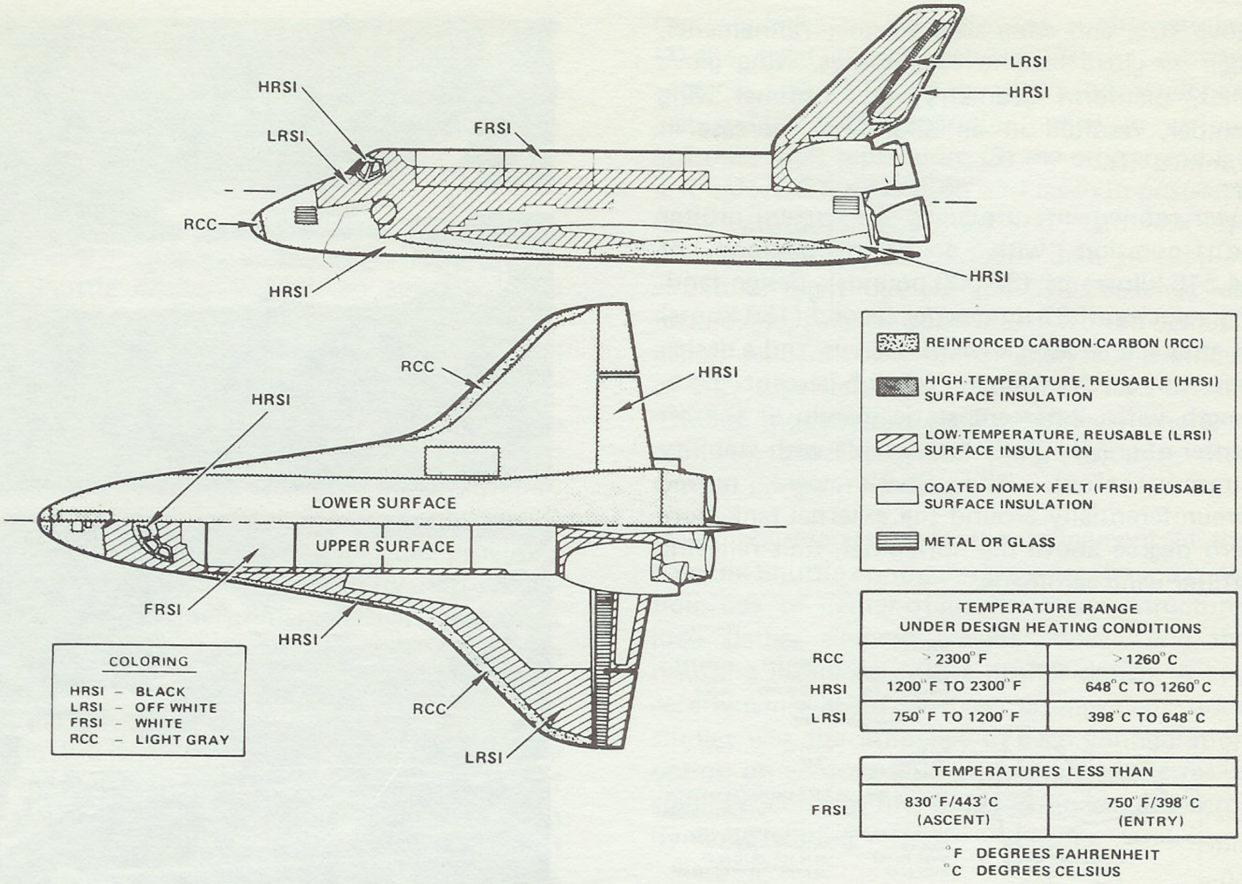
AEROTHERMODYNAMICS. Although flight regimes similar to the Shuttle have been encountered on past spacecraft, such as Apollo and Gemini (for shorter more intense periods), the geometrical complexity of the Shuttle vehicle and the propulsion system arrangement and characteristics made the prediction of induced environments a technically challenging task. Past flight experience on basic aerothermodynamic phenomena was an invaluable aid in analyzing the heating sources for the Shuttle vehicle. Although analytical approaches to solving aerothermodynamic problems are increasingly better known, the complex flow fields enveloping the Shuttle configuration posed problems of far greater magnitude than for earlier spacecraft. Surface flow patterns are quite intricate, as recorded by the oil flow technique during wind tunnel tests at Arnold Engineering Development Center (AEDC).



Space Flow Patterns—Wind Tunnel Model

The prediction of aerodynamic heating for the Shuttle vehicle was highly dependent upon wind tunnel data to determine the flow field effects on heating and pressure distributions. These experimental observations were correlated with well known theoretical analyses for simple shapes such as flat plates, cones, cylinders, and spheres, which were used to simulate various local regions of the elements. The wind tunnel data provided information as to how the simple theories should be externally factored to arrive at the observed heating level for the complex Shuttle geometry. By correlating the wind tunnel data with theories proved by past flight experience, the tunnel data were scaled to flight conditions with an adequate degree of confidence for the design of the reusable thermal protection system.

A key feature of the Shuttle wind tunnel program involved the cyclical acquisition of aerodynamic, thermodynamic, and aeroloads



COLORING
HRSI – BLACK
LRSI – OFF WHITE
FRSI – WHITE
RCC – LIGHT GRAY

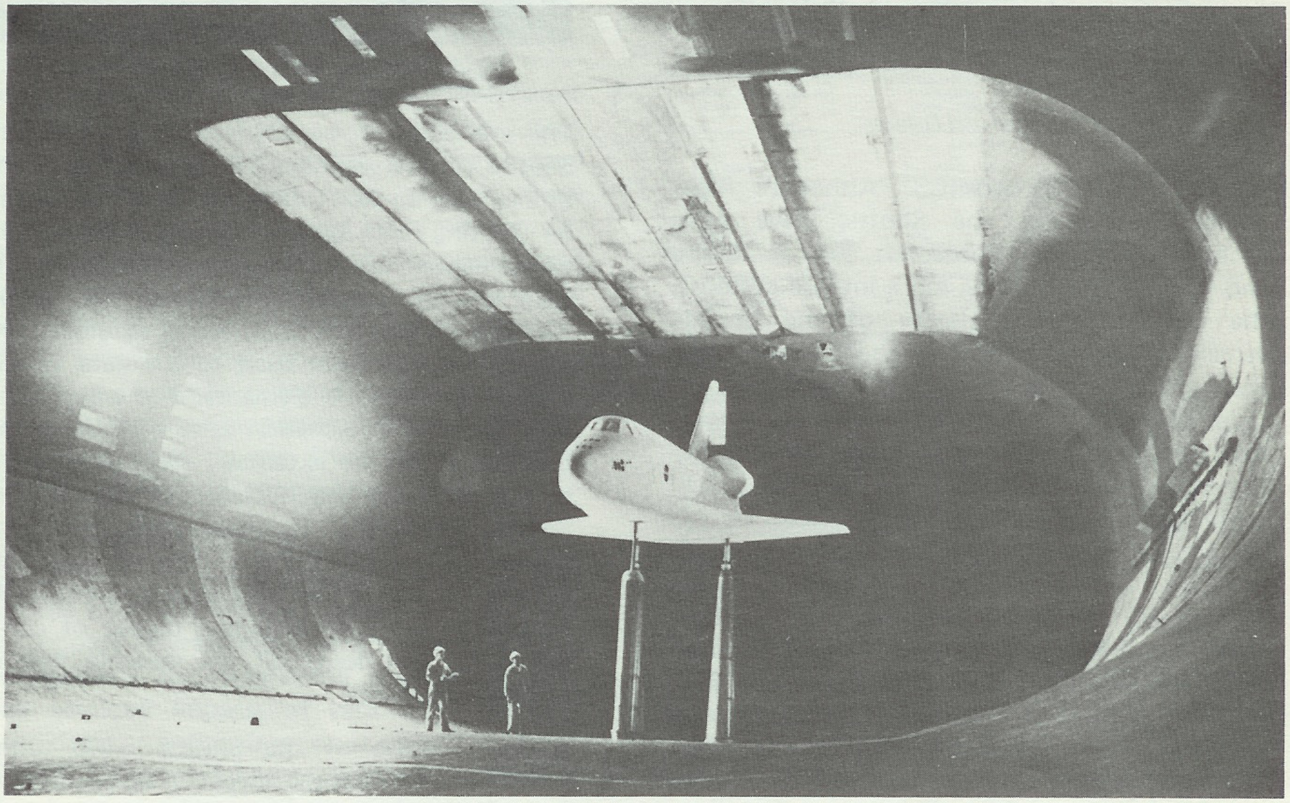
▨	REINFORCED CARBON-CARBON (RCC)
■	HIGH-TEMPERATURE, REUSABLE (HRSI) SURFACE INSULATION
▨	LOW-TEMPERATURE, REUSABLE (LRSI) SURFACE INSULATION
☐	COATED NOMEX FELT (FRSI) REUSABLE SURFACE INSULATION
▤	METAL OR GLASS

	TEMPERATURE RANGE UNDER DESIGN HEATING CONDITIONS	
RCC	> 2300° F	> 1260° C
HRSI	1200° F TO 2300° F	648° C TO 1260° C
LRSI	750° F TO 1200° F	398° C TO 648° C

	TEMPERATURES LESS THAN	
FRSI	830° F/443° C (ASCENT)	750° F/398° C (ENTRY)

°F DEGREES FAHRENHEIT
°C DEGREES CELSIUS

Thermal Protection System

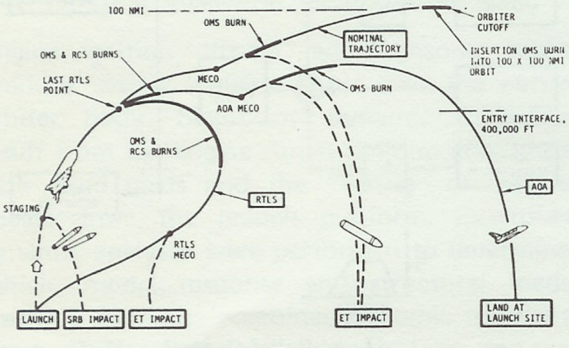


Large-Scale Testing

data banks to establish a continuously maturing data base that reflected the evolving details of element designs. Over 40,000 development wind tunnel hours have been run to date; these hours include support of the integrated vehicle verification aerodynamic analysis cycle and loads evaluation. All wind tunnel tests were coordinated with and approved by the NASA Shuttle program management at Johnson Space Center (JSC). Major tests were run at Ames Research Unitary Tunnels, significant support and supplementary tests having been provided by other NASA centers.

POWERED FLIGHT ANALYSIS. Early in the program, the major concerns of trajectory design and vehicle performance evaluation were to optimize individual element performance-related requirements (e.g., propellant loads, nozzle expansion ratio, thrust levels), to support configuration trade studies, and to develop abort mode concepts. As element designs progressed and hardware fabrication was underway, the major concern of the trajectory designer shifted to development of flight modes that recognized element and subsystem capabilities and limitations. Keeping wing aeroloads during powered flight within allowable structural design limits was a major factor in ascent trajectory shaping.

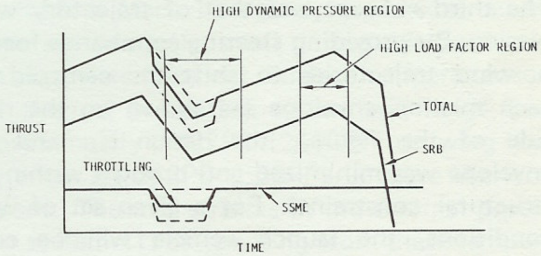
The challenge of total system integration involved a combination of requirements and constraints. Two launch sites with substantially different energy requirements and significantly different design winds and natural environments were involved. Two trajectory constraints, maximum dynamic pressure of 3174 kilograms per square meter (650 pounds per square foot) and maximum load factor of 3 g's, were also imposed. Furthermore, cost constraints required sizing the elements (SRB and ET) with minimum system performance margins. Intact abort requirements (no loss of the orbiter or crew) for the orbiter dictated consideration of three different abort modes, depending on the mission phase. Structural and heating constraints were also major considerations in trajectory design.



Ascent Trajectory

Control of Load Factor by First-Stage Thrust Shaping. The first-stage thrust-time relationship balanced performance against maximum dynamic pressure ($\overline{q}$) and excessive inertia loads that may occur in the high-g period prior to SRB burnout. The factors involved were the SRM grain design and throttling of the SSME's. The SRM grain design had the major influence on first-stage performance because of the 4:1 thrust ratio as compared to the SSME's. The general requirement called for a drop in SRB thrust after about 20 seconds to control dynamic pressure and a gradual rise to a sensitive shoulder (maximum load factor of 3 g's) to maximize performance before grain tailoff.

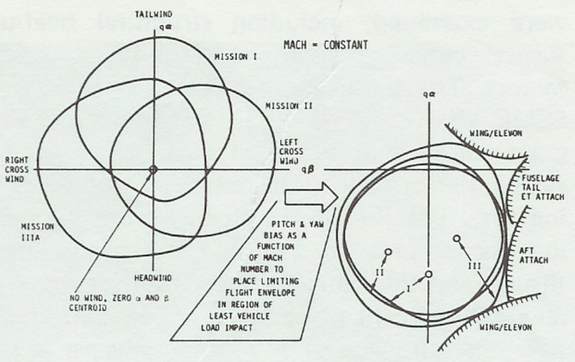
During detailed evaluation of SRB thrust dispersions due to seasonal temperature variations, flight-to-flight variations, and development tolerances, it was found that structural design loads incurred during the high-load-factor portion of first stage could be exceeded. Several solutions were examined, including structural beef-up, thrust curve redesign, and reduced safety factors. The thrust curve redesign coupled with SSME throttling was the most attractive program solution in terms of cost, schedule, and system performance. The redesign involved shifting total impulse (lower thrust) from the high-load-factor area to the high-$\overline{q}$ area (increased thrust) and then throttling the SSME's down to about 90-percent power level to control $\overline{q}$ to the specification value of 3174 kilograms per square meter (650 pounds per square foot).



Thrust Profiles

Adopting SSME throttling as a standard first-stage procedure produced an additional benefit. In the mission planning phase, the throttle schedule can be adjusted to minimize dynamic pressure or to compensate for payload weight and for predictable thrust-to-weight ratio variations from SRB batch dispersions, seasonal temperature variations, and changes in aerodynamic drag.

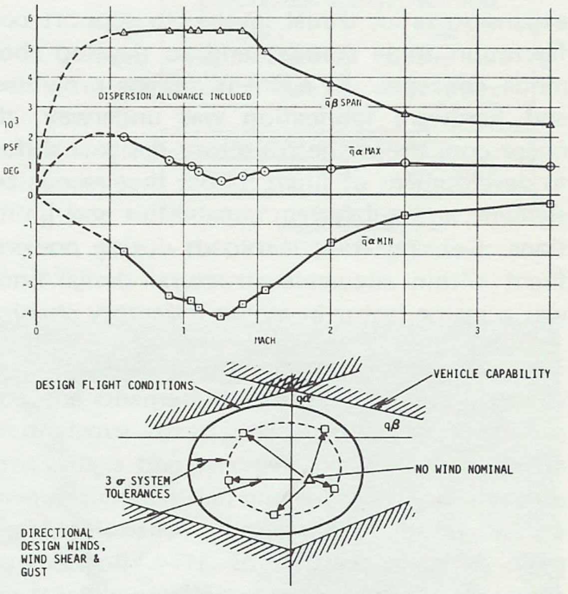
Control of Load Factor by Attitude Control. A major interdisciplinary integration activity concerned the control of vehicle attitudes during the transonic flight regime to minimize element structural loads. Three concepts were involved. First, the major structural constraints were expressed as functions of $\bar{q}\alpha$ and $\bar{q}\beta$. (These are shown as the boundary condition lines on the right side of the illustration below.) Second, the capability of the flight control system to limit the exposure of the vehicles to maximum values of $\bar{q}\alpha$ and $\bar{q}\beta$ for combinations of design winds, gusts, and failures (engine out) were expressed by $\bar{q}\alpha / -\bar{q}\beta$ envelopes at Mach numbers of concern for each mission. (Typical $\bar{q}\alpha / -\bar{q}\beta$ envelopes for three reference missions at a specific Mach number, shown on the left side of the figure, are representative uncorrected trajectories.)



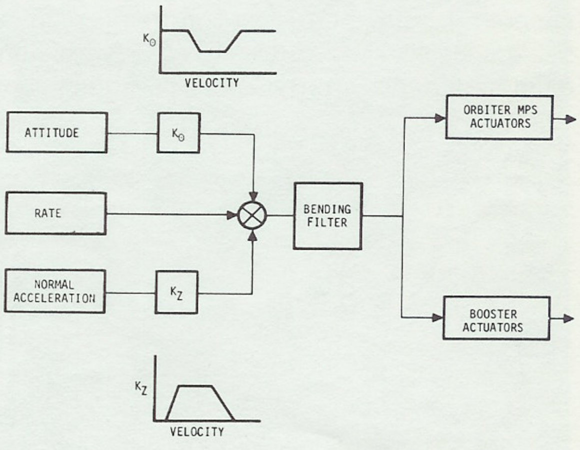
Trajectory Biasing

The third concept was that of trajectory wind biasing. By providing steering commands for the no-wind trajectories to shift the centroid for each mission envelope (as shown on the right side of the figure), the design $\bar{q}\alpha$ and $\bar{q}\beta$ envelope was minimized and brought within the structural constraints. For a given set of wind conditions, the launch vehicle will be commanded to fly $\bar{q}\alpha$'s and $\bar{q}\beta$'s corresponding to these centroids. The structural loads, then, are maintained within the design limits. Envelope size can be minimized by updating the wind profiles as closely as possible to the launch time.

This is the first booster flight system to incorporate such a capability, although analytical studies of load relief systems date back to the pre-Apollo period. The key issue here is that the loads condition to be controlled is the $\bar{q}\alpha / \bar{q}\beta$ envelope, together with correlated body rates. The vehicle monitors the onset of excessive $\bar{q}\alpha / \bar{q}\beta$ conditions through vehicle-mounted accelerometers that sense pitch and yaw acceleration. The signals are blended with the attitude and rate commands and are filtered to avoid exciting vehicle bending modes, since the sensitive accelerometers may react to vehicle modes or random vibration in addition to the desired external accelerations. The filters have been designed to avoid passing the extraneous signals, but pass the desired load indicator signals.



Load Relief Requirements



Load Relief Control

Elevon Load Relief. A significant ascent flight control design problem arose from aerodynamic hinge moments on wing-mounted elevon control surfaces. No single fixed elevon deflection was found to be adequate at all Mach numbers to maintain aerodynamic hinge moments within a range acceptable to the structural capability of the elevons, their actuators, and the actuator/wing attachments. Wind tunnel testing determined the cause to be shifting aerodynamic flow fields during first-stage ascent. The original plan was to deflect at least the outboard elevon panels according to a preprogrammed load-relief schedule and to include provisions for adaptive support if necessary. Subsequent studies showed that aerodynamic and system uncertainties exceed the load-relieving capability of this approach. An adaptive feedback unit to modify the deflection schedule in the event that sensed elevon hinge moments approach design limits has been implemented in the flight control system (FCS).

Structural Design and Analysis

The complexity of the Shuttle structural configuration—four bodies in a nonaxisymmetrical arrangement with a high degree of aerodynamic sensitivity, together with two parallel burning propulsion systems with throttling capability—provided a challenge to the loads analysis community in terms of the detail of math models required and the scope of dynamic situations to be assessed. Analysis of acoustic environment and its impact on the flight vehicle and ground facility design demanded attention not only because of the high acoustic levels anticipated but also because of the potential sensitivity of present and planned payloads to vibratory environment. Besides the challenge offered by the baseline vehicle design, the mission profile resulted in a wide variety of structural loading conditions.

Engine ignition, lift-off, and transonic flight produce severe acoustic levels over the entire orbiter body. Significant dynamic transients result from the engine thrust buildup combined with wind gusts and the "twang" of vehicle release from the launch platform. Extensive dynamic analyses were performed to determine vehicle modal response and structural loads resulting from the combined dynamic transient inputs. Stiffness of the launch platform and the SRB aft skirt support pedestals was considered in these analyses, as well as flight vehicle stiffness characteristics.

STRUCTURAL DESIGN REQUIREMENTS. The region of high dynamic pressure during ascent produces critical loading on the aerodynamic surfaces. Air loads in pitch and yaw directions are imposed as a result of winds, wind shears, and gusts. The regime of high loading extends from approximately Mach 0.9 to Mach 1.5. Again, extensive analyses were required to determine an envelope of structural design loadings for the vehicle that would encompass the range of Mach number, angle-of-attack combinations in pitch and yaw, and thrust vector forces resulting from control system responses to atmospheric disturbances. Shortly before SRB burnout, the vehicle maximum longitudinal acceleration of 3 g's is achieved, but aeroloads are relatively small at this time.

Loads on the orbiter during ET separation, orbit insertion, and orbital operations are relatively benign. Significant temperature gradients, some in excess of 149°C (300°F), may be induced on the orbiter structure during fixed-attitude holds associated with on-orbit operations. These temperature distributions establish initial conditions prior to entry that aggravate the severity of thermal gradients that must be considered in combination with flight loads during the descent and landing approach phases. It is also necessary, for adequate mission flexibility, to consider random orientation of the fixed-attitude hold—i.e., tail sun, top sun, bottom sun, etc.—in establishing preentry temperature distributions.

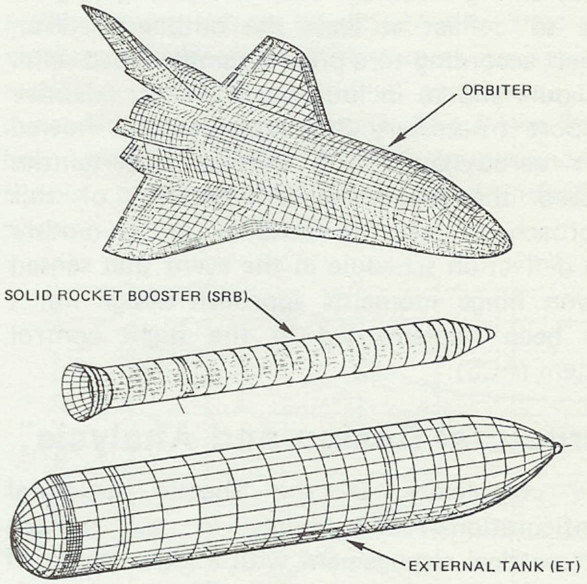
Very high aerodynamic heating flux is encountered on the orbiter during entry over the Mach 25 to Mach 12 regime; however, structural loads are relatively small during this portion of the unpowered descent. Surface temperatures on the thermal protection system will range from approximately 1427°C (2600°F) on wing leading edges to 343°C (650°F) in more sheltered regions. Thermal stresses in the thermal protection system (TPS) resulting from these temperatures and associated severe thermal gradients must be considered in the design and material selection for TPS components. Because of the insulating effectiveness of the TPS, the orbiter primary structure will experience maximum temperature considerably later; some regions will not reach maximum temperature until after landing.

Structural design conditions during the aerodynamic portion of descent flight are similar to those of conventional aircraft. A velocity/load-factor envelope must be defined to set limits of required structural capability; flight anywhere within this envelope is permissible, based on structural constraints. The load factor limits have been identified at +2.5 g's and -1.0 g to permit adequate pull-up from the entry trajectory and energy management maneuvers required to ensure successful dead-stick approach and runway touchdown. This phase of the mission profile imposes critical design loadings on orbiter wing, vertical tail, aerodynamic control surfaces, and portions of the fuselage. Significant thermal-induced loads must be considered in combination with aerodynamic and inertia forces for most structural regions.

The orbiter is designed for a relatively "hot" landing to minimize wing area and vehicle weight. Significant dynamic transients occur during touchdown and landing rollout, and extensive dynamic analyses have been performed to determine orbiter structural response and loadings for this phase. Critical design loads are induced on the forward fuselage and supports of major mass items in addition to the landing gear and its local support structure. Again, thermal-induced loadings must be considered in combination with landing dynamic loads.

STRUCTURAL ANALYSIS. Idealized beam models and classical methods of analysis are inadequate to predict structural behavior accurately, considering the complexities of the mated vehicle configuration and orbiter structural arrangement. Therefore, a large-scale finite-element mathematical model of the vehicle served as the heart of the structural analysis approach for Space Shuttle, allowing a detailed representation of local load paths and stiffness characteristics, as well as a description of the basic three-dimensional characteristics of the structure.

A detailed finite-element stress analysis model was developed for each element of the vehicle, based on current knowledge of basic configuration geometry, internal structure arrangement and sizing, and mass distributions. These characteristics evolved from mission performance requirements and preliminary design development. An example of this type of finite-element model for the orbiter, ET, and SRB is shown in the illustration below. Approximately 7000 node points were contained in the orbiter portion of the model. The total model was substructured into individual nets to facilitate preparation, checkout, and execution of the large-scale computer program.



Finite-Element Stress Models

This level of detail was required to develop accurate and directly usable internal load distributions throughout the structure; however, it was not necessary or practical to use this large a model to determine vehicle modal characteristics and dynamic responses. Therefore, the stress model was mathematically collapsed to a simpler dynamic model. The dynamic model for the complete vehicle contained 750 dynamic degrees of freedom. Stiffness and mass matrices for the dynamic model were used to extract the natural mode shapes and frequencies of the vehicle. These modal results formed the basis for evaluating structural loads resulting from dynamic inputs and related disciplines of flutter, aeroelasticity, flight control, and other structural dynamic analyses. As many as 30 to 50 modes were used, depending on the requirements of a specific analysis.

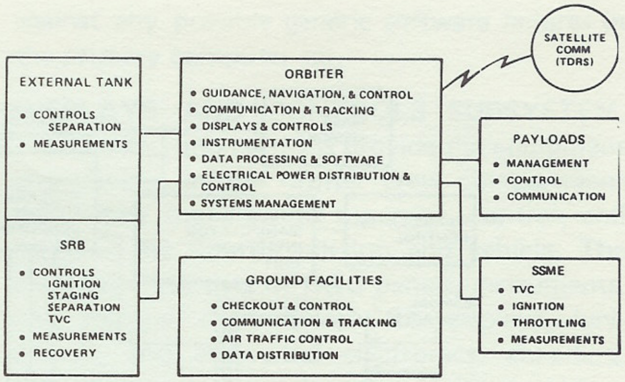
External loadings in terms of air loads, propulsive thrust loads, etc. were applied as lumped forces at appropriate node points on the dynamic model. If the condition being analyzed was a dynamic event, a time-dependent description of these forces was required. The mass matrix provided unit inertia loads at each node point, and the actual inertia forces were determined as a function of vehicle rigid body and modal response to the external force system. Because the vehicle trajectory and flight control system characteristics affect the definition of the external force system and vehicle response, it was necessary to integrate data from these disciplines, as well as aerodynamic pressure distributions, into the model, modes, loads, stresses (MMLS) cycle.

Internal loads for the element structures were developed for selected cases determined by the survey of external load results. The net external nodal forces determined from solution of the dynamic model were apportioned to the finer grid node points of the stress model. Internal forces at each node point were determined on the basis of static equilibrium and elastic strain compatibility. This effort was equivalent to solving a structural distribution problem with several thousand redundancies for each load case. Since internal loads from temperature gradients over the structure also are significant, thermal models for temperature distributions were analyzed by specifying appropriate temperatures at each node point as input data.

The internal loads results for thermal and/or load cases served as the basis for detailed structural strength and stability analyses and sizing of the individual structural members. The structural development of Space Shuttle was an iterative process involving major cycles of the MMLS system. Each update improved the fidelity of data as results of the preceding cycle were reflected in refinement and better definition of the structural characteristics. The same evolution is true for many of the external input parameters, such as configuration geometry, aerodynamic data, and flight control system characteristics.

Data Processing and Software Subsystem

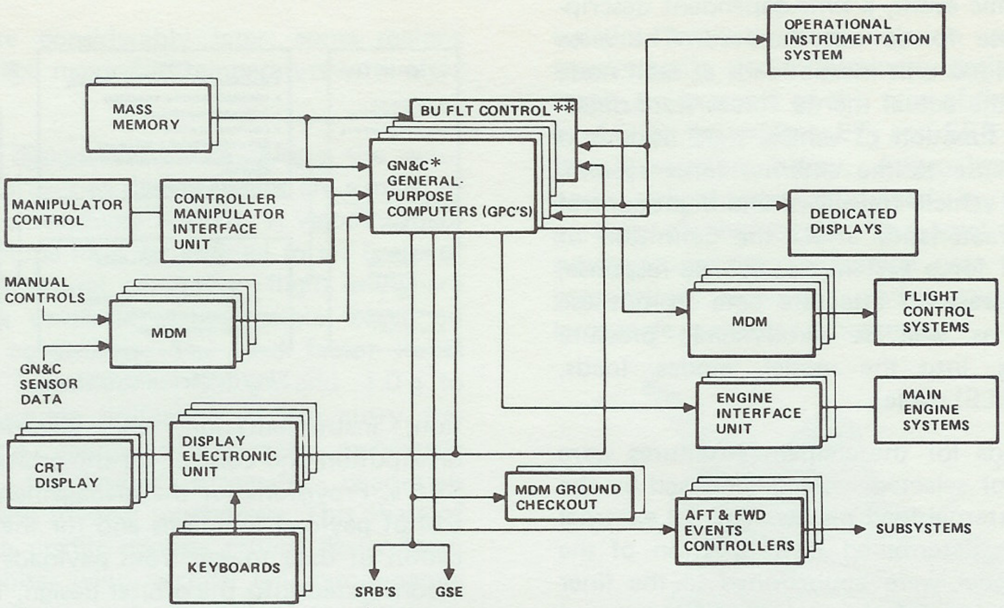
The Shuttle avionic system provides command functions and implementation; displays and controls (D&C); guidance, navigation, and control (GN&C) capability; communication; computation; instrumentation; and electrical power distribution and control for the orbiter, ET, and SRB's. Provisions for the management and control of payload functions and for the communication of data to and from payloads have been incorporated into the orbiter design. The orbiter flight deck is the center of both in-flight and ground activities, except during hazardous servicing.



Shuttle Avionic System

The avionic system provides overall subsystem management, determination of vehicle status and operational readiness, and required sequencing and control functions to the ET and SRB during mated ascent. Automatic vehicle flight control is provided for all mission phases except docking, and manual control options are available at all times. A fail-operational/fail-safe capability is provided by a combination of hardware and software redundancy. Orbiter avionics interfaces with payloads through the mission and payload specialist stations by means of hard-wired controls and displays when the payloads are attached to the orbiter and by RF links when they are detached. S-band communication links between the orbiter and ground stations permit the orbiter to transmit voice and data and to receive commands, voice, and data. Both S-band and Ku-band can be used for communication through the NASA tracking and data relay satellite system (TDRSS). Automatic fault detection is provided for all vehicle flight-critical functional paths. A caution and warning (C&W) subsystem monitors payload health and status while the payload is aboard the orbiter.

The data processing and software subsystem (DP&SS) provides data processing capabilities for GN&C, communication and tracking (C&T), D&C, system performance monitoring, payload management, payload handling, subsystem



*FOUR COMPUTERS DEDICATED TO GN&C DURING CRITICAL FLIGHT PHASES. ONE OR MORE CAN BE RECONFIGURED FOR OTHER USES DURING NONCRITICAL FLIGHT PHASES.

**FIFTH COMPUTER IS USED FOR BACKUP FLIGHT CONTROL DURING ASCENT & ENTRY.

Data Processing and Software Subsystem

sequencing, and selected ground functions. The DP&SS accepts input commands and/or data from the crew, on-board sensors, and external sources; performs computations and processing; and generates output commands and data to meet the requirements specified for GN&C, C&T, D&C, instrumentation, electrical power distribution and control, performance monitoring function, and payload handling and management.

The DP&SS equipment configuration is organized around a computer complex consisting of five general-purpose computers (GPC's) that are interconnected so that they can be operated in redundant groups for critical services. The operational memory capacity of each GPC is 106,496 36-bit words. Additional storage of programs and fixed data is provided by two redundant mass memory units whose data capacity is 134 megabits each. Each crew data CRT display utilizes a computer of 8000 16-bit words, and each of the three orbiter main engines is managed by dual redundant computers of 16,000 16-bit words.

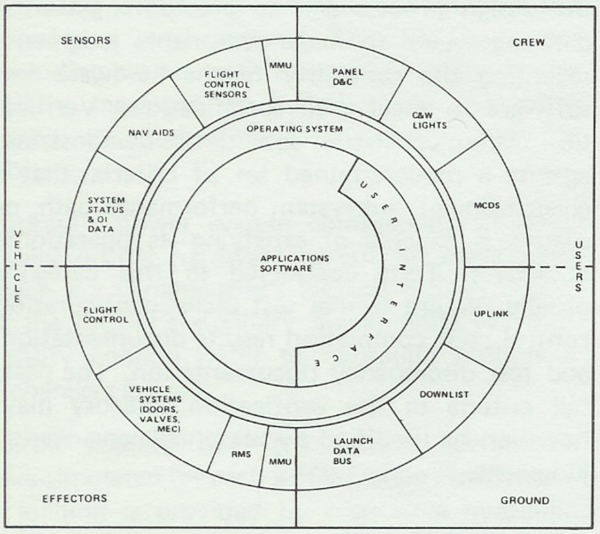
Data are transferred between the computer complex and data users through a data bus network composed of serial, half-duplex data channels. Each data channel processes up to 30,000 data words per second. Each word contains 25 information bits at one microsecond per bit, and each GPC interfaces with 24 data buses.

Interface adaptation between the data bus network and most orbiter subsystems is accomplished by multiplexer/demultiplexer (MDM) units. These units provide signal conversion capability: digital to analog, analog to digital, discrete input, discrete output, and serial digital to serial digital.

One GPC acts as a commander of a given data bus in the flight control busing scheme and initiates all bus transactions. The noncommander computers on the same bus listen to all incoming data that the commander requests. Thus, each response to a request by any computer is heard by all computers performing the same redundant operations.

Redundant sensors measure at a common sense plane. Redundant data paths transfer and convert the data for simultaneous input to all GPC's within the redundant set. The redundant GPC community synchronizes and exchanges redundancy management data to ensure a common, homogeneous processing plane that rejects elements when necessary to maintain the integrity of the set. Each GPC generates commands separately to one of the redundant effector paths but simultaneously with the GPC redundant set. These commands are transferred and converted to the effector plane, where voting takes place to establish the net commanded value. In the hydraulic actuators, this voting process occurs through hydromechanical summing; and sustained differences can result in the deletion of one of the redundant inputs. In the orbiter main engine, thrust commands are compared and executed if two of three inputs agree within a preassigned tolerance.

The primary system flight software (necessary to operate four redundant GPC's) consists of an executive or flight control operating system with system control and a user interface. The redundant computer set maintains synchronization by exchanging input/output times and other critical time events approximately 500 times per second. Application modules are added as required to control the Shuttle vehicle. The degree of control varies with the mission phase that is being executed, i.e., vehicle checkout, ascent, on-orbit operations (including payload activity), and entry.



Flight Software Overview

Ten different memory configurations are necessary to satisfy the various mission requirements. These memory configurations add the application schedules that are needed to satisfy the requirements. A separate GPC is allocated to a backup role (but provides such unique functions as subsystem noncritical function monitoring and payload command and monitoring). The backup system has a separate, independent software design and coding activity to protect against any possible generic software failures in the primary computer set.

DISPLAYS AND CONTROLS SUBSYSTEM. The displays and controls provide the equipment and devices in the orbiter crew compartment that allow the crew to supervise, control, and monitor the Shuttle mission and vehicle. The subsystem consists of D&C panels, instruments, and manual controllers; CRT displays, keyboards, and associated electronics; encoding, decoding, and conversion electronics for instruments and manual controllers; crew compartment interior, integral, and annunciator lighting; exterior lighting; timing; and C&W subsystems.

The D&C subsystem provides for normal operation of all mission phases, exclusive of payload operations, with a minimum crew of two. It is designed for the safe return from either commander's or copilot's seat, and the flight-critical D&C must be accessible from the forward flight station from launch to on-orbit operations and from deorbit burn to rollout.

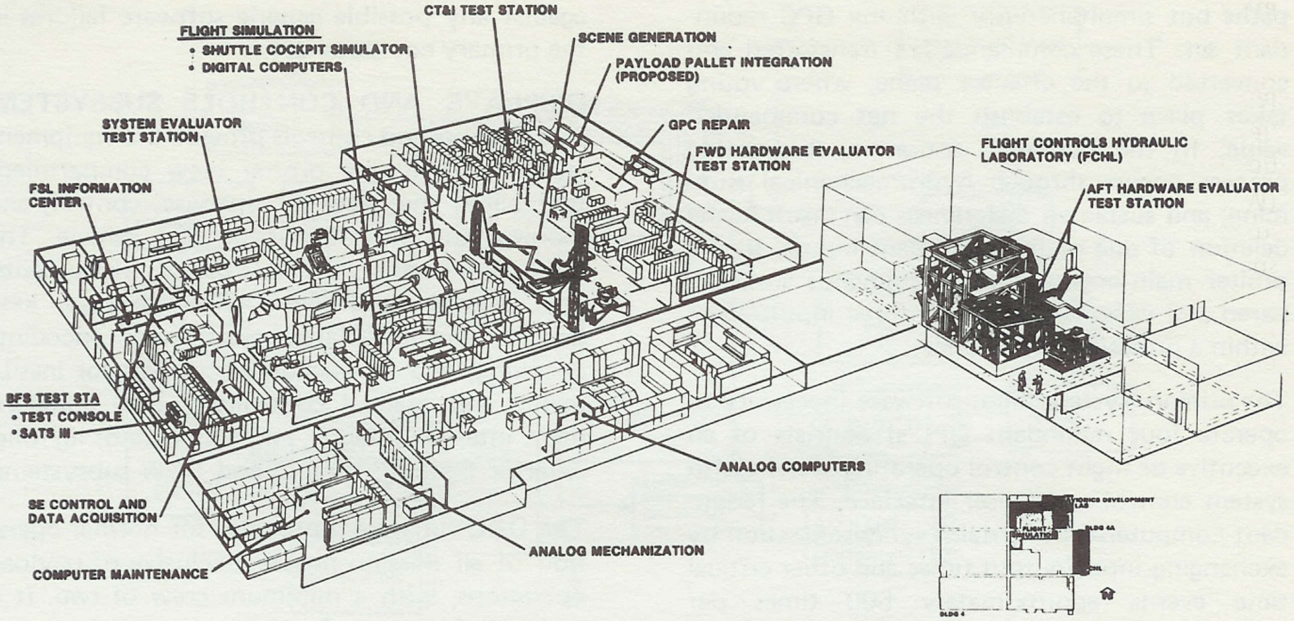
GUIDANCE, NAVIGATION, AND CONTROL SUBSYSTEM. The GN&C subsystem provides (1) automatic and manual control capability for all mission phases except docking (which is manual only), (2) guidance commands that drive control loops and provide steering displays for the crew, and (3) inertial navigation updated by star sensors or Doppler signals and by RF navigation aids for approach and landing.

The basic aerodynamic stability of the orbiter is augmented with body-mounted rate gyros and accelerometers. Side-stick rotation controllers, rudder pedals, and tril controls allow manual control; and the GN&C computer provides commands for automatic flight control functions, such as automatic landing.

Automatic landing is accomplished by means of a computer flight path generated in the GN&C computer. The inertial navigation system is used for reference, with continuous updates from tactical air navigation (TACAN) and the microwave scan-beam landing system (MSBLS). Radar altimeter updates are used near touchdown.

Simulation and Simulators

Various avionics/simulation laboratories have been developed at NASA's Johnson Space



Avionics, Flight Simulation, and Hydraulics Laboratories

Center (JSC), Marshall Space Flight Center (MFSC), and Langley Research Center (LaRC); Rockwell's Space Division; and associate and subcontractor facilities—all supporting respective portions of the overall Shuttle program. Installed at NASA JSC, for example, is the Shuttle Avionics Integration Laboratory (SAIL), the Shuttle Engineering Simulator (SES), and the Shuttle Procedures Simulator (SPS), as well as various training simulators. The Shuttle Flight Systems Laboratories at Rockwell emphasize both open- and closed-loop testing in three laboratories: the Avionics Development Laboratory (ADL), Flight Simulation Laboratory (SIM), and Flight Control Hydraulics Laboratory (FCHL). A general layout of these labs is shown in the illustration above.

Flexibility has been designed into the laboratory complex so that it can support a wide spectrum of test activities, such as independent laboratory tests, integrated laboratory tests, and vehicle and flight support. The laboratories are designed to support both parallel and serial test activities in stand-alone and integrated environments. For example, the ADL can support a single-string, man-in-the-loop study in parallel (on the same shift) with a multicomputer checkout; and the SIM Laboratory can support both a closed-loop, all-math-model, man-in-the-loop activity in parallel with an ADL closed-loop stability study. For closed-loop tests that include FCHL, a large portion of the trilaboratory complex is required; for most open-loop tests, a reduced complex is used.

Development testing, conducted with a minimum of rigor and control, is intended to support the design process and to provide engineering data necessary to make reasonable judgments regarding the capability of the hardware and software to meet their specifications. Verification testing consists of activities to demonstrate, against a predetermined set of criteria, that a given element, subsystem performance path, or system is capable of satisfying its operational objectives. Tests conducted in this category usually require formal test plans, configuration control, test completion results documentation, and test discrepancy documentation. The pass/fail criteria in the verification category may, however, be modified by reasonable engineering judgment.

AVIONICS DEVELOPMENT LABORATORY.

The ADL provides a laboratory environment for testing orbiter avionics at the unit level, subsystem level, and system level. To provide this flexibility, the cabling in the test stations is designed so that various configuration arrangements can be made easily and yet maintain approximately the same length as that in the orbiter.

The ADL can perform separate unit and subsystem tests through the use of vendor-supplied unit test sets and a variety of Rockwell Shuttle Avionics Test Sets (SATS's). The SATS can be configured and programmed to test individual components, perform stand-alone tests of avionic subsystems, simulate components, monitor data bus data, and be used in conjunction with the general-purpose computers to test flight software.

All of the on-board Shuttle avionic systems can be exercised in an open-loop mode in the ADL. With the exception of certain sensors (e.g., the radar altimeter and air data transducers), the orbiter avionic systems can be operated in conjunction with the simulation equipment in a closed-loop mode. This equipment may consist of engineering breadboards, prototypes, or flight-rated systems.

FLIGHT CONTROL HYDRAULICS LABORATORY. The FHCL provides the test bed for the vehicle's hydraulic components and subassemblies. The facility provides hydraulic systems, aerosurface actuators, simulated aerosurfaces (inertia, weight), and aerosurface load actuators. The FCHL may be operated independently, open-loop with either the ADL or SIM, or in the closed-loop environment. The FCHL layout (including plumbing) is arranged to duplicate the relative locations of the hydraulic interfaces (within the limitations of the building) of the orbiter.

Hydraulic power system components are principally orbiter hardware except for the drivers, which are variable-speed electric motors in lieu of the orbiter's auxiliary power units (APU's). Facility cooling water to hydraulic fluid heat exchangers is used.

Inertia loading of flight control surfaces is mass-simulated for each surface while aerodynamic loading is provided by a separate hydraulic servo-controlled loading system. Simulated flight control surfaces and hinges are provided for the elevons, and simulated flight control surfaces with orbiter hinges are provided for the rudder/speed brake and the body flap.

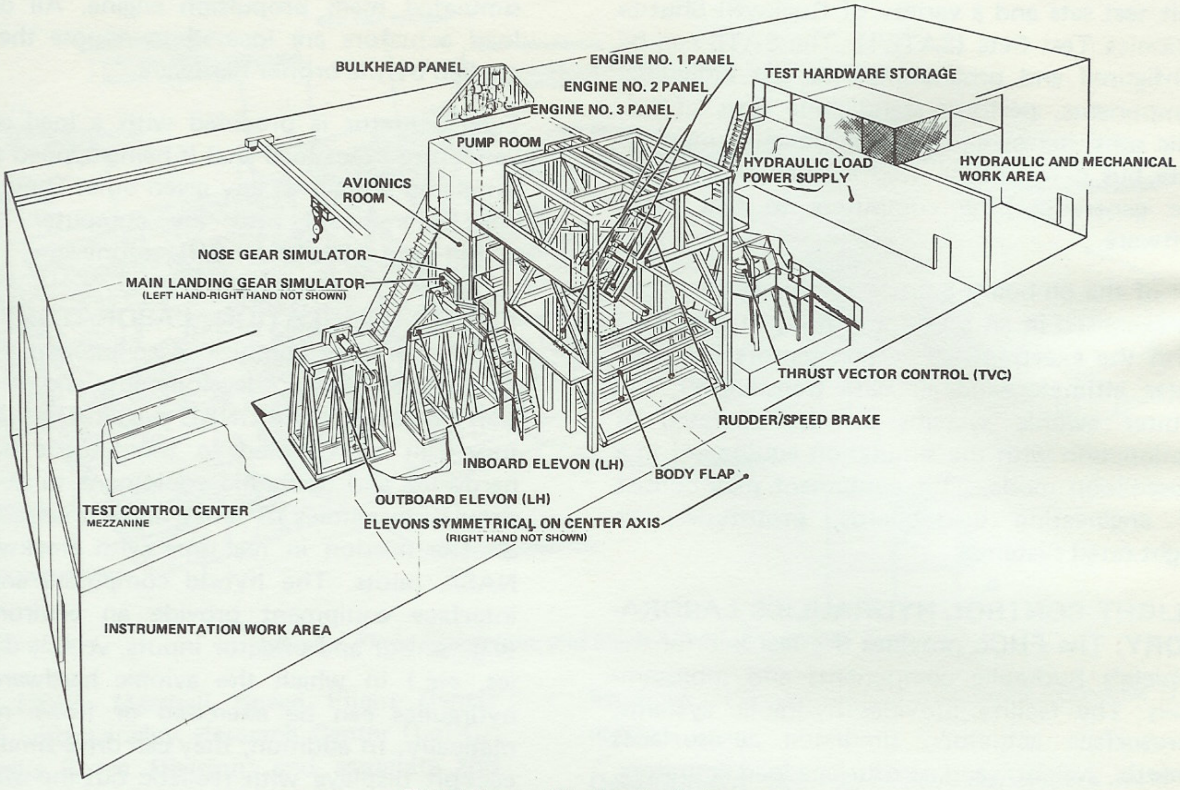
There is a hydraulic load system to simulate aerodynamic loading for the following aerosurfaces: both inboard and outboard elevons, upper and lower rudder panels, and the body flap. In addition, there are two load actuators located 120 degrees apart on the periphery of the simulated main propulsion engine. All of the load actuators are located to oppose the load applied by the orbiter hardware.

Each actuator is provided with a load cell to verify the exact load that is being applied to the simulated surface at any given time. These loads are programmed into the computer during closed-loop ADL/SIM/FCHL testing.

FLIGHT SIMULATION LABORATORY The SIM Laboratory complex is an integral part of the Shuttle design, development, and verification process for the GN&C system. The laboratory can be coupled to the Shuttle avionic hardware and hydraulic equipment to conduct simulation studies of most flight phases of the Shuttle mission in real-time with Rockwell or NASA pilots. The hybrid computers and the interface equipment provide an environment (e.g., sensor and effector inputs, vehicle dynamics, etc.) in which the avionic hardware and hydraulics can be exercised or flown mathematically. In addition, they can drive simulation cockpit displays with realistic out-the-window, dynamic, color scenery during the terminal area energy management (TAEM), approach, landing, and rollout study phases.

The facility contains the following major equipment items: 2 Shuttle flight decks (mockups) with operational displays and controls, 2 digital computer systems, 12 sections of analog computers, a general-purpose visual scene generation system that includes 4 scaled terrain models including Kennedy Space Center recovery runway, a 3-degree-of-freedom (DOF) gimbal model, a pilot/computer-controlled transport system, a closed-circuit television/optics system, and a color projector. A master control console with selected cockpit displays that monitor pilot operations is used to conduct study operations.

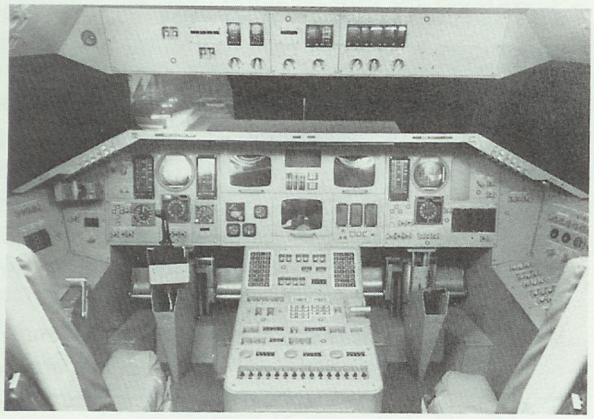
The hybrid computer math models simulate the orbiter 6-DOF equations of motion, environment, the Shuttle airframe, GN&C sensors, actuators (with loads), cockpit display and control functions, and visual display drive equations. These models are solved in near real time at 20-millisecond or 40-millisecond frame times so that pilot response, the vehicle, the sensors, or the solutions of the on-board GPC's are not degraded. The problems are solved in the analog or digital domain as dictated by interface or



Flight Control Hydraulics Laboratory

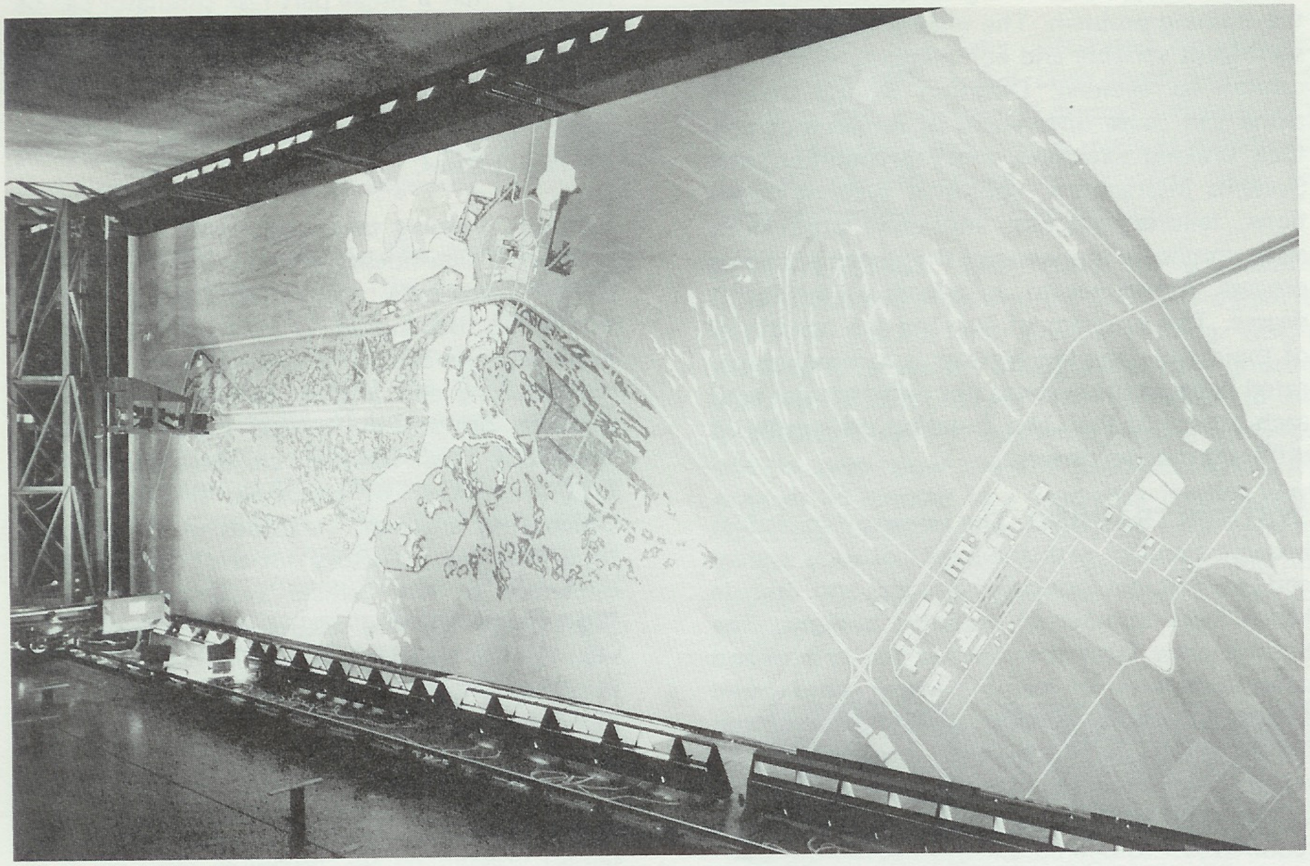
frequency response requirements. The math models are configured to support static or dynamic, open- or closed-loop solutions for point stability and orbiter 6-DOF analyses. The environment math model can be initialized from the landing field, the inertial, or the heading frame of reference and produce enough parameters to define its initialization state fully.

The SIM Laboratory contains two Shuttle flight deck mockups. Each contains the Shuttle orbiter's forward station, consisting of the commander's station, the pilot's station, and the mission specialist's station. The flight decks are interfaced to operate with digital computers in support of math model simulations or ADL/SIM verification/certification tests. The flight decks are configured for mounting a complete complement of simulation displays, controls, and controllers or selected Shuttle prototype displays, controls, and controllers. The Shuttle prototype displays, controls, and controllers are the airspeed/Mach indicator, altitude/vertical velocity indicator, attitude director indicator, horizontal situation indicator, surface position indicator, rotational hand controller, speed brake thrust control, rudder pedal transducer assembly, and multifunction CRT display system. The visual display system provides the pilot with out-the-window scenery. It produces a full-field-of-view color television display in the left forward window.



Flight Deck Simulator

A failure injection system is designed to permit over 9000 accurate, realistic, time-controlled system failures. The failures have been classified into three categories: flight control, guidance and navigation, and data processing system. Approximately 300 failure paths are identified for flight control system failures: they consist of



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aerosurface and line replaceable unit (LRU) failures and discrete failures. The failure capability for each LRU consists of bias, hardover noise, opens, and others. Finally, approximately 230 failures are identified for the guidance and navigation system, consisting of hold, set, zero-bias, noise, and discrete failures.

Crew Training

Crew training for manned spacecraft, and especially for the Shuttle orbiter, is fundamentally different from training for conventional aircraft. In the latter case, the pilot first learns to fly the aircraft under benign conditions; once familiar with the characteristics of the airplane, he proceeds into more stringent missions, eventually extracting the maximum performance from himself and the airplane. In the case of the orbiter, however, the crew and the spacecraft must perform at nearly maximum capability on every flight. The cost of each flight is far too expensive to permit missions solely for training as in the case of conventional aircraft; the crew learns to fly and operate the orbiter only during the mission.

The training program that was set up for the Shuttle flight crews drew heavily from the experience gained over the years in training crews for conventional aircraft and the earlier manned spacecraft. And because the orbiter is both an aircraft and a spacecraft in a single vehicle, the crew must be proficient in handling the vehicle in both operating modes and under normal and abort conditions on every flight—including their very first. Thus, the crews must undergo a comprehensive and intense training program to reach the proper level of proficiency before each flight.

The various phases of the training program begin in the classroom and progress to the fully integrated simulation, or final rehearsal. In planning each step of the training, the nature of the requirement, the conditions to be dealt with, the training variables, and the conditions under which the student must acquire the knowledge were carefully considered. Moreover, the personal traits of each crew member were recognized; a "train to proficiency" philosophy was instilled as a goal rather than an arbitrary number of training hours.

Unfortunately, nontraining variables complicate the training problem. The mission time line is a significant variable and complicating factor that cannot be avoided. Duration of the mission alone can cause differences in rendezvous profiles, braking schedules, entry preparation, etc. Systems interactions, abnormal systems operations, failures, glitches, and crew proficiency also complicate the scope of the systems training process, sometimes to an almost unimaginable degree. The problem of learning the operations of the many complex systems is further complicated because the systems not only interact with each other but they also function differently in different mission phases.

SYSTEMS TRAINING. The astronaut must first become familiar with the basics of each system and its nominal operating modes, and Shuttle has a large number of complex systems. The Shuttle crew faces the task, at the system and subsystem level, of learning many complicated system operations, many of which are controlled by the intricate avionic/computer system. The result is that an unparalleled combination of complex crew hardware/software actions is required just to operate the basic systems.

Despite the fact that the Shuttle systems operations are in themselves complex and the mission variables add to the problem, the basic approach to systems training is quite conventional. Introductory briefings, study guides, manuals, procedures, performance data, and schematics are given to the pilots. They learn by self-study, by classroom sessions, and participation in system design reviews and early engineering simulation programs. Thus, by the time they are ready to start working in the training facilities, they understand the systems and how to operate them.

PART-TASK TRAINING. After the astronaut has developed his individual skills in vehicle operations, he then learns the basics of the various mission phases. Some mission phases that obviously require extensive "part-task" training are launch, launch abort (including the procedurally difficult return to the landing site and the abort once around), entry, terminal area energy management, final descent, and landing. Each of these phases has its own peculiarities and can be taught with a separate simulator. However, there are enough areas of commonality that a single part-task simulator can be used for several phases. In addition, each phase requires a number of Shuttle mission simulator (SMS) training hours with the control center active; therefore, the SMS is capable of simulating all phases.

Part-task training takes place with a full flight crew in a high-fidelity cockpit with closed-loop dynamic feedback and at least partial systems simulation, depending on the particular session. Most sessions call for a crew of two for flight test training and a crew of two or more for missions beyond the orbital flight test phase. Therefore, the training variables expand to include number of crewmen, the manner in which they interact, variations in the mission time line, the trajectory for the phase, and the dynamics of the vehicle systems. The basic flight-phase training occurs at this point; and high-fidelity simulations, specialized and expert instructors, and accurate training checklists are mandatory.

The current baseline training complex includes three primary simulator crew stations for part-task and nonintegrated training. The three devices are the Shuttle procedures simulator (SPS), the orbiter aeroflight simulator (OAS), and the fixed-base SMS.

Shuttle Procedures Simulator. The SPS has a two-man crew station, dedicated instruments, and a cathode-ray-tube (CRT) display system in the cockpit; a visual display system; and a computer complex—all of which are tied together with appropriate interface equipment. It is capable of simulating launch, launch abort, entry, landing, and orbital maneuvering (primarily rendezvous). The SPS also has an actual spacecraft digital computer so that flight software is used to drive on-board displays exactly as they will be driven in flight.

Orbiter Aeroflight Simulator. The OAS is similar to conventional aircraft flight simulators, featuring a moving-base cockpit and the physical arrangement of the actual major components. It also has a motion-base-mounted crew station, a visual display system, a landing-scene image-generating system, a computer complex, and an instructor's station. There is also a visual tie-in to the SPS (which shares the OAS landing model) and a flight computer tie-in to the simulation computer complex. The job of tying a flight computer into this general-purpose complex and making it function to represent a multiredundant on-board system was a worthy challenge for the simulation engineers.

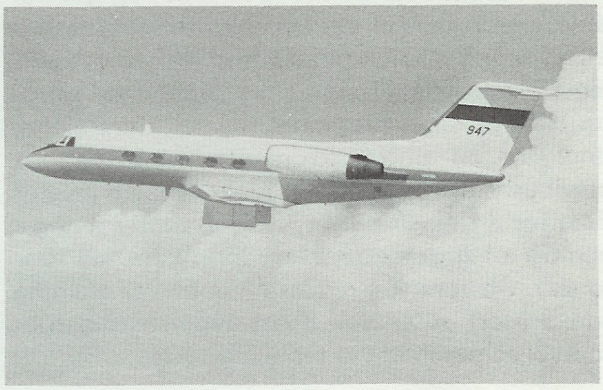
Shuttle Mission Simulator. The SMS features both a moving-base cockpit (the OAS integrated into the SMS system) and a full fixed-base cockpit. The SMS computer complex is greatly expanded in comparison to the OAS system. Basically, it is a series of high-power general-purpose computers with extensive peripheral equipment, input/output devices, and a multiple set of flight computers. This complex of computers performs more than 8 million calculations per second. The unique feature of the SMS complex is its interface with the Mission Control Center, which consists of the hardware and data lines to send telemetry to the Shuttle Control Center and drive ground displays as an actual spacecraft does in flight.

INTEGRATED TRAINING. The SMS functions as a part-task simulator for all mission modes with the ground controllers tied in (integrated training) or without the ground controllers tied in (nonintegrated training). The new variables that occur during integrated training involve a relatively large ground control complex and the necessary telemetry to transmit systems data to the control center. Voice communications, complete with such network effects as no-communication periods, are also simulated. These variables add a major complicating factor because the ground crew is large, the communication network is large and complex, and the simulations—often fraught with failures—are long and arduous.

Present plans do not call for full-duration simulation of Shuttle missions, but it is likely that some relatively long phases will be practiced for the full duration. Long-period simulations covering several days were performed for the Skylab missions and more recently for the joint U.S./U.S.S.R. mission (Apollo-Soyuz). However, it is neither necessary nor practical to simulate missions for the full duration; the last Skylab mission lasted 84 days. Shuttle durations exceeding 30 days are not yet baselined, for a 30-day period is still too long to simulate from beginning to end.

In summary, the fully integrated simulations involve the SMS, a full crew (both flight and ground), and a simulated ground network and control center. Everything is made as realistic as possible because there is no other way to practice manned space flight missions.

SPECIAL-PHASE TRAINING. A specialized type of training unique to the Shuttle program is the final descent and landing training, which involves an unusual training device—the Shuttle training aircraft (STA). The elements to be simulated involve a relatively low-performance vehicle with slow control response, flying an unpowered descent to a dead-stick landing with restricted visibility. The pilot must be in control of the situation during this simulation, and his energy management problem must be solved correctly.



Shuttle Training Aircraft (STA)

Variables include turbulence, winds, possibly adverse weather, vehicle weight and center of gravity, and the control mode to be used. The STA features a flight environment like the environment that actually will be encountered; spacecraft displays and controls like those of the Shuttle; handling qualities that are accurately reproduced; and motion cues, visual scenes, and descent dynamics exactly like those of an actual mission.

The STA has a student seat (left side) that approximates the Shuttle visibility envelope, special aerodynamic devices (such as the side-force generators on the bottom of the aircraft), and simulated avionics (including the side-arm controller and appropriate pilot displays). The student is thus able to simulate the descent fairly accurately. The right seat is for the instructor pilot who monitors the student's performance, the aircraft descent, and his own displays to ensure that the training run does not exceed safe limits.

The unpowered descent of the Shuttle requires an STA or similar device because the pilot task is so demanding. The nominal descent trajectory calls for a rate of descent of 3658 meters (12,000 feet) per minute and a landing flare maneuver at 518 meters (1700 feet) above the runway. At flare and at a descent rate of 3658 meters (12,000 feet) per minute, the vehicle is only 8.5 seconds from the ground. The training task is critical and challenging, but the STA is adequate for the project.

RETRAINING. To reduce training costs for future space missions, more frequent flights are planned for each pilot because it costs less to stay proficient than to become proficient. The Shuttle astronauts of the future will fly several times per year, will use standardized procedures for different mission phases, and will, as a result, require much less training per flight than astronauts of previous programs. Clearly, the training time for an untrained person who has not previously flown a Shuttle flight is much greater than for a trained pilot who is currently flying a number of flights each year (approximately four to six). Obviously, a reduction in overall training and critical simulator hours represents a substantial achievement in reducing costs.

Verification

As in other recent space programs, the design of the Space Shuttle vehicle was verified by a combination of analyses, ground tests, and limited flight tests to prepare for the first orbital flight. Subsonic approach and landing tests of the orbiter have been completed; the first six orbital flights, which will be launched from KSC (Florida), are designated as design, development, test, and evaluation (DDT&E) flights. The seventh flight is designated as the first operational flight.

Since the emphasis is on cost effectiveness in the Shuttle program, extensive studies were conducted to achieve balance in the various approaches to verification. Generally, the extent of planned testing was less than that performed on past space programs. Many verification tests were conducted independently on the orbiter, main engines, external tank, and solid rocket boosters. However, several significant test programs verified the Shuttle's capability for flight operations. Some of the major tests are described below.

GROUND VIBRATION TESTING. A major program requirement was to determine the vehicle's structural modal characteristics and transfer functions. The Shuttle ground vibration tests (GVT's) were a series of vibration tests at different sites. They were unique in that the Shuttle is one of the first space vehicles to utilize a four-body system, which is a departure from the standard or typical cylindrical booster spacecraft launch configuration.

The basic objective of the GVT was to verify the math models that were used to determine the Shuttle analytical structural dynamic characteristics over the frequency range of interest (0 to 40 Hz). The objective was accomplished by obtaining verification data from modal surveys and transfer function measurements. As in all such programs, the difficulty was in duplicating the flight constraints and environment. Therefore, data from modal surveys of representative configurations were obtained from ground tests to validate math models, which are in turn used to calibrate flight modal characteristics.

The first major test was the orbiter horizontal GVT (HGVT), which comprised two subtests, soft- and rigid-mounted. The test was conducted at Rockwell's Palmdale, California, manufacturing and test facility to acquire orbiter modal characteristics for both free flight (using a low-frequency or soft suspension system) and mated test conditions (using rigid links). Aerodynamic flight control frequency response data also were acquired during the soft GVT. The first full-scale flight orbiter (Orbiter 101) was used for this test.

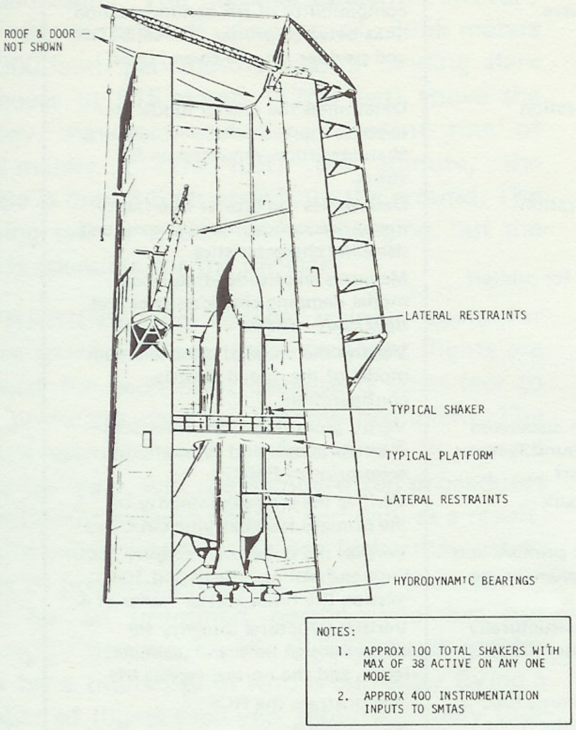
The second major test was the quarter-scale-model GVT, conducted at Rockwell's Downey, California, facility. This test utilized models of the orbiter, external tank, and three sets of solid rocket boosters. Subtests consisted of influence coefficient tests on each element, individual element tests, combined tests of the orbiter/ET for various tanking levels (to simulate several

Integrated Ground Test Program

Test and Location	Configuration	Purpose
Shuttle Avionics Integration Laboratory (SAIL) (JSC)	Orbiter 101 avionics hardware for ALT phase; Orbiter 102 avionics plus mated elements avionics hardware/simulations for OFT phase	Verifies functional performance of Shuttle-integrated avionics system (orbiter, SSME, ET, SRB, payload) and validates selected LPS software programs.
Electronics Systems Test Laboratory (ESTL) (NASA Task 501) (JSC)	Prototype hardware (Orbiter 101) for ALT support; flight equivalent hardware (Orbiter 102) for OFT support	Validates system design and verifies compatibility of RF communication links between orbiter, TDRS, STDN, and payload on end-to-end basis.
Ground vibration test		
Horizontal hard mount (Palmdale)	Orbiter 101 in pre-ALT configuration	Determines the orbiter modal frequency, mode shapes, and damping characteristics—mounted on ET struts.
Horizontal soft mount (Palmdale)	Orbiter 101 in pre-ALT configuration	Determines the orbiter free-free modal frequency, mode shapes, and damping characteristics.
One-quarter-scale model (Downey)	One-quarter scale replica model for orbiter/ ET and SRB	Measures amplitude—frequency modal damping characteristics and rigid body modes.
Full-scale mated (MSFC)	ET/SRB/Orbiter 101	Verifies the coupled dynamic math model of the mated Shuttle configuration.
Umbilical systems verifications (LETF) (KSC)	Flight-to-ground umbilicals with associated flight vehicle skin panels and ground systems (i.e., swing arms, tail service mast)	Verify ground-to-flight interfaces in performance and compatibility areas prior to FMOF.
Structural test article (ET) (MSFC)	LO_2 tank, LH_2 tank, and intertank	Verifies the strength integrity of the primary load-carrying structure.
Structural static/fatigue (Orbiter) (Palmdale)	Airframe structure, including all primary and selected secondary structures; generally, no systems	Verifies the structural integrity for limit and ultimate loads and 100-mission life times scatter factor of 4.
Static structural test (SRB) (MSFC)	SRB short-stack configuration—structurally flight-type vehicle with four center motor segments eliminated	Verifies structural integrity for critical design limit and ultimate loads, and the normal service life.
Forward RCS static firings (WSTF)	Consist of structure and components functionally configured to represent the flight article.	Demonstrate the RCS performance.
MPTA (NSTL)	Three main engines + flight-weight external tank + flight-weight aft fuselage, interface section, and a boilerplate mid/forward fuselage truss structure	Verifies MPS performance and compatibility with interfacing elements and subsystem.
OMS/RCS static firings (WSTF)	Consist of flight-weight primary and secondary structures. Flight-weight qualifiable components functionally configured to represent the flight article	Demonstrate OMS/RCS performance.
ECLSS (JSC)	Boilerplate test article—complete ECLSS, partial avionics, crew equipment, airlock	Verifies ECLSS integrated operations and performs manrating of ECLSS for FVF (8 psi); verifies airlock performance.
Flight readiness firing (KSC)	First Shuttle vehicle Orbiter 102 Flight external tank Flight SRB's	Performs unmanned SSME firing at completion of the first wet countdown demonstration test. Final verification of flight and ground systems prior to FMOF. Performed one time only.

boost conditions), and combined tests of the orbiter/ET/SRB for lift-off, maximum dynamic pressure, flight conditions, and SRB burnout. SRB models filled with various quantities of inert propellant were used. Objectives of the quarter-scale program were to determine modal characteristics and compare math modeling and modal analysis results with actual test data.

The final major test was the mated vertical GVT (MVGVT), which consisted of five subtests of full-scale hardware. This test was conducted at MSFC in Huntsville, Alabama, to determine modal characteristics and frequency response characteristics at the guidance and control sensor locations. One series of subtests utilized Orbiter 101, which was also used for HGVT, and an ET loaded with three different levels of water in the LO_2 tank to simulate different propellant loads. A set of empty SRB's was added to simulate SRB burnout; and a set of SRB's, full of inert propellant, was utilized to simulate lift-off. All of these articles will be refurbished and later used in the flight program.



Mated Vertical Ground Vibration Tests

APPROACH AND LANDING TESTS. The Shuttle orbiter has been described in the following manner: "It is launched as a rocket, orbits the Earth as a spacecraft, and returns as a powerless aircraft to a runway landing." The approach and landing test (ALT) program was conducted to verify the capability of the orbiter to operate in the latter mode after entry and transition to subsonic flight. The program consisted of a series of steps leading to the demonstration of the orbiter's capability to approach and land safely under conditions similar to those planned for the final phases of an orbital flight. The tests were conducted with the orbiter mounted on a specially modified Boeing 747 carrier aircraft.

The primary objectives of the ALT program were as follows:

1. Verify orbiter's subsonic airworthiness, integrated systems operations, and selected subsystems operation for first orbital flight.
2. Verify the orbiter's pilot-guided approach and landing capability.
3. Verify the orbiter's subsonic automatic terminal area energy management/automatic landing capability.
4. Verify the orbiter's capability to approach and land safely in selected gross-weight/center-of-gravity configurations within the operational envelope.

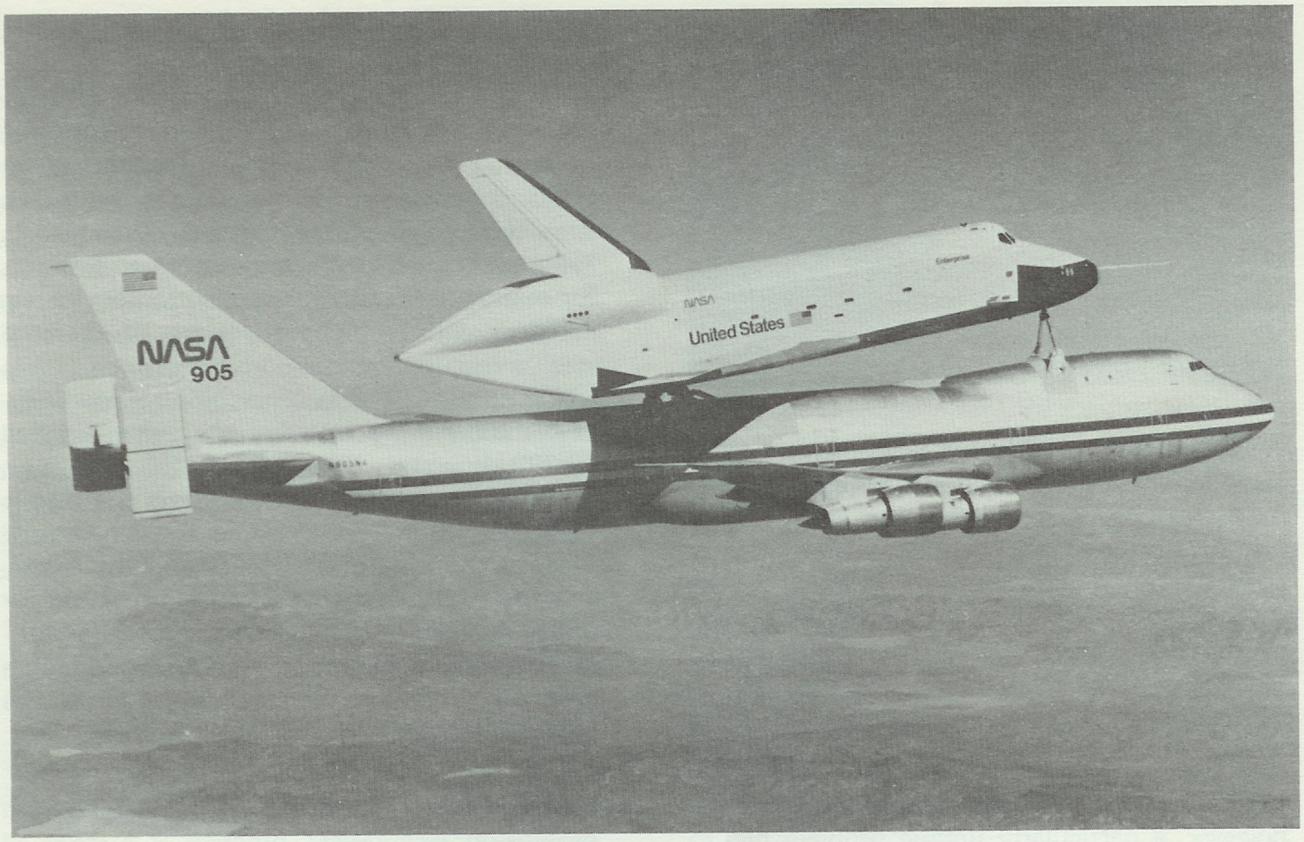
These objectives were accomplished by flying well within the flight envelope and extrapolating the results to the limits of the flight envelope.

There were a total of 13 flights in the ALT program. Five were unmanned "captive" flights with the orbiter—its systems inert—mated atop the 747 Shuttle carrier aircraft (SCA). Three manned captive flights followed with an astronaut crew aboard the orbiter (still attached to the SCA) operating its flight control systems. Finally, there were five "free flights" in which the astronaut crew separated the spacecraft from the SCA and flew it back to a landing.

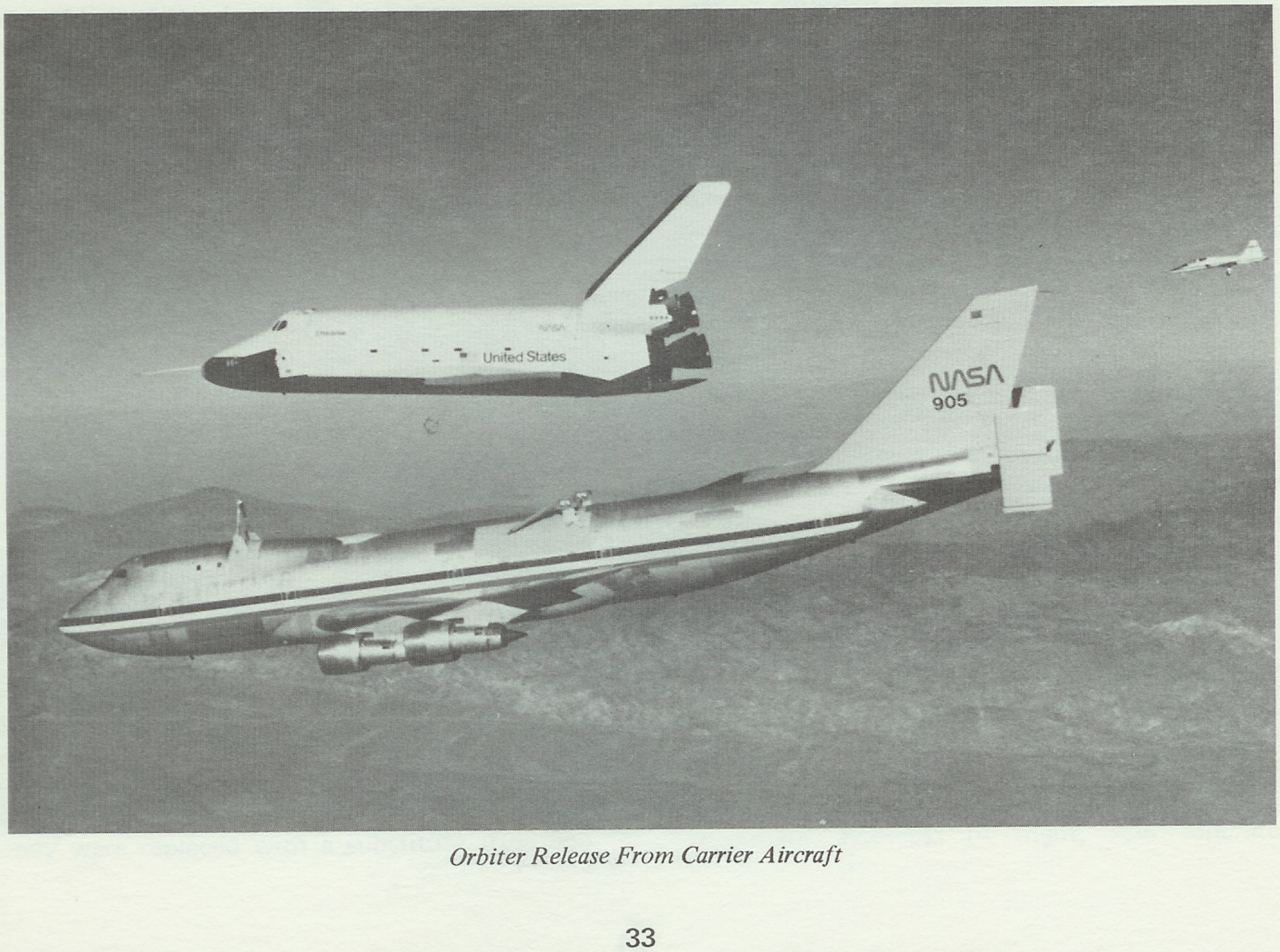
During the taxi tests of the mated SCA/Orbiter 101, structural loads and responses were determined and the mated capability for ground handling and control characteristics up to flight take-off speed were assessed. The taxi tests also validated SCA steering and braking.

The five unmanned orbiter flights tested the structural integrity and performance handling qualities of the mated craft. The manned captive active flights exercised all systems in the flight environment in preparation for the orbiter release (free) flights. These flights included flutter tests of the mated craft at low and high speed, a separation trajectory test, and a rehearsal for the first orbiter free flight.

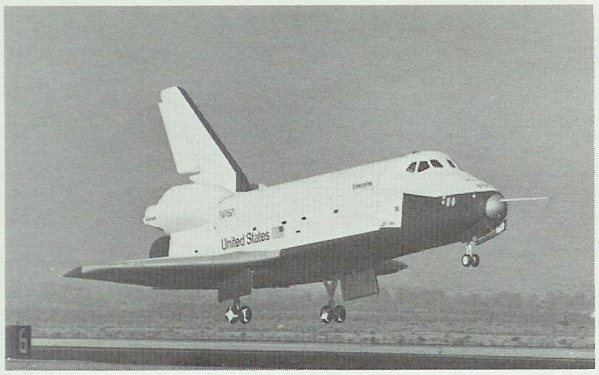
The free flights verified the orbiter's pilot-guided approach and landing capability, demonstrated its subsonic auto terminal area energy management and autoland approach capability, proved its subsonic airworthiness, and validated integrated system operation and selected subsystem operation in preparation for the first manned orbital flight. These free flights demonstrated the orbiter's capability to approach and land safely with a minimum gross weight and several center-of-gravity configurations within the operational envelope.



Mated Shuttle Carrier Aircraft and Orbiter



Orbiter Release From Carrier Aircraft

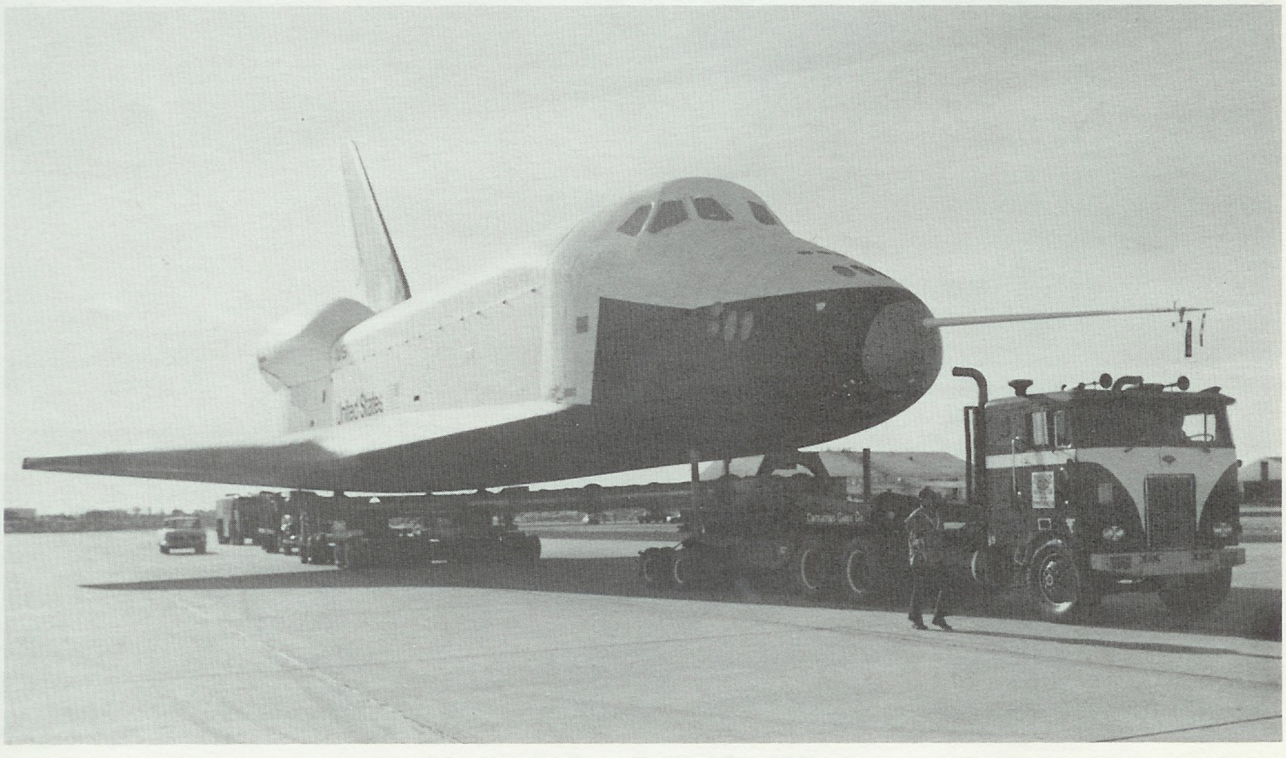


Orbiter Touchdown

Upon completion of additional "ferry" flight tests, in which the orbiter was mated in a lower drag attitude, Orbiter 101 was returned to NASA at Dryden Flight Research Center (DFRC) for modification in support of the vertical ground vibration tests at MSFC, which started in late May of 1978. After being ferried to MSFC, the orbiter was mated with an external tank and solid rocket boosters for a nine-month series of tests.

Before the ALT program could be initiated, however, a particularly unique problem had to be solved. The orbiter final assembly facility is located at the Rockwell plant in Palmdale, California; but the massive fixture used to mate the orbiter and the Boeing 747 carrier aircraft is installed at DFRC at Edwards Air Force Base, some 58 kilometers (36 miles) away. The fixture was located at DFRC to support the initial series of orbital flights in which the orbiter lands at Edwards and is then ferried back to the launch sites. After the orbiter had been assembled in Palmdale, it had to be transported to Edwards for mating to the SCA. A special transporter was designed with a Y-shaped frame structure of steel and aluminum supported on three dollies and a total of 90 tires. The complete assembly, with the orbiter mounted on the frame, weighed 99,792 kilograms (220,000 pounds) and, with its standard truck tractor, was 37 meters (120 feet) long. Police cleared a two-lane road through the city of Lancaster and the desert, and the Army Corps of Engineers arranged for utility companies to move telephone and electrical lines before the move. The Corps also built a new 12.9-kilometer (8-mile) road across the desert to provide easier access to Edwards.

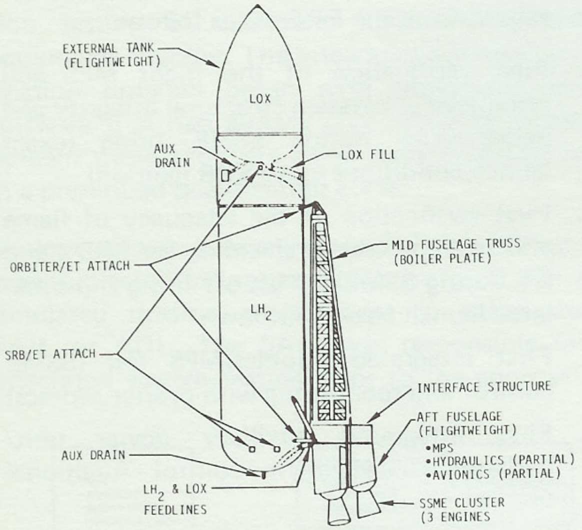
MAIN PROPULSION TEST. The ongoing main propulsion test (MPT) program is a series of cryogenic tankings and static firings designed to integrate and evaluate the functional integrity and performance of the main propulsion system



Orbiter Ground Transporter

(MPS), which includes interfacing orbiter subsystems, clustered Space Shuttle main engines (SSME's), the external tank (ET) and associated ground support equipment (GSE).

The MPT program is designed to satisfy two principal test objectives: to demonstrate main propulsion system performance and compatibility with interfacing elements and subsystems, and to investigate off-nominal conditions and verify design changes. These two overall objectives encompass many more specific objectives, involving each element and subsystem that contributes to the test program. The MPT program is being conducted at the National Space Technology Laboratories (NSTL) in Mississippi with a modified Saturn S-IC test stand.



Main Propulsion Test Article

System/Subsystem Verification. Verification of the main propulsion system and associated subsystems to support flight readiness firing (FRF) and the first manned orbital flight (FMOF) dictated that primary functional hardware used in the test approximate the flight configuration as closely as possible. To carry out this objective, a flight-weight external tank was mated in the test stand with simulated orbiter test article.

The simulated orbiter had a flight-configuration aft fuselage structure with a substitute covering in place of the flight thermal protection system for ground test acoustic fatigue protection. Since the forward and mid-fuselage structures of the orbiter were not functional for this test, they were replaced with a substitute truss and interface section. A flight-configuration MPS with three flight-configuration SSME's was mounted in the aft fuselage. The portion of the flight hydraulic system associated with SSME valve control and thrust vector control (TVC) servoactuators for engine gimbaling was included in the aft fuselage; ground support equipment (GSE) supplied hydraulic power to drive these systems. One ground computer, the Shuttle avionics test set (SATS) controlled the avionics and monitored functions for the test in place of the five orbiter flight computers. Also included in the aft fuselage was a flight purge, vent, and drain system that must operate during tankings and firings for aft compartment conditioning.

The external tank was a complete flight-weight tank with provisions for the auxiliary drain, vent, and pressurization systems that are required for safety reasons. The structural connections between the tank and the simulated orbiter were flight hardware, except that pyrotechnic devices used for in-flight separation were not included.

Unique Shuttle Propulsion Problems. The Space Shuttle has some unique design features that impose unusual requirements on the major propulsion systems test compared to previous programs. The first major difference is the externally mounted tank. In past static firing programs, the vehicle was held in the test stand in the aft region, close to the main propulsion system being tested. The Shuttle MPT article is held in the stand at the forward and aft SRB attach points on the ET to approximate more closely the dynamic responses of flight and facilitate investigation of any pogo that might be present in the design. To evaluate tank feed-out characteristics, the test article is canted 9 degrees in the test stand to approximate the angle of attack at propellant depletion in flight. Holding the test article so that all thrust loads go through the ET, as in flight, and canting the test article at 9 degrees in the stand have created analytical problems never encountered on prior programs.

Another unique design issue is the close spacing of the engines in the aft end of the orbiter. In flight, engine collision is prevented by the flight control system logic. For the MPT article, a different approach is used due to lack of redundant avionics. In flight, four separate computer systems protect against erroneous TVC commands; but on the MPT article, there is only one command computer. Therefore, each engine on the test article has external mechanical stops on critical actuators to limit engine travel. In addition, the SATS computer has software programs to check engine position versus TVC commands to prevent collision. When sufficient static firing operating confidence is gained, the mechanical stops will be removed, placing SATS in total control.

SEPARATION SYSTEMS VERIFICATION. During boosted flight, there are two separation functions. The first takes place at solid rocket booster burnout when the boosters are jettisoned. The retention struts attached to the forward and aft ends of the external tank are severed, and separation velocity is provided by small solid-propellant rocket motors mounted in the forward and aft ends of the boosters.

The second separation, which takes place after main engine shutdown (just prior to orbital insertion), consists of jettisoning the external tank from the orbiter. The separation is in three parts: (1) the umbilical assembly between the orbiter and tank is hydraulically retracted, (2) explosive bolts in the forward and aft attach fittings are fired, and (3) separation velocity is imparted to the orbiter by the firing of reaction control system (RCS) engines.

Early in the Shuttle program, the scope of the separation test program was analyzed to define the most cost-effective approach. As a result of this study, a decision was made not to conduct full-scale all-element separation tests but to conduct a series of tests at the subsystem or component level. These tests, in combination with wind tunnel and math-model analyses and use of mockups, were presumed sufficient to ensure proper in-flight separation verification.

FLIGHT READINESS FIRING. The final step in the Space Shuttle system verification before the first DDT&E flight is a static firing of the Space Shuttle main engine with mated flight vehicle elements in as near as possible a flight configuration attached to the mobile launch platform (MLP) on the launch pad at Kennedy Space Center. The flight readiness firing (FRF) will be conducted as part of the countdown demonstration test for the first Shuttle manned vertical flight.

In previous space and missile programs, static firings and integrated flight control and propulsion tests were conducted at a test site before the vehicles arrived at the launch sites. However, because of the unique design and many elements of the Shuttle, all flight systems (propulsion, flight control, and avionics) will not be integrated until final mating at the launch site. Although each element and subsystem of the Shuttle goes through development and verification testing—including a main propulsion system test utilizing a flight ET and orbiter aft fuselage with SSME's—the total integrated system will not be available until the vehicle is mated at the launch pad. Two other important factors necessitate a flight readiness firing: (1) no unmanned Shuttle flights are scheduled, and (2) there is no facility checkout vehicle. Specific objectives to be realized from the FRF are as follows:

1. First verification of the flight MPS and associated subsystem structural integrity and performance during SSME firing (exact launch conditions up to SRB ignition)
2. First verification of the adequacy of flame and heat protective shielding for SRB's and ET during SSME pre-lift-off firing and simulated launch abort shutdown
3. First integrated avionics/MPS test (SSME control and monitoring with orbiter avonics)
4. First integrated auxiliary power unit/hydraulics/SSME/flight control functional test
5. Additional verification of prelaunch servicing procedures and countdown time lines
6. Additional SSME cluster firing data to verify first flight vehicle MPS predicted performance

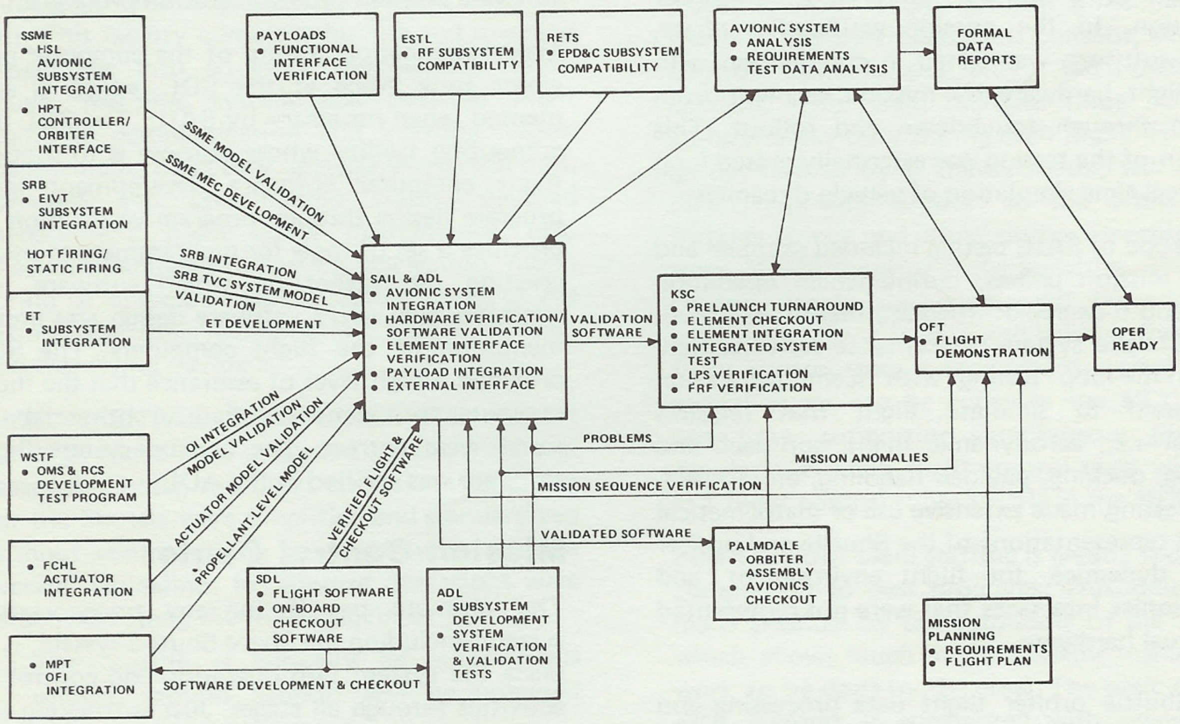
The FRF will be conducted with an unmanned orbiter. Additional switch control functions are provided in the orbiter for ground control through the launch processing system (LPS) that would not be required for a manned FRF. These additional ground control functions, plus a modified flight software program, allow the Shuttle MPS to be tested at the launch pad with the vehicle configured for flight. The SRB's and flight control systems will not be activated for the FRF; however, SRB ignition commands and SRB hold-down release signals will be verified. The orbiter T-O umbilicals and the ET lift-off umbilicals will remain connected during the

20-second firing of the MPS. The orbiter's orbital maneuvering subsystem (OMS) and the forward and aft reaction control system (RCS) will not be activated during FRF. OMS and RCS propellant will not be loaded. Orbiter flight control commands will be exercised during the 20-second firing. At the termination of the firing, the three SSME's will be sequencially shut down to simulate a prelaunch shutdown. Following the postfiring securing, a vehicle inspection and data analysis will be conducted; and the vehicle will be reconfigured and prepared for the first vertical flight.

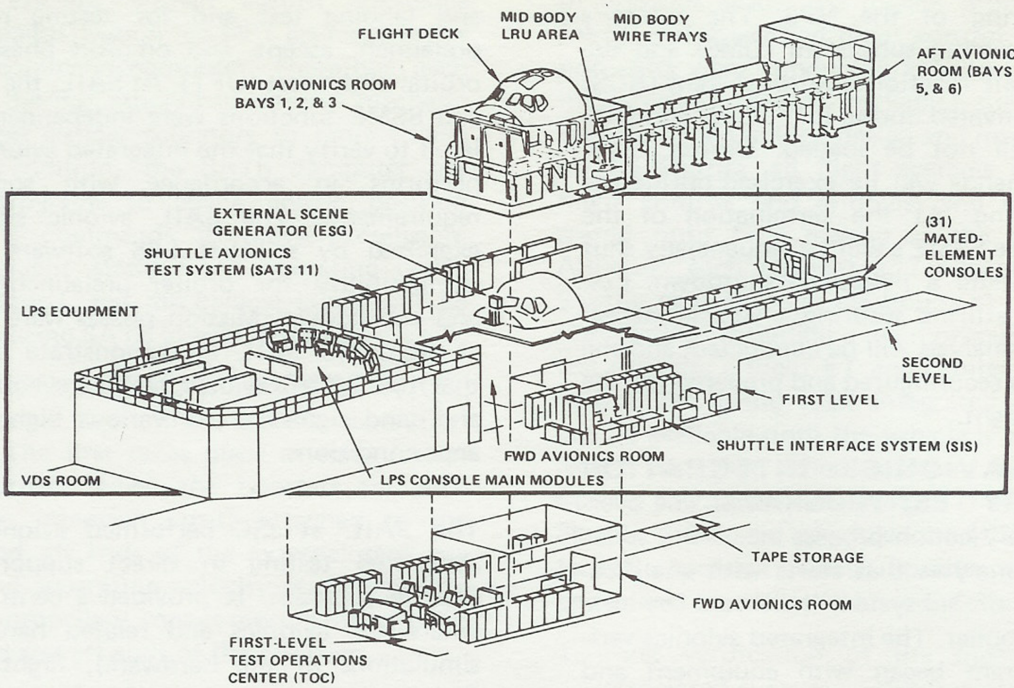
SHUTTLE AVIONICS INTEGRATION LABORATORY TEST PROGRAMS. The overall avionics verification process includes a series of tests and analyses that starts with qualification testing of subsystem hardware by the equipment supplier. The integrated avionics verification program began with equipment and software that had already completed the development cycle and were either fully qualified or in a prescribed qualification cycle.

Various avionic subsystems and flight software were subjected to integrated system testing in a simulated mission environment in either the SAIL or ADL. The SAIL was responsible for integrated system testing prior to the approach and landing test and for testing related to prelaunch, ascent, and on-orbit phases of the orbital flight test (OFT). At SAIL, the SRB, ET, and SSME functions were independently simulated to verify that the integrated avionic system performs in accordance with specification requirements. The SAIL avionic system was exercised by selected LPS software to verify compatibility for orbiter prelaunch checkout and countdown. Mission phases were simulated at ADL and SAIL to demonstrate and verify that the GN&C avionic hardware could receive and send signals under various flight performance conditions.

The SAIL at JSC performed avionic system integrated testing in direct support of the Shuttle program. It provided a central facility where the avionics and related hardware (or simulations of the hardware), flight software flight procedures, and associated ground support equipment were fully integrated for testing. The ultimate aim of the SAIL was to operate a complete avionics configuration of each orbiter flight or mission before actual flight. The laboratory provided for the verification of all avionics interfaces between the orbiter and the following Shuttle program elements: ET, SSME, SRB, LPS, and the payload.



Avionics Verification Activity Relationships



Shuttle Avionics Integration Laboratory

The primary SAIL test phases consisted of systems integration and mission verification. In the systems integration phase, the various avionic subsystems, including mated-element avionics, were tested in an end-to-end, open-loop fashion. The system test configuration was initially single GPC/multisensor and ultimately evolved to a full-up, multi-GPC/multisensor operation. In the mission verification phase, flight software was tested in conjunction with the flight hardware by mission segment from launch through touchdown and rollout. This portion of the testing was essentially closed-loop with real-time simulation of vehicle dynamics.

The scope of SAIL testing included nominal and abort mission phases, during which open-loop tests and 6-degree-of-freedom, real-time, closed-loop Shuttle system performance were verified. Man-in-the-loop testing with scene generation was used to simulate flight that requires control—i.e., aerodynamic flight, approach and landing, docking, payload handling, etc. Closed-loop testing made extensive use of mathematical model representations of the Shuttle and orbiter flight dynamics, the flight environment, and nonavionics interfaces that were not represented by actual hardware.

The Shuttle orbiter flight data processing and software subsystem was verified primarily in the Software Development Laboratory (SDL) by means of computer simulations. Validation and certification were performed in the SAIL, where the flight computer program operated with the actual hardware. The analysis effort consisted of an examination of the functional requirements to support development of the required test software and computer simulation programs.

Major verification testing of the computer programs took place at the SDL, which is augmented when necessary by SAIL. The SDL is a computing facility whose purpose is to support flight computer software development from program design through program verification. It provides a set of tools for programmers to use in creating the means by which software test engineers can verify software design and implementation of the flight computers. The SDL provided a high level of assurance that the flight computer programs supplied to other laboratories were correct. The backup system flight software was verified in the ADL.

Mission Control Center

The ultimate payoff for any transportation system, including the Space Shuttle system, is to place the system into operation and control its activities through all stages. Just as trucking and taxi system operators have their dispatchers to follow the individual units, the Shuttle system has the Mission Control Center for directing and monitoring real-time operations. It is staffed with specialists representing each system function.

During the past decade, three major (American) manned space programs were completed. These programs, although different in goals and scope, were similar with regard to operations philosophy and approach. Each program involved costly, though essential, ground and flight operations support. To achieve the Shuttle program goals of low-cost operations combined with convenient and responsive service to users, a new approach was necessary. The large numbers of men and women needed to monitor and control all phases of the flight mission during the Apollo and pre-Apollo days are well known. The maturation of the space flight program enables the number of staff personnel for real-time operations to be substantially lower than for previous manned programs. At the same time, through extensive application of automated computing equipment, these few people will be able to monitor the progress of the mission, orbiter, crew, and payloads to a greater extent than in prior programs.

The Mission Control Center (MCC) is the central control point for the Space Shuttle from launch through orbital flight, entry, landing, and rollout. This facility combines human and machine capabilities into an extremely flexible, interactive, real-time system that provides flight planning, communication and instrumentation management, trajectory analysis and prediction, software and consumables status, payload management, flight safety maintenance, test, checkout, guidance, targeting, navigation, monitoring of on-board systems, and control of the orbiter, the other launch systems, and attached and free-flying payloads.

FUNDAMENTAL GUIDELINES. To support the high flight rates proposed for the 1980's at reasonable costs, the flight operations functions for the Shuttle were simplified and standardized without compromising crew safety or mission success. Guidelines for Shuttle operations were established along the following lines:

1. The Shuttle is basically an autonomous vehicle; ground support will be provided only on an exception basis.
2. Standard flight packages will be developed. These packages can be used for multiple Shuttle launches and will require only a minimum amount of new trajectory data.
3. Procedures will be standardized to apply to as many types of Shuttle flights as possible. Noncritical system failures will not be dealt with in real time.
4. Normal planning will stay well within the established performance and capabilities of the Shuttle system. Thus, the intensive planning that was necessary in past programs will be avoided and user costs will remain low.
5. Systems management will now be the primary responsibility of the flight crew. Real-time ground systems support will be limited to that needed by the flight controllers to stay abreast of the mission.

In contrast to past programs, ground support now evaluates only those failures that reduce vehicle redundancy below the level required to continue the flight. Failure analysis is provided only for cases involving crew safety. Planning support for upcoming flights is the primary work of the ground crew. The new Shuttle ground support is built upon the three teams described below.

Flight Control Team. Of the three basic elements in the new operations concept, the flight control team is the only "flight-dedicated" element. This team includes three shifts for 24-hour-a-day duty during each flight. This small group, headed by a flight director, will provide direct, real-time support to the orbiter crew through launch and entry; during on-orbit operations, it will monitor flight activities. The flight control teams are augmented by additional specialists during launch and landing. Since each flight control team is dedicated to a single flight, several teams can be active in the MCC at any one time, supporting simultaneous flights or simulations. Each flight control team will work in a flight control room (FCR) in the MCC.

Flight control team staffing is greatly reduced in comparison to past programs. This reduction is made possible by the autonomy of the Shuttle, which allows much of the systems management work to be done by the crew. The basic on-orbit FCR support is augmented with systems and trajectory experts for the launch, entry, and landing phases. Following the on-orbit stabilization of Shuttle systems and trajectory condition, the launch team support will terminate and the on-orbit team will continue support.

For launch, entry, and landing phase support, the FCR team is composed of the following:

Flight director
Communications systems engineer
Environmental/consumables/mechanical engineer
Flight computer systems engineer
Avionic systems engineer
Propulsion systems engineer
Flight dynamics officer
Trajectory officer
Flight activities officer (if required, he will act as crew communicator)
Public affairs officer

The on-orbit team consists of the following:

Flight director
Communications systems engineer
Flight activities officer
Payload officer

Multipurpose Support Team. The second element in the new operations concept is one of major importance—the multipurpose support organizations. Each of these multipurpose teams will represent one support discipline and will handle planning and support functions.

The primary job of the these teams is to plan operations for upcoming flights under the direction of the planning and operations management team (POMT). A secondary function is to provide real-time support to flight control teams. Staffing includes personnel for the following disciplines:

Guidance and propulsion
Avionic systems
Main propulsion system
Main engine control
Orbital maneuvering subsystem/reaction control subsystem
Controls (flight control system)
Sensors
Data processing system
Environmental, mechanical, and electrical systems; the four positions and their responsibilities are as follows:

1. Electrical power system: fuel cells and electrical power and distribution system
2. Auxiliary power unit/hydraulics: structural and mechanical systems, landing systems
3. Thermal: atmospheric revitalization system H_2O loops, active thermal control system, and structural temperature
4. Life support: waste management system; potable H_2O system; purge, vent, and drain systems; food management; extravehicular activity and airlock; power reactant supply and distribution; active repressurization and pressure control system; and ventilation systems

Payload support systems
Natural (earth) environment support
Crew activities support
Configuration/logistics support
Trajectory and flight design
Ground data systems
Flight data management
Assistant for flight data requests

Planning and Operations Management Team. The POMT performs the vital function of managing the JSC Shuttle Payload Integration and Development Program Office (SPIDPO). The POMT is responsible for the detailed development, planning, scheduling, and statusing of all Shuttle flights. Staffing for the POMT includes the following positions:

STS operations director
Communications/data manager
Shuttle flight status manager
Payload integrator
Headquarters representative
Ground data systems manager
Crew activity integrator
Public affairs officer
Training officer
Flight design and scheduling manager
Department of Defense (DOD) representative
Medical representative
SPIDPO representative

COMPUTER COMPLEX. The MCC contains a number of different processing systems, many directly associated with Shuttle operations and others only peripherally associated with ongoing mission operations. The computer complex is divided by function into three areas: (1) the communication interface system, (2) the Shuttle data processing complex, and (3) the display control system.

Communication Interface System. The communication interface system is the MCC door for the three support teams to and from the outside world. During Apollo and Skylab, data, voice, and television were routed to and from MCC and the spacecraft via the Goddard Space Flight Center in Greenbelt, Maryland. Goddard runs the NASA communications network, which links the tracking stations with the various NASA control centers (MCC in Houston, Texas, and the Jet Propulsion Laboratories in Pasadena, California). The Shuttle era is the beginning of a new communications philosophy for manned spaceflight. With the tracking and data relay satellite, the numerous remote-control facilities for attached and detached payloads, and the simultaneous uplink and downlink of engineering and scientific data to different sections of the orbiter, a new method of data routing will be implemented. The communication interface system gives the MCC great flexibility for communications routing. It is like a combined television, facsimile, voice, teletype, and video switchboard—all programmable.

Shuttle Data Processing System. The Shuttle data processing complex processes communication, command, trajectory, and telemetry data. This complex is one of the most sophisticated real-time systems in use. Command and control functions of the SDPC consist of a set of four application programs, totaling about 600,000 lines of programming. These programming lines are the computer instructions that translate the telemetry data streaming into the MCC into meaningful information to be used by the flight controllers. Typically, the data are identified, broken out of the telemetry code form, and then put into one of thousands of formulas stored in the computer. The formulas integrate the incoming data and compare them with limits or desired values. Hours of manual math problems are calculated within hundredths or thousandths of a second. The ground controller sees information about things that are happening at that very moment; hence, the computers are said to operate in "real time."

Display Control System. The display control system provides the link between the information being processed in the computer complex and the presentation of that data on strip chart recorders, scribing plot boards, event lights (similar to the warning lights on autos), and the digital television system (which represents information in tabular or other form on television "pages" or channels). The display control system operates so that console operators can request information and specify the manner in which it is presented.

Most of the data are available on the digital television system, which accounts for most of the equipment in the control system. The digital television system converts the data into alphanumeric symbols arranged in predetermined formats on a 945-line scanning television system. This system is similar to that used by the commercial television networks to present election tabulations, although the MCC system has a higher resolution and, therefore, is capable of reproducing smaller (hence, more) numbers and letters with its greater scanning capability (945 lines versus 525 lines for the U.S. standard color system). The display control system is also used to reconvert spacecraft color television images into a format that can be used on the home television screen. It also converts certain 945-line computer channels into regular 525-line format.

EXTERNAL INTERFACES. Real-time interfaces for operations and planning with various organizations external to JSC are required throughout the Space Shuttle operations phase. The following agencies and locations are included in the interface network.

Launch sites: The launch sites at KSC and Vandenberg Air Force Base will provide the Shuttle trajectory and flight design multipurpose support room (MPSR) with site, vehicle, and launch schedule status information from which MCC and line organization personnel can determine the impact on overall planning/operations.

Landing airfields: The Trajectory and Flight Design MPSR representatives will maintain liaison with all landing airfields (primary, secondary, and contingency) to maintain current airfield configuration and support capabilities as they relate to Shuttle operations planning.

Department of Defense: The DOD will obtain authority for use of military airfields, facilities, and ground support. It will obtain military aircraft and ship support for logistics, special studies, and search and rescue operations.

Federal Aviation Agency (FAA): The FAA must be kept advised of flight status. The FAA will provide airspace reservations for the orbiter and carrier aircraft over the United States and act as the interface with the International Civil Aviation Organization (ICAO) for airspace reservations over international waters.

State Department: The State Department coordinates support from foreign countries pertaining to orbiter landings on foreign soil and overflight clearances over foreign soil for logistics aircraft.

Network Operations Control Center: The Goddard Space Flight Center Network Operations Control Center (NOCC) will be the focal point for space tracking and data network (STDN) support. STDN management, scheduling, and voice/data interface will be controlled by the NOCC.

U.S. Coast Guard: The Configuration and Logistics Support MPSR representatives will maintain liaison with the U.S. Coast Guard in case search and rescue operations require its support to locate an orbiter.

WHERE DO WE GO FROM HERE IN SPACE?

When the Space Shuttle begins to fly its missions, it will bring about significant changes in the way we operate in space. As a transporter, it will reduce the cost of getting into space to more affordable levels and on a routine service basis. As a service system and an experimental platform, it will permit, for the first time, space workers to position and assemble large elements that have been launched together or separately; materials may even be fabricated in space. The Shuttle will, of course, provide opportunities for greatly expanded experimentation on orbit with relatively low-cost instruments and/or laboratories and without the need to develop satellites to carry them.

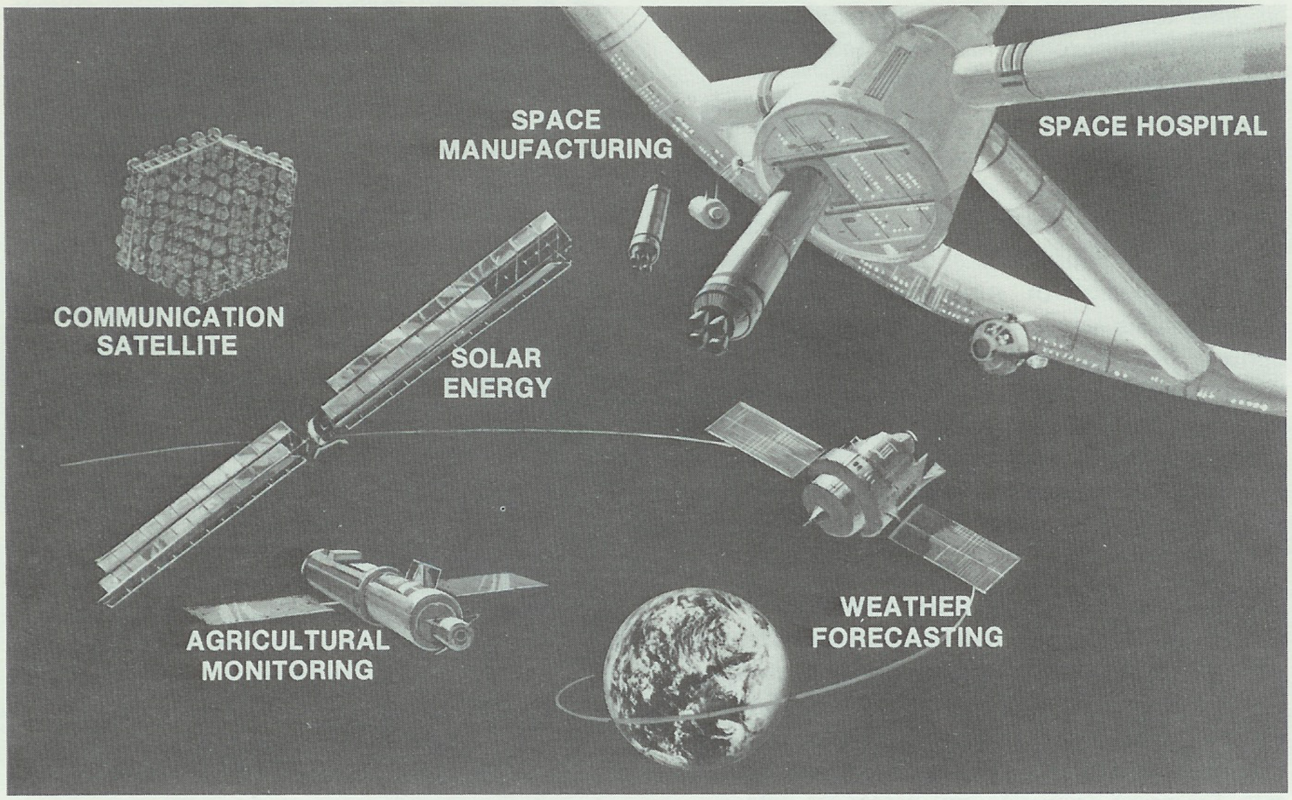
The Space Shuttle is a first step into future space programs and it is the key to providing large-scale benefits from space through economical transportation. The program for the first decade of Shuttle operations should, therefore, plan to exploit the Space Transportation System to the maximum extent possible in all areas—scientific, industrial, and general technology advancement.

The scientific community is considering the economy offered by Shuttle launches for continuation of its investigations in physics, astronomy, life sciences, and the solar system. The Shuttle/Spacelab pallets and free flyers will add greatly to the ability to do scientific work in space. This work will be facilitated by the presence of scientists and technicians in orbit made possible by Shuttle and by the ability to return these scientific facilities to earth for modification and possible reuse. The space telescope will be among the first of the new generation of automated free flyers to be delivered, maintained, and retrieved by Shuttle.

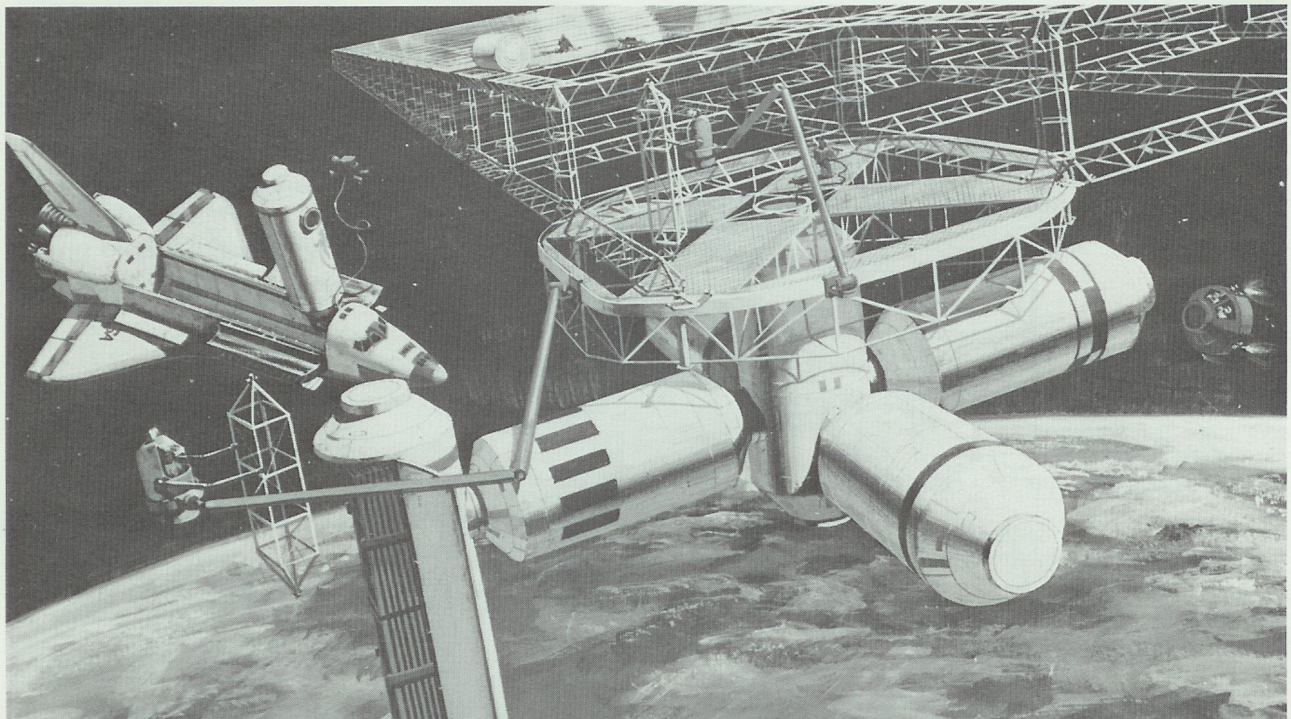
To support industrialization missions, the power and duration capabilities of space systems must be extended. The 1980's should witness the development of expandable solar power modules that use thermal and direct conversion cycles; large space structure assembly and construction technology; jigs, fixtures, tools, and extravehicular activity systems; plus the training, other special equipment, and facilities needed for people to live and work in space. As part of this effort, the capability to conduct manned operations in geosynchronous orbits should be developed.

Extended Shuttle Usage

Shuttle-supported systems in this first decade can expand into platforms assembled in space, initially attached to Shuttle, and then be



Future Space Programs



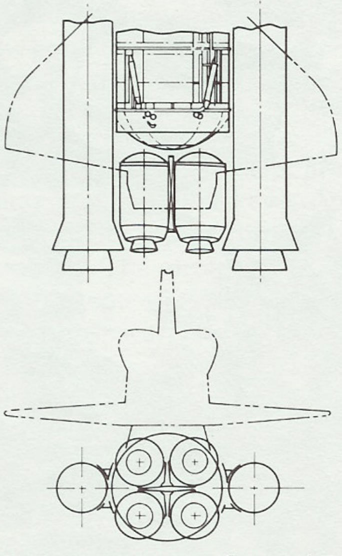
Large Space Structures

grouped together to form mission modules for flexible, multipurpose, multiuser (e.g., defense, scientific, and industrial) facilities.

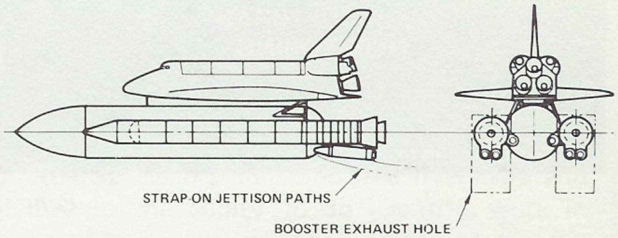
Just as the present Space Shuttle system performance specifications and development timetables were guided by the space program plans and forecasts of the 1960's, so the next decade's space systems must be planned in parallel with the development of supporting technologies. Propulsion advances will probably set the development pace for heavy-lift launch vehicles and should precede other efforts. Rapid developments in electronics and materials should enable space systems to be planned for the 1990's as advanced, compared to the Shuttle, as the Shuttle is compared to the Mercury/Redstone configuration.

Advanced space mission conceptual studies conducted during the past five years reveal potential operational space transportation requirements beyond those of the present Space Shuttle system. Requirements for increased payload delivery weight and volume, increased launch rate, increased crew size and passenger delivery, increased mission duration, increased electrical power, and increased waste heat collection and rejection have been defined to support potential future missions.

INCREASED PAYLOAD WEIGHT OPTIONS. Requirements for increased payload delivery weight beyond the present Shuttle system capability are anticipated during the latter half of the 1980's. A concept developed by Hubert P. Davis and his associates at NASA JSC is illustrated below. This design, utilizing a cluster of solid rocket motors attached to the rear of the external tank, was configured to have minimum impact on the present flight hardware; up to four motors could be added incrementally to permit delivery of payloads of up to 42,185 kilograms (93,000 pounds) into a 28.5-degree inclination, 185-kilometer (100-nautical-mile) circular orbit. The present solid rocket boosters would be retained without change. A less substantial improvement in payload delivery capability can be attained by strapping solid rocket motors onto the solid rocket boosters, as illustrated below. The six strap-on units would provide an increase of about 4482 kilograms (9880 pounds) in payload delivery capability over the present baseline Shuttle configuration.

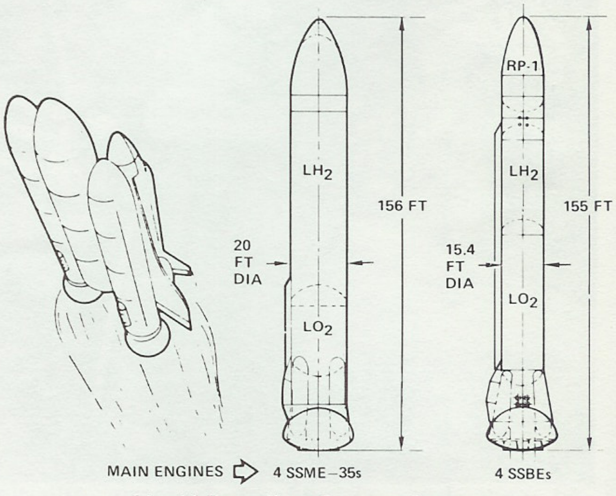


Payload Augmentation—External Tank Strap-on Motors



Payload Augmentation—Booster Strap-on Motors

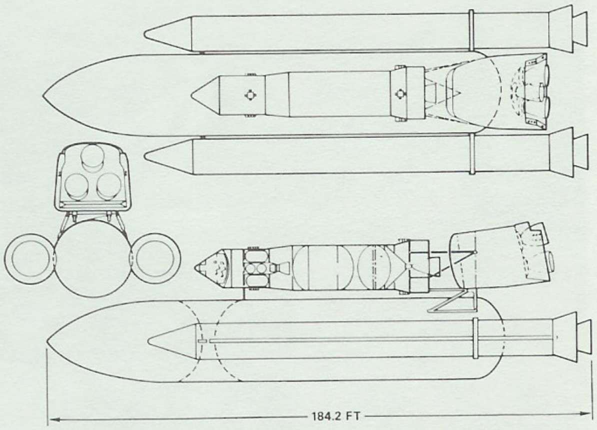
An earlier NASA study project, conducted under the direction of R.E. Austin of the Marshall Space Flight Center, investigated methods of increasing Shuttle payload delivery capability to 45,360 kilograms (100,000 pounds) or more while reducing recurring cost per flight. The preferred booster configurations are fully reusable, liquid propellant, and rocket-powered. A pair of these units



Liquid Propellant Booster Options

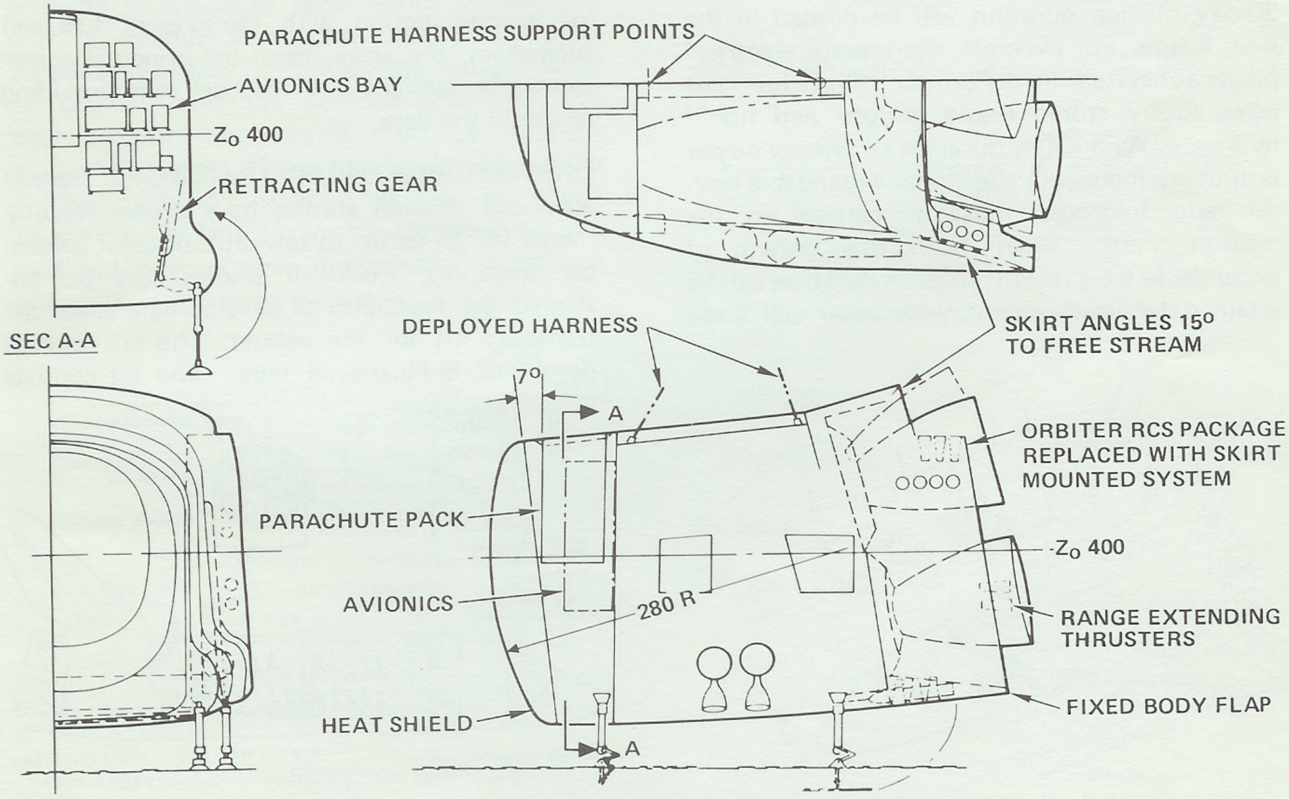
would replace the solid rocket boosters in the current Shuttle. One booster concept utilizes four Space Shuttle main engines equipped with 35:1 expansion ratio nozzles optimized for low-altitude performance. The other configuration utilizes four booster engines derived from the main engines: these booster engines are high-chamber-pressure, hydrogen-cooled, tripropellant engines that use RP-1 and the hydrogen coolant for fuel and liquid oxygen as oxider.

HEAVY-LIFT LAUNCH VEHICLE. The future mission studies mentioned earlier also revealed requirements for delivering payloads that weigh 68,040 kilograms (150,000 pounds) or more to low-altitude orbit. Studies performed by Rockwell International, Boeing, and NASA JSC have shown the feasibility of adapting present Shuttle vehicle hardware for use as a heavy-lift launch vehicle (HLLV). The Rockwell study configuration, illustrated here, uses the present baseline external tank and solid rocket boosters. The orbiter's aft fuselage is modified into a fully reusable propulsion module (also shown below). Baseline orbiter structure, main propulsion, guidance, navigation and flight control, and reaction control subsystem hardware are used in the propulsion module to provide a program of very modest development cost and low recurring costs. The payload is located forward of the propulsion module in the space now occupied by the orbiter's forward and mid-fuselage assemblies and wing.

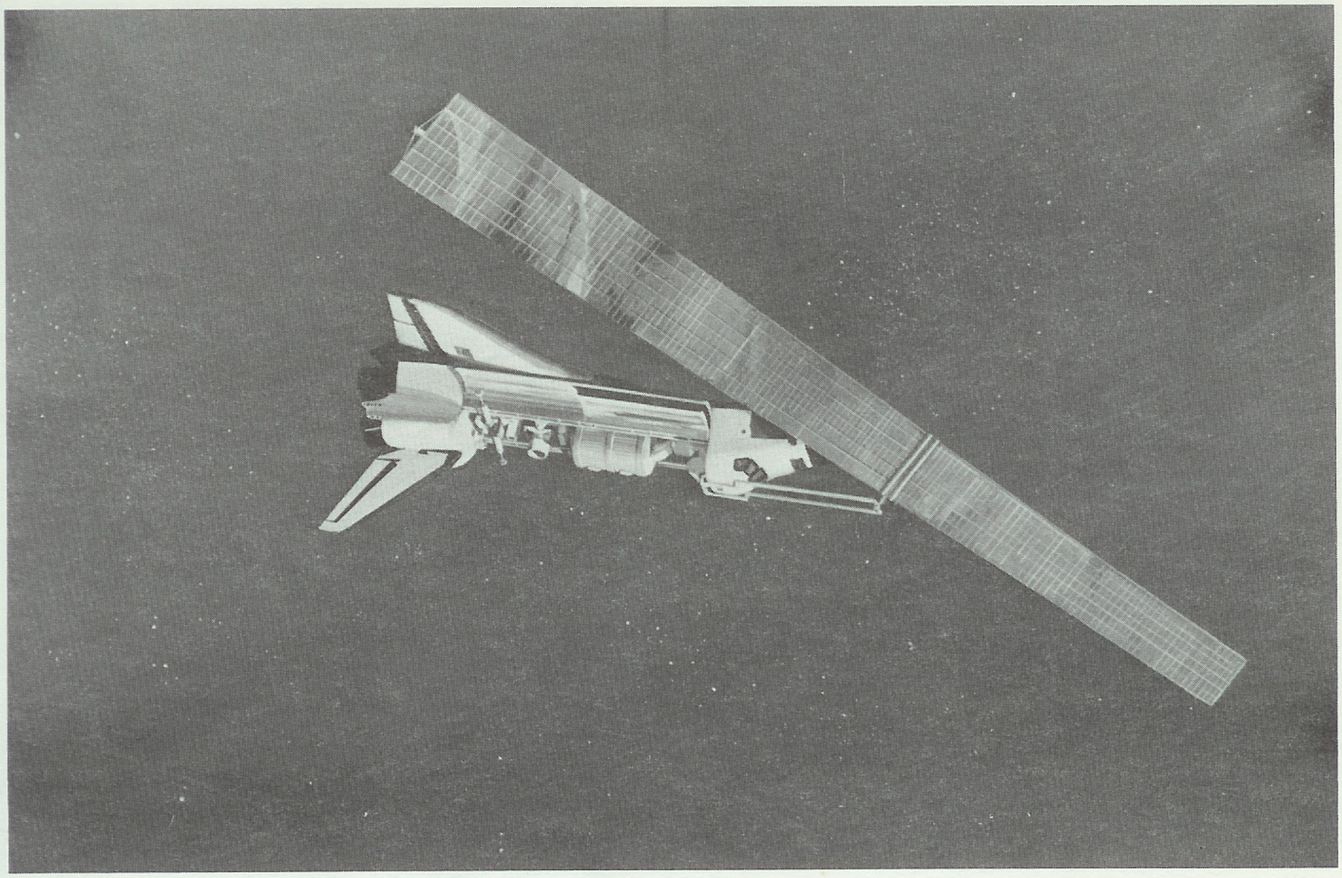


Heavy-Lift Launch Vehicle—Shuttle Derivative

EXTENDED-DURATION-MISSION ORBITER. Extended mission duration has been identified as another cost-effective Shuttle system growth concept. The current baseline was designed to permit extending mission duration up to 30 days by adding kits. Evaluation of evolving mission requirements indicates that kits for 14- to

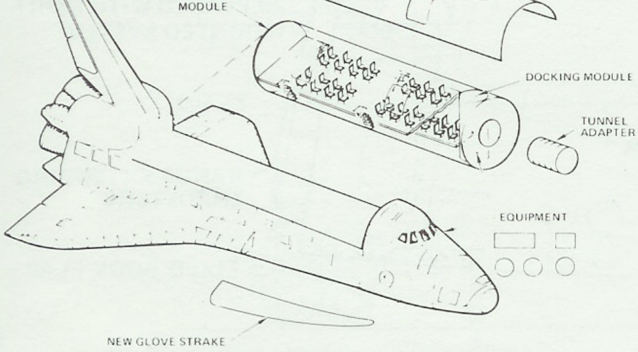


Reusable Propulsion Module



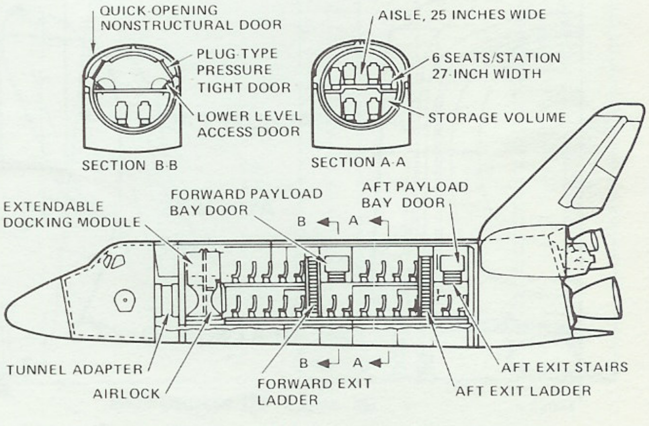
Extended-Duration Missions

30-day mission duration will be needed in the near future. For example, the present electrical power subsystem in the orbiter utilizes fuel cells powered by stored liquid oxygen and liquid hydrogen. As mission duration or average power output are increased, additional expendable oxygen and hydrogen must be carried on the mission. Partial relief from this growth of expendable weight with mission duration can be attained by using a deployable solar cell array kit in conjunction with the present fuel cell subsystem, the array being the principal power source in sunlight and the fuel cells providing power in the dark.



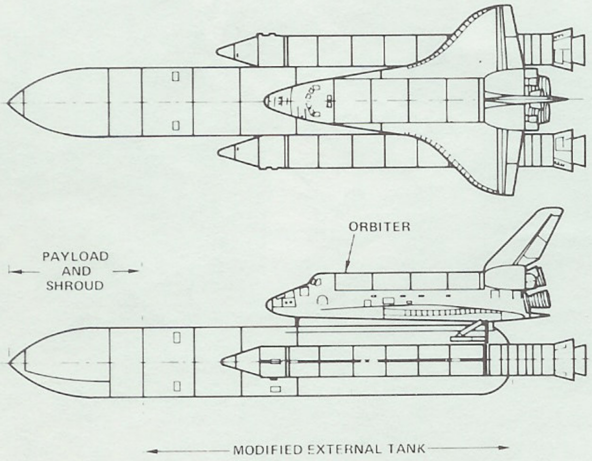
Passenger Orbit Transport

ORBITER PASSENGER TRANSPORT. Several advanced mission studies have shown requirements for an earth- to low-altitude-orbit passenger transport. Rockwell studies have demonstrated the feasibility of developing a passenger transport kit for the orbiter. The kit concept developed is illustrated here. The kit consists



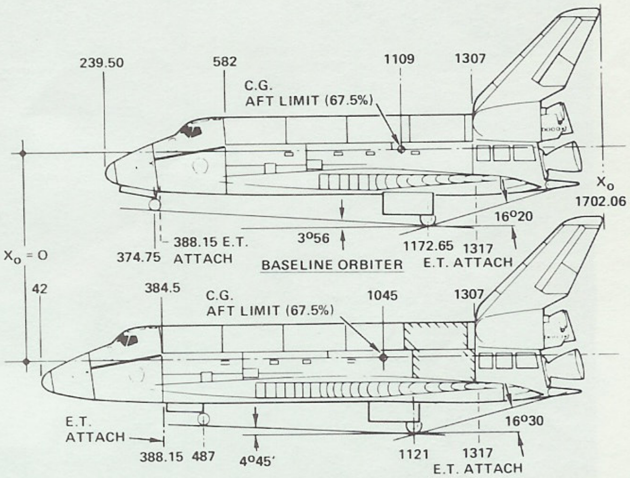
Inboard Profile–74-Passenger Orbit Transport of a passenger module including seating, supplemental environmental control and life support equipment and water storage; special payload bay doors for passenger ingress and egress; and new, larger area, wing glove sections to shift the aerodynamic center of pressure forward to accommodate an excessive forward center-of-gravity location. The waste heat radiator panels are removed, and all heat is rejected in space by water boiling. The passenger module capable of supporting up to 74 passengers is also shown here.

LARGE-DIAMETER PAYLOAD DELIVERY. Although the diameter of the orbiter's payload bay is 50 percent greater than the 3-meter (10-foot) outer diameter of the standard Titan series shrouds, various conceptual studies have revealed potential requirements for delivering substantially larger diameter payloads. Rockwell studies have demonstrated the feasibility of modifying the external tank to permit delivery to main engine cutoff (MECO) of payloads of up to 8 meters (25 feet) in diameter within a shroud of the same diameter as the external tank—8.4 meters (27 feet 7 inches). In this configuration, illustrated below, the external tank's intertank structure would require strengthening; and the tank's ogive nose would be replaced with a cylindrical section and an elliptical forward bulkhead. At MECO, the shroud would be opened, and the payload separated and powered into the desired orbit by its own propulsion system. It also appears feasible to use a "hammerhead" shroud of up to about 11 meters (37 feet) in outer diameter on the modified external tank, thus permitting delivery of even larger diameter payloads.

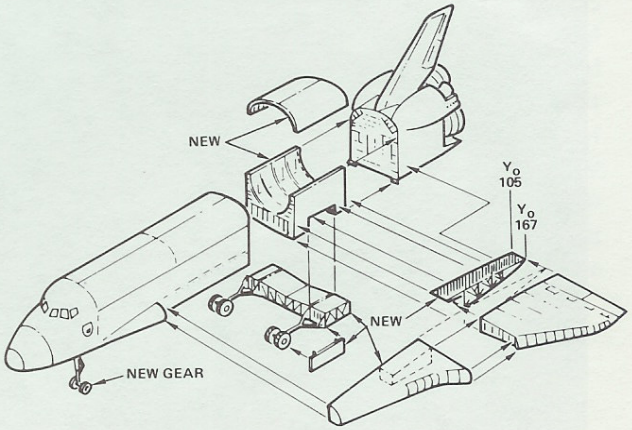


Large-Diameter Payload Delivery

"STRETCHED" ORBITER. Another option for relieving payload dimension constraints is the "stretched" orbiter concept. This configuration, illustrated below, would require use of an uprated booster. In the concept illustrated, the payload bay is stretched 5 meters (16.5 feet) to accommodate a 23-meter-long (76-foot), 45,360-kilogram (100,000-pound) payload. The modification approach, also illustrated here, was conceived to utilize as much existing structure as possible. The forward fuselage, crew module, mid fuselage, aft fuselage, and wing panels are retained. A new fuselage section is installed between the mid fuselage and the aft fuselage. Inboard wing panels 157 centimeters (62 inches) wide are spliced between the fuselage and baseline wing panels. A new wing box carry-through structure, landing gear, and wing glove structure are required. The resulting configuration is aerodynamically almost identical to the present orbiter except for its finer fuselage, which improves aerodynamic performance.



Comparison With Baseline Orbiter



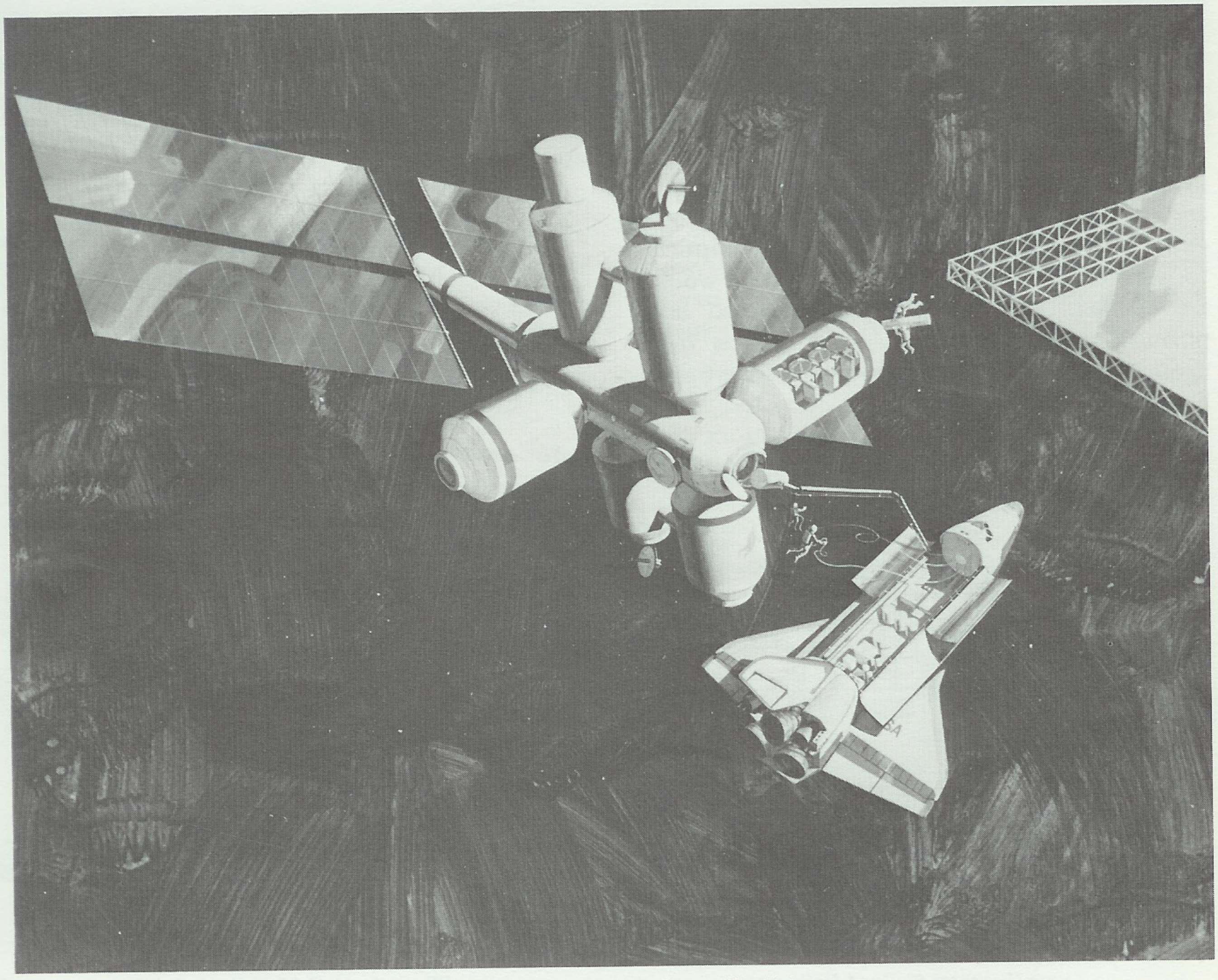
"Stretched" Orbiter Exploded View

Longer Range Ideas

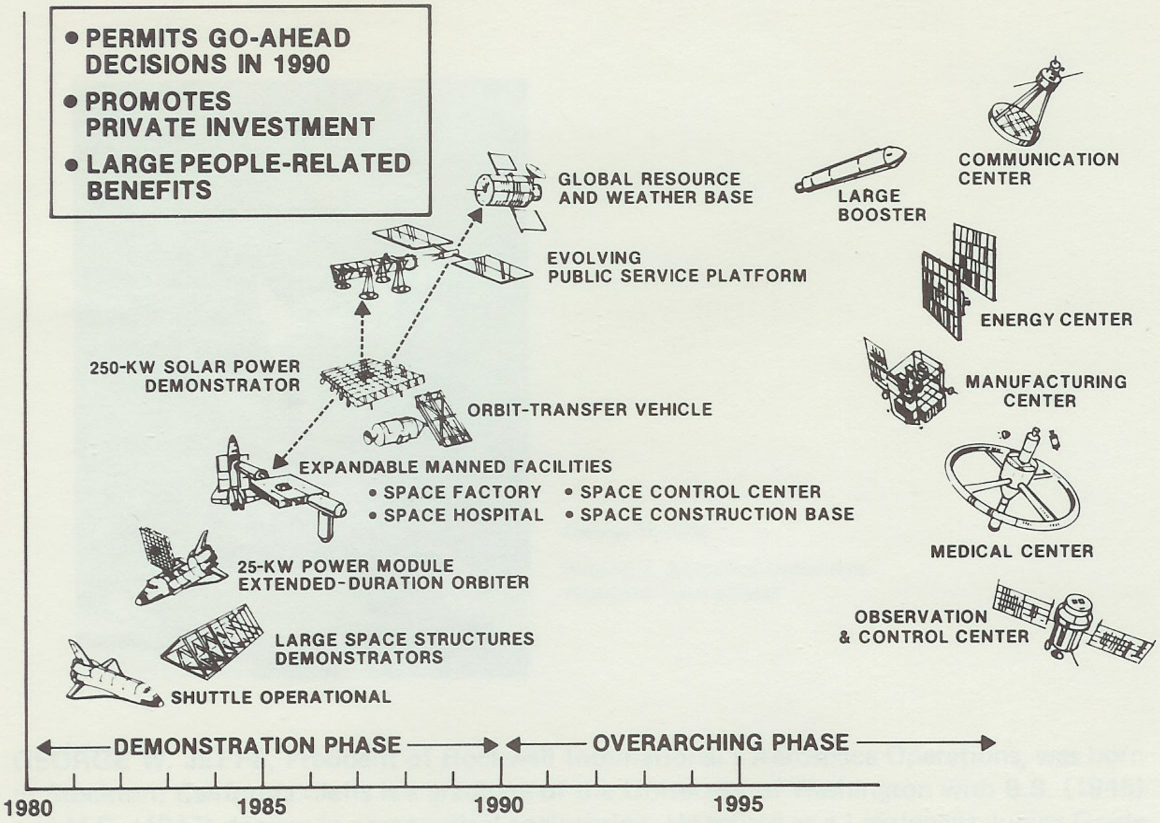
The Space Shuttle System design has been shown to be economically adaptable to a wide spectrum of advanced missions, substantially more demanding in their requirements than envisioned when the Shuttle system requirements were delineated. This economical growth potential—coupled with the fundamentally new capabilities being introduced by the Shuttle for payload recovery and reuse, on-orbit construction, assembly, maintenance and repair, and performance of other complex functions—is expected to result in an extended program lifetime. Evolutionary growth of operational space mission capabilities is anticipated during the program.

Establishing modular, multipurpose facilities as the primary new space systems of the 1980's and supporting them with growth versions of the present Shuttle will form the basis for a large "overarching" program, which should be planned for in the 1990's. With the experience and knowledge gained in using and supporting these facilities, a goal could be established to have a major permanent operational center in space by the Year 2000, designed to provide large-scale contributions to the people on earth. By 1990, the proper mix of mission objectives and users, the optimum location of the center, and its detailed development plan could be determined.

In the 1990's, during design and construction of the major space center for the Year 2000, science and technology must continue to advance on a broad front to provide the basic support and needs for additional centers in the 21st century.



Modular Multipurpose Space Facilities



Expanded Space Industrialization Program

SUMMARY

The basic tools and techniques for managing the interdisciplinary character of major technological efforts were refined and polished during the Apollo and Skylab programs. This development produced the legacy of today's systems engineering process—a mature concept whose time has come in stride with the next step in space transportation, the era of the Space Shuttle.

This paper has shown, by way of a few examples, how many diverse technological disciplines merged and interacted during the development of the Space Shuttle through the application of this process. These examples represent only a microcosm of the entire Shuttle development but serve to illustrate the process at work. The essential ingredients of the whole program were the close cooperation, coordination, and communication among all of the individuals and organizations involved and their collective dedication to a common goal.

The Shuttle program has been imbued with the confidence of proven experience: this time the challenge was not one of exploration and adventure, but one of development—much like settlers and merchants that followed into new lands discovered by the early explorers. By rigorous application of multidisciplined technological development, man has learned how to live and work in this new medium—space. Now he must learn to use it to advantage in all areas of scientific, industrial, and general technology development, for it is the record of human endeavor that our greatest benefits come not from the opening of frontiers but from the imaginative pursuit of their potential.

George W. Jeffs

President, Aerospace Operations
Rockwell International

GEORGE W. JEFFS, President of Rockwell International's Aerospace Operations, was born in Stockton, California. Jeffs is a graduate of the University of Washington with B.S. (1945) and M.S. (1947) degrees in aeronautical engineering. He served as a Lieutenant Junior Grade in U.S. Naval Aviation. Jeffs joined Rockwell International (North American Aviation) in 1947. As a key executive managing major national space programs, Jeffs has been honored with election to the National Academy of Engineers and is a fellow of the American Astronautical Society. He has been awarded NASA's highest honor, the Distinguished Public Service Medal, as well as the NASA Public Service Award, three NASA Certificates of Appreciation, and the NASA Associate Administrator Commendation. He has received the Presidential Medal of Freedom, the Institute for Advancement of Engineering Merit Award, and the Apollo Lunar Science Community Award. Jeffs has served as President of Space Operations (1976-1978), President of the Space Division (1974-76), Executive Vice President of the Space Division and Program Manager of the Space Shuttle (1972-74), Vice President and Program Manager of Apollo CSM (1969-73), Assistant Program Manager and Chief Program Engineer of Apollo CM (1966-69), Rockwell Corporate Executive Director of Engineering (1965-66), Vice President and Program Manager of the Paraglider Program (1963-65), Manager of Corporate Technical Development and Planning (1959-63), and Chief of Advanced Design and Chief of Systems Engineering at the Missile Division (1955-59). From 1948-55 Jeffs supervised company efforts under the Aerophysics Laboratory, directing preliminary design and analysis of the Navaho Program. Jeffs is a rated instrument pilot.