THE DANIEL AND FLORENCE GUGGENHEIM MEMORIAL LECTURE

SPACE TRANSPORTATION SYSTEMS

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Abstract

Technology advancements in rocketry, guidance and flight control, thermal protection, and other critical areas have led to a reusable orbital transportation system. This system, the Space Shuttle, demonstrated the system's readiness for the operational phase with outstanding performance in the ascent, on-orbit, entry, and approach and landing flight modes during the orbital test program. Beyond the early missions, the Shuttle will be the key element in the evolution of advanced space operations capability. Operating in a long-duration mode (14 to 30 days) and coupled with elements of the Spacelab and an external power source, the orbiter will provide the function of a mini-space station. The most versatile spacecraft ever designed, the Space Shuttle is already expanding our thinking and planning about the future use of space. It is, indeed, the key element in near-term and advanced space operations capabilities for future commercial, security, earth-resources, and scientific exploitation of space.

Launch Vehicle History

Today's efficient launch vehicles, including the Space Shuttle, owe their origins in large part to early rocket experimenters. Although solid propellant rockets had been known and used for centuries, it remained for theoretical studies and test firings of gyroscopically controlled rockets in the 1920's and 1930's by the American university professor Robert H. Goddard to demonstrate the feasibility of liquid propulsion.

In 1955, American scientist and engineer J. R. Pierce stated: "At this point, some information from astronomers about orbits and from rocket men about constructing and placing satellites would be decidedly welcome." Two years later, in October 1957, the Soviet rocket men partly satisfied his curiosity with the launch of Sputnik, the first artificial satellite, with their Vostok space vehicle.

Vostok provided lift-off thrust of over 1 million pounds. Weighing 184 pounds, Sputnik consisted of a polished metal sphere with four whip-type aerials. It was positioned in a 136- by 568-mile orbit and transmitted signals for 21 days.

This startling event stimulated more activity than any other toward the realization of the practical spacecraft being used today. Among other things, it led to the beginning of a visionary American space program.

In 1958, the Explorer was the first U.S. satellite to be successfully launched into orbit, setting the course for extraordinary studies in space. It was launched by a four-stage Jupiter C rocket, which had evolved from the U.S. Army's Redstone rocket. Explorer weighed 31 pounds and was placed in a 216- by 1,520-mile orbit.

The subsequent evolution of launch vehicles has been driven by the demands of increasingly complex payloads. The communications satellite operating at geosynchronous orbit (22,300 miles) has been limited by the capacity of the launch vehicles. The growth of the Intelsat series (Table 1) provides a vivid example of the growth of payload capability with the availability of increasing launch vehicle capability. Note that the Atlas-Centaur launch vehicle was required for the much heavier Intelsat IV and Intelsat V versions. The first Intelsat V was launched in 1979. It weighs over 4,100 pounds and has fifty times the capacity of an Intelsat I.

Launch Vehicle Development For Early Manned Flight

In the 1960's the United States manned space program was begun in three major phases, that is, the Mercury, Gemini, and Apollo spacecraft. Each manned flight led to increased knowledge of the systems and techniques needed to operate successfully in space, and each phase represented a significant advancement over the previous one.

Because of mission requirements, spacecraft experienced growth in both size and weight, and subsystems were refined.

Electrical power is a good example of increased system capability. Electrical power for Mercury was supplied by six batteries, which sustained the 4,265-pound spacecraft and its single astronaut for a day and a half. In Gemini, seven batteries and two fuel-cell powerplants provided sufficient power to operate a typical 7,000-pound craft containing two astronauts for as long as two weeks. The Apollo power system, which was supplied by five batteries and three fuel-cell powerplants, supported a spacecraft carrying three astronauts for up to two weeks.

The launch vehicle development to accommodate these increased requirements represented a tremendous stride forward in rocket propulsion.

In 1966, the Saturn 1B was the first space test of an Apollo spacecraft. Its 1.5 million pounds of thrust was able to boost 40,000 pounds into a low earth orbit. Its successor, the Saturn V—which had the capability of boosting 270,000 pounds into low earth orbit and 100,000 pounds for translunar insertion with 7.5 million pounds of thrust—was used for the remaining Apollo missions. These two launch vehicles supported the U.S. manned space program during the 1960's and 1970's.

Launch vehicle development is shown in Figure 1.

Table 1. Intelsat Satellite Capability Growth as a Function of Launch Vehicle (Intelsat I through Intelsat V)

Satellite Type	Date of First Launch In Series	Satellite Capacity (Telephone & Television)	Payload Weight(lb) Launched	Payload Weight(lb) Orbited	Launch Vehicle
Intelsat I	1965	240 voice circuits or TV	150	86	Thrust augmented delta
Intelsat II	1966	240 voice circuits or TV	356	189	Improved thrust augmented delta
Intelsat III	1967	1,200 voice circuits plus 2 TV channels	646	189	Improved thrust augmented long-tank delta
Intelsat IV	1975	4,000 voice circuits plus 2 TV channels	646	334	Atlas Centaur launch vehicle
Intelsat IV A	1975	6,000 voice circuits plus 2 TV channels	3,120	1,610	Atlas Centaur launch vehicle
Intelsat V	1980	12,000 voice circuits plus 2 TV channels	3,335	1,899	Atlas Centaur for first 3-4 satellites in series. Remaining satellites to be launched by Space Shuttle

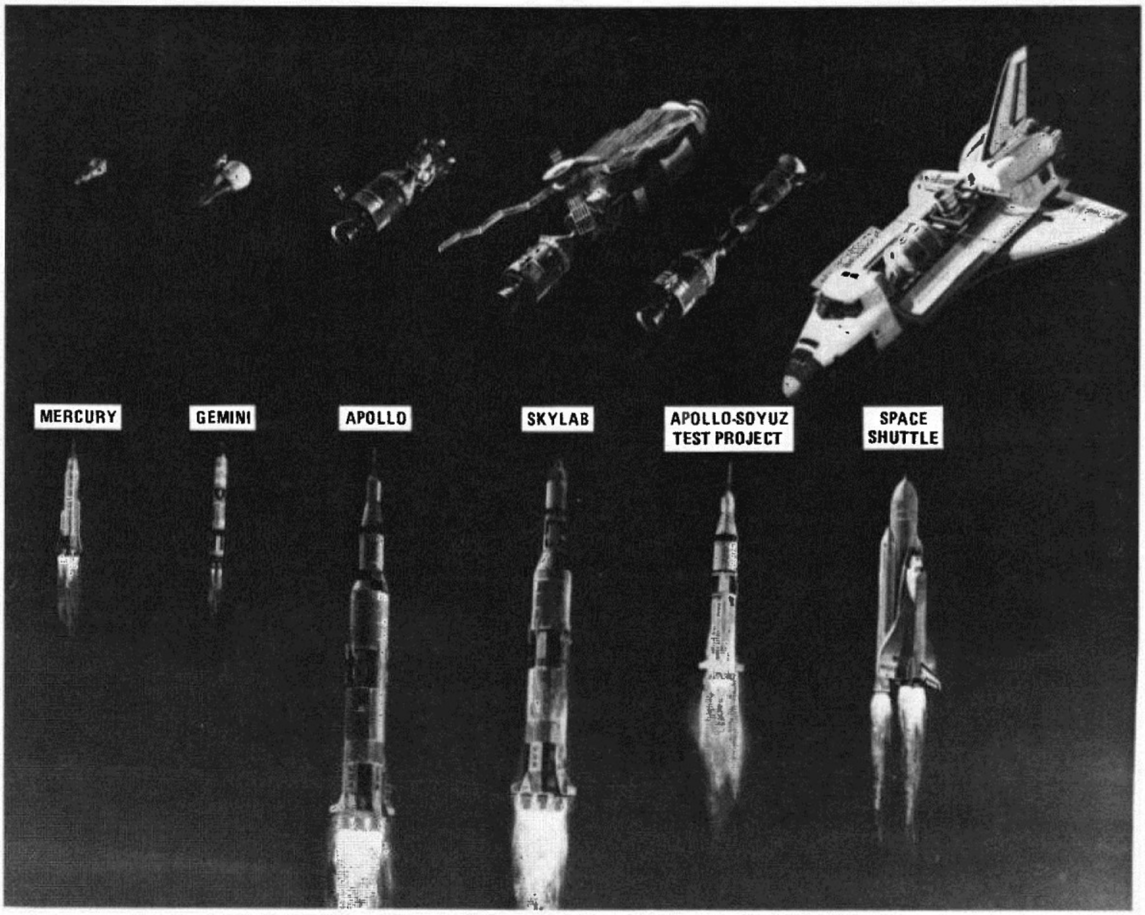

Figure 1. U.S. Manned Spacecraft/Launch Vehicle Size Comparison

The Evolution of the Space Shuttle Configuration

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 acceptable technical risks.

Studies of reusable transportation systems in the early 1960's were generally devoted to the design of launch vehicles that could place very large payloads in orbit. Designs of such vehicles incorporated technology advances in high-performance rocket engines and high-strength, lightweight structural materials in order to enhance the feasibility of different concepts.

Reentry vehicle 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, as well as thrust vector control methods. But 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. A workable system demanded high-performance, long-life, and low-refurbishment-cost rocket engines.

The detailed definition of the Space Shuttle began with NASA's July 1970 award of contracts 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.

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. The technology of manned spaceflight had been 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.

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 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.

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.

Because Shuttle system performance required a highly efficient ascent propulsion system, a new rocket engine was

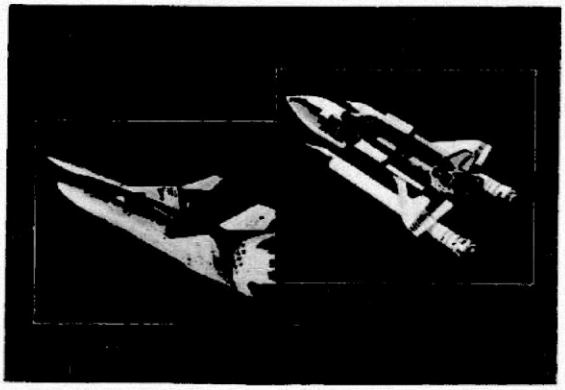

Figure 2. Space Shuttle Fully Reusable Concept Development

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.

Space Shuttle Design and Development

The design, development, test, and evaluation phase of the Space Shuttle program was initiated in 1972. To ensure that it could carry out a wide variety of missions, the system was designed to deliver 65,000 pounds into a 100-nautical-mile orbit on a due-east launch, carry 32,000 pounds into a polar orbit, and land with 32,000 pounds of payload. The orbiter had to accommodate large payloads, up to 15 feet in diameter and 60 feet long, and be capable of deploying and retrieving them.

Vehicle System and Subsystem Testing

Confidence in the Shuttle was derived from highly successful vehicle testing and systems verification. Development and qualification testing of major system elements, subsystems, and components proceeded with few surprises.

The first orbiter was seen by many viewers in 1977, when the approach and landing tests at Edwards Air Force Base were performed. During this test phase, through which the orbiter's flight capabilities within the atmosphere were assessed, the vehicle was carried to approximately 25,000 feet atop the Shuttle carrier aircraft and released. The orbiter flight characteristics were proved to be as predicted, and system operation/hardware problems were minor.

Orbiter 099, designated Challenger, was a test article that has since been refurbished for use as the second Shuttle flight vehicle, a decision that has resulted in significant cost savings to the orbiter program. As a test article, Orbiter 099 completed ground tests, which certified the orbiter's structural design integrity.

Flight Systems Laboratories are a significant orbiter test tool, with three interrelated laboratories—Flight Simulation, concentrating on vehicle dynamics and flight environment; Avionics Development, dealing with computer-oriented avionics systems; and Flight Control Hydraulics, set up not only to emulate the orbiter flight systems, but also to "think" it is the orbiter in flight.

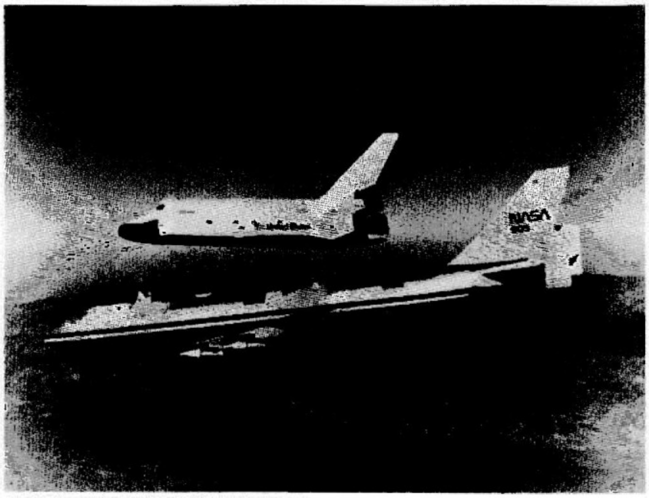

Figure 3. Space Shuttle Approach and Landing Test

The Shuttle Avionics Integration Laboratory is a central facility where the avionics and related hardware (or simulations of the hardware), flight software, flight procedures, and associated primary ground support hardware and software are fully integrated for testing.

The main propulsion test program consisted of a series of planned cryogenic tanking and static firings designed to integrate and evaluate the functional integrity and performance of the main propulsion system at the National Space Technology Laboratories in Mississippi. In this program, the entire propulsion system was tested under simulated flight conditions.

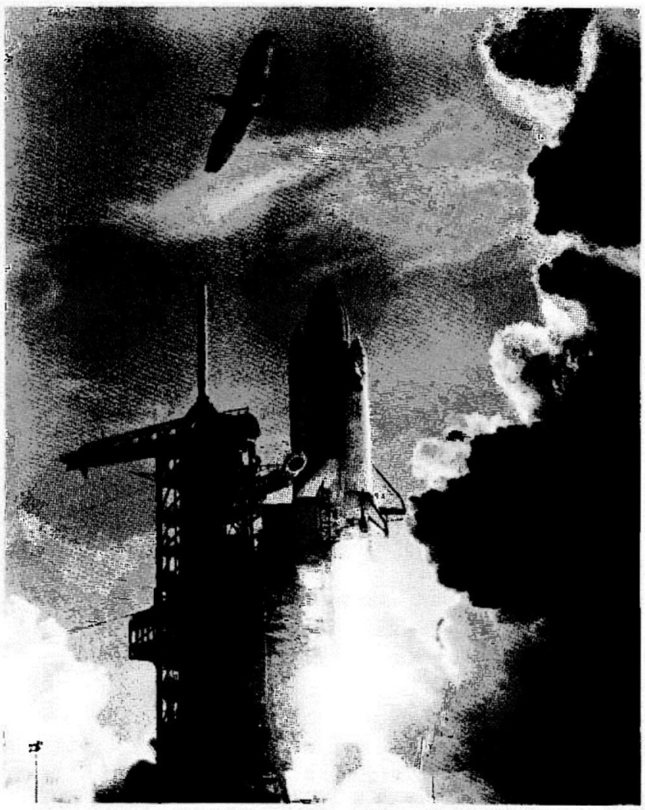

Figure 4. Space Shuttle Launch (STS-1 Mission) from Kennedy Space Center, Florida

In addition, it was necessary to determine the vehicle's structural modal characteristics and transfer functions. The mated vertical ground vibration test successfully determined with full-scale hardware the modal and frequency response characteristics of the vehicle.

Excellent design and development progress, the highest standards of quality workmanship, coupled with intensive qualification testing, in-depth ground test programs, and rigorous checkout processes, were essential preparatory steps for confidence in the flightworthiness of the world's only reusable spacecraft.

Flight Test Results

The reusable Space Shuttle four-flight orbital test program has been designed to demonstrate the system's readiness for the operational phase measuring performance in the ascent, on-orbit, entry, and approach and landing flight modes.

Table 2. Space Shuttle Flight Tests

STS-1 MISSION

Commander - John W. Young
Pilot - Robert L. Crippen
Mission Duration - 54 hours, 21 minutes, 57 seconds
Orbits of Earth - 36
Orbital Altitude - 145 nautical miles
Orbiter Weight at Landing - Approximately 196,500 pounds
Landing Speed at Main Gear Touchdown - 207 to 212 mph

STS-2 MISSION

Commander - Joe Engle
Pilot - Richard Truly
Mission Duration - 54 hours, 13 minutes, 11 seconds
Orbits of Earth - 36
Orbital Altitude - 137 nautical miles
Orbiter Weight at Landing - Approximately 204,000 pounds
Landing Speed at Main Gear Touchdown - Approximately 224 mph

STS-3 MISSION

Commander - John Lousma
Pilot - Gordon Fullerton
Mission Duration - 192 hours, 4 minutes, 46 seconds
Orbits of Earth - 130
Orbital Altitude - 128.56 nautical miles
Orbiter Weight at Landing - Approximately 207,500 pounds
Landing Speed at Main Gear Touchdown - 269 mph

System Performance

All major flight test requirements were accomplished for missions flown and the crews reported that the vehicle's performance and flight characteristics were outstanding and were considerably better than expected.

Significant performance results of the flight test program are summarized as follows:

Main Engines. The Shuttle's three liquid-fueled main engines exceeded performance goals throughout the start, transition to mainstage, power throttling, and shutdown phases of each test mission. Postflight inspections have been nominal.

Solid Rocket Boosters. The twin solid rocket boosters (SRB's)—the first ever used in manned spaceflight—performed nominally, and longitudinal vibrations were lower than expected. The SRB's have splashed down within the planned target areas and have been successfully recovered for future reuse.

Orbiter Consumables. Consumables usage for the orbiter's systems has been more effective than predicted. This is a positive step toward providing improved orbiter performance for the operational phase, including longer on-orbit stay times and/or increased power availability for payloads.

Avionics. The avionics systems' performance was superior. The Guidance, Navigation, and Control system and associated hardware and software demonstrated excellent performance during prelaunch, ascent, on-orbit, and entry mission phases. Sequences, commands, computations, communications, etc., were performed as required.

No problems occurred with the orbiter's computers or associated hardware. The operation of this system is vital to most orbiter functions. Its performance was nominal and orderly.

Figure 5. Space Shuttle Landing (STS-3 Mission) at White Sands, New Mexico

Communication was demonstrated in essentially all modes and types. Data, voice, and video received from the orbiter as well as the uplinked data and voice from the ground via the various tracking sites attest to communication and tracking system performance.

The flight software throughout the missions fully performed to expectations. Throughout the flights, the systems management function was effectively accomplished.

Aerodynamics. Columbia's performance and stability and control have been as planned, indicating that aerodynamic characteristics are as predicted.

Flight Evaluation - Effect on Reusability

One of the more significant conclusions of the Columbia's first flight was verification of the planned reusability of the Space Shuttle system. The most critical issues are discussed below.

The thermal protection system (TPS) maintained all structural backface temperatures well within established parameters and performed as predicted with very minor exceptions. Postflight inspections maintenance, and refurbishment have required significantly less effort than predicted, which affirms the reusable capability of the TPS.

The flight missions have demonstrated and verified the readiness of the main engines for Shuttle operations. Ground operations for the main engines were streamlined to enhance turnaround times, and postflight inspections have been successfully completed.

The recovered solid rocket boosters are in good condition and will be reused for subsequent Shuttle flights. In addition, the recovered parachutes are also planned for reuse.

The duration of the vehicle's checkout and turnaround activities has been substantially reduced as the team at KSC attains increased effectiveness with each mission cycle.

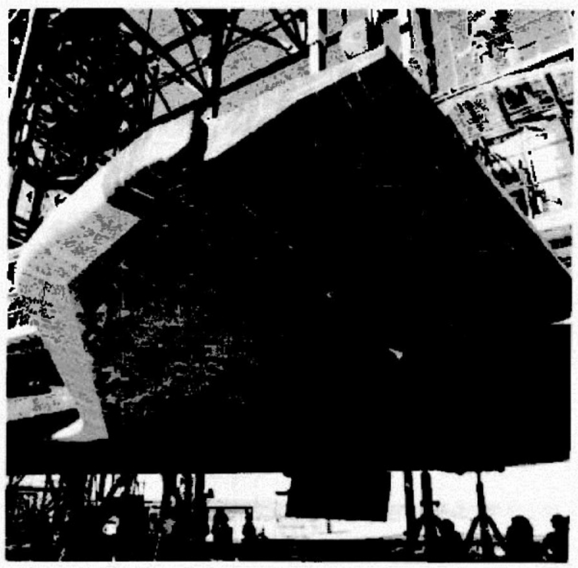

Figure 6. Thermal Protection System After Flight Test (STS-2 Mission)

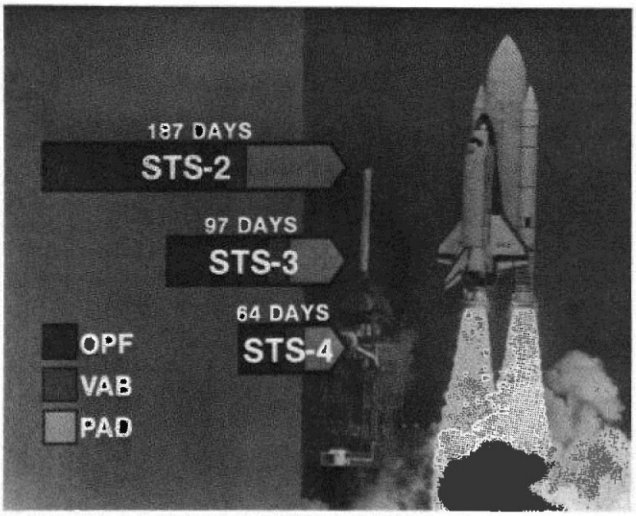

Figure 7. Shuttle Turnaround Reduction

The conditions of Launch Pad 39A and the mobile launcher have been better after lift-off than expected. No major structural damage has been experienced, and clean-up has entailed a minimum amount of time.

Follow-On Orbiters

Rockwell International is currently on contract with NASA to build a fleet of four orbiters. An option to proceed with a fifth orbiter is currently under consideration.

The three additional orbiters, designated Challenger, Discovery, and Atlantis, are on a schedule with deliveries in June 1982, September 1983, and December 1984. These vehicles will progressively incorporate such improvements as improved thermal protection system elements, structural and system weight reductions, improved navigation with the Global Positioning System, and improved fuel cell capability.

Heavy Space Shuttle user demands currently exist among commercial satellite enterprises, government agencies, worldwide, multinational groups, and others. The projected demand for space transportation substantially exceeds the projected expendable launch and Space Shuttle fleet capabilities, so that additional orbiters will be required.

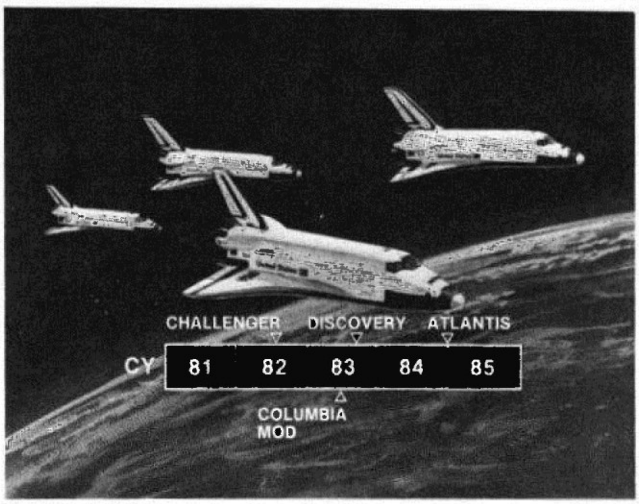

Figure 8. Orbiter Production Schedule

The Space Shuttle system will be the mainstay of space transportation well into the 1990's. The utility and efficiency of the present Shuttle design will be incrementally improved, increasing payload delivery capabilities and extending mission duration. In addition, the unique capabilities of the Shuttle system will enhance its utilization far beyond that of simply a launch vehicle.

Unique Shuttle Characteristics

The Space Shuttle system introduces a new era of space transportation, reducing the cost and increasing the effectiveness of space for commercial, scientific, and defense purposes.

Along with its 65,000-pound payload capacity, the Shuttle provides access to and from space for men and equipment, relatively unlimited payload capability through multiple missions, and unmatched versatility of operations once in orbit.

It is these unique capabilities of the Shuttle that set it apart from launch vehicles as they have been known.

- **Payload Size Advantage** - The Shuttle's large payload bay (60 feet by 15 feet) does not limit spacecraft designers to the size constraints inherent in expendable launch boosters.
- **Man in Loop** - Man's presence in space will provide the capability for operating, maintaining, and assembling equipment on orbit.
- **Monitoring of Payloads** - The status of critical space equipment functions is monitored through the Shuttle's caution and warning systems to provide an extra margin of safety during the boost phase and while operating on orbit.
- **On-Orbit Retrieval/Resupply** - Spacecraft such as the Space Telescope will be routinely serviced on orbit for extended use. Low-orbiting spacecraft may have sensors, experimental packages, high-resolution film, and other elements retrieved, and may be resupplied with new experiments, film, or consumables.
- **On-Orbit Repair** - The Shuttle will be used to prolong the life of active spacecraft (e.g., the planned 1983 repair of the Solar Maximum Spacecraft, which failed in 1980).

Increased Effectiveness Through Sortie Capabilities

The Shuttle system adds a new order of space transportation capability by providing the unique services of a sortie operating mode, which accommodates payloads attached to the system for earth- and space-oriented missions. Major benefits of the sortie mode include:

- **Proof of Concept** - This feature, typified by its use for the DOD Talon Gold laser pointing and tracking demonstration, is a cost-effective means to permit an advanced new system to be flown, tested, assessed, returned, upgraded, and subsequently deployed as a free flyer.

- **Faster Development** - Through the use of the sortie mode, space components can be tested on board the orbiter and returned for modification and retested, if necessary, in space. This will speed the development cycle by obviating the need to develop a unique satellite carrier and by permitting man to work with the system elements both on the ground and in the actual space environment.

- **Control and Monitoring** - As demonstrated on the STS-2 mission, control and monitoring of the Office of Space and Terrestrial Applications (OSTA-1) remote sensing equipment was an integral mission function. This advantage ensures optimum utilization of the payloads by adjusting to varying mission conditions with real-time data interpretation and experiment observation.

- **Scientists and Researchers** - The international Spacelab will provide a laboratory and shirtsleeve environment for scientists and researchers in astronomy, life science, biomedicine, and industrial technology and for conducting earth surveys. This general purpose orbiting laboratory enables personnel to employ specialized laboratory equipment rather than space-rated hardware.

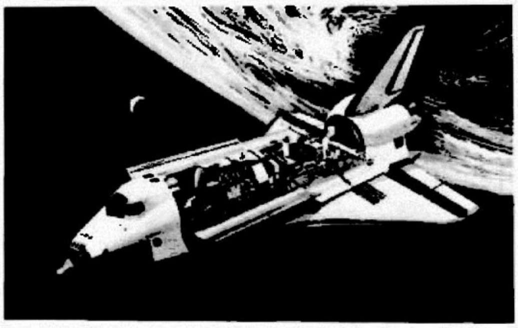

Figure 9. European Space Agency's Spacelab

- **Small, Self-Contained Payloads** - Referred to as Getaway Specials, these units provide opportunities for low-cost scientific and research and development experiments for universities, companies, and private citizens.

- **Comprehensive Mission Services** - Shuttle services to payloads make possible a wide range of sortie missions.

    - **Power** - The Shuttle provides ample electrical power in dc current to payloads through its fuel cell energy system.

    - **Cooling** - The Shuttle's active thermal control subsystem provides efficient payload heat rejection and coolant during ascent, while on orbit, for entry, and after landing.

    - **Avionics** - The Shuttle's complete avionics services include the transmittal of data (text, graphic, and video). The orbiter also records and stores data; provides communication among crew, ground, and payload personnel; conveys ground-initiated commands to payloads; monitors critical parameters; and provides master timing signals to payloads.

Future Potential

The Shuttle is a demonstrable quantum leap beyond expendable launch vehicles considering its unique capabilities and the potential of sortie missions and on-orbit assembly.

Figure 10. Shuttle—Key to Assembly of Large Structures in Orbit

To date, size and complexity of space systems have been limited by launch vehicle capability. Because of the capability to use several Shuttle launches to place payloads and upper stages in low earth orbit, no longer is the launch vehicle a constraint to system size. As this capability is exploited, larger and larger on-orbit systems will be developed. The Shuttle can transport elements of large space structures to orbit and support construction crews in space. Such large structures could include large communication antenna farms, permanent space stations, multisatellite service platforms, and orbiting manufacturing facilities.

With the Space Shuttle, activities in space are at the threshold of an exciting new era. The future rewards to be reaped from the accomplishments over the past 25 years are virtually limitless.

Man must be capable of continued growth and have the freedom to leave this planet. The Space Shuttle opens the door to this promise—a promise we cannot afford to ignore.