Bob Thompson

AIAA'84

AIAA-84-0574

Von Karman Lecture: The Space Shuttle---
Some Key Program Decisions

R.F. Thompson, McDonnell Technical
Services Inc., Houston, TX

AIAA 22nd Aerospace Sciences Meeting

January 9-12, 1984/Reno, Nevada

1984 VON KARMAN LECTURE

THE SPACE SHUTTLE - SOME KEY PROGRAM DECISIONS

Robert F. Thompson*
McDonnell Douglas Technical Services Co.
Houston, Texas

Abstract

Selected key Space Shuttle configuration decisions are discussed from the viewpoint of the logic behind the choice and the influence of the decision on the ensuing development and flight program. The technology base available to the management team had a significant influence on the choices made and an appeal is made for a continuing effort to upgrade this base for future undertakings.

Introduction

At the core of the development of a complex vehicle such as the Space Shuttle is a Government/Industry team charged with the responsibility of making certain basic configuration decisions. The composite of these decisions establishes the development path the program will ultimately follow and, in many cases, the degree of success of the program will depend on the collective wisdom of these choices.

Theodore Von Karman contributed greatly to the technology upon which many of the Space Shuttle decisions were based and, in keeping with the

---

*Fellow, AIAA. 1970-1981 Space Shuttle Program Manager, NASA, Johnson Space Center.

tradition for Von Karman lectures to be broad in scope and of general interest, it seems appropriate to review and subjectively comment on some of the key configuration decisions made during the Shuttle design and development phase. Eleven years ago as the Shuttle was entering the detailed design and development phase, a colleague of mine from the Langley Research Center, Gene Love, presented (Reference 1) the Von Karman lecture wherein he discussed some selected topics on advanced technology relative to the Space Shuttle. Some of the configuration choices that I plan to discuss were still open at that time, and Gene postulated on the adequacy of the technology base available to support some of these pending choices. He also pointed out in that lecture the need to sustain advanced research such that future systems could emerge from a combination of Shuttle and non-Shuttle technology advancements. This concern for a proper advanced research program is even more valid today than it was a decade ago, and it is hoped that the Shuttle program as it conducts flight operations will endeavor to make a meaningful contribution to the technology of follow-on vehicles.

The selection of the configuration decisions to be discussed will, of course, be arbitrary and the retrospective evaluation of the influence of these decisions on the program must be speculative since the merits of the unchosen options will remain unknown. However, it should be enlightening to revisit some of the key configuration choices from the vantage point of a successful flight vehicle and see what lessons may be learned from this review.

Background

The basic performance capability established early in the Shuttle program and stated in terms of weight to orbit, payload bay size, entry maneuver volume, crew size, lifetime, etc. remain independent of the basic implementation decisions that I plan to discuss. With these performance parameters fixed, the relative balance between development costs and operational costs was a key configuration driver in the design approach. The early program emphasis was toward minimum perceived operational costs which, early on, translated into an effort to conceive a fully reuseable system. This emphasis on operating cost was driving the program configuration to an unacceptably high level of vehicle complexity and unacceptably high level of development cost. This groundrule of "full reuseability" and the associated development costs and vehicle complexities was causing the program to "stall out" during the early design phase. By "stall out," I mean that the development cost of the program was considered too high for national level support and the vehicles, as then conceived, were too complex for a reasonable feeling of creditability on the part of many of those charged with the development responsibility.

Expendable Fuel Tank Decision

The decision to abandon the "fully reuseable" groundrule and employ expendable tankage for the Orbiter main rocket engines propellant was perhaps the single most important configuration decision made in the Shuttle program. This change in program approach, which occurred late in the program definition phase, allowed for a significant reduction in the size and weight of the Orbiter vehicle which translated into a very different booster requirement. This reduced booster requirement ultimately permitted the choice of solid propellant booster rockets, thereby significantly reducing the booster development task and conveniently supporting a simplified parachute recovery approach for booster reuse. Utilizing expendable tankage in this manner significantly changed the overall development task, and considerably reduced the development cost at some perceived increase in operating cost. The projected cost and size effects of this configuration decision are shown on Figures 1, 2 and 3 as they were perceived in 1971. It is of some interest to speculate today on where the program might be had we chosen the more complex development path in search of reduced operational costs. The flyback booster would have been a very difficult development challenge and the larger, more complex Orbiter configuration would have further compounded what proved to be a formidable development task. With the chosen configuration, the program came very close to the anticipated development costs and moved forward along a development path that has had a very successful conclusion. Whether or not the relative operational cost savings depicted in Figures 1 and 3 could have been realized in actual practice with the larger, somewhat more complex vehicles will remain an unknown. In retrospect, the basic decision to follow a less complicated development path at the future risk of possible higher operating costs was, in my judgement, a very wise choice. However, the ultimate effect of operating cost on Shuttle utility is unanswered at this time and remains a significant program challenge. For those who struggle with the cost of building tanks and reloading boosters, it might be of some comfort to realize that maintaining a flyback booster with many rocket and turbojet engines would also be costly. The relative merits must remain unanswered.

Orbiter Main Engine Configuration

Another lively debate early in the Shuttle design was the issue of what technology to strive for in the main liquid rocket engine. With the maturity of cryogenic technology, hydrogen and oxygen were the logical propellant choices, and some very useful advanced development work had been done on a staged combustion cycle approach operating at very high internal pressures. When compared to the hydrogen/oxygen gas generator cycle engine at the lower operating pressures utilized in the upper stages of the Apollo program, the higher specific impulse and thrust-to-weight ratios promised were very attractive from an overall vehicle sizing point of view. Shuttle systems considerations also required a thrust level permitting engine-out abort capabilities, a throttle range-to-control maximum dynamic pressure and maximum acceleration during launch, together with lifetime and reuse capabilities commensurate with reasonable operating costs.

In this case the decision was made to strive for the higher technology engine in order to gain the overall system benefits offered by the higher specific impulse and higher thrust-to-weight ratios. Principal new technology involved high internal operating pressures, dual turbo pumps, dual combustion stages, and an engine-mounted digital controller. I would characterize the ensuing engine development program as difficult but successful, and the problems encountered have been more in the nature of mechanical engineering type issues (bearings, vibrations, cooling, materials, etc.) rather than combustion or combustion stability issues which were some postulated pre-development concerns. Start cycle, mixture-ratio control, mixing and energy release, and combustion stability have all fallen into place very well and the digital controller has had a very beneficial influence on the total development task.

The Orbiter main rocket engines was, as expected, a critical path during Shuttle development and some work still remains to certify the engines at full power level, and lifetime/maintainability effects on engine operating costs remain unknown. How well the program would have progressed had we chosen to merely upgrade the Apollo gas-generator cycle engine must remain speculative. However, the overall system benefits of the high performance engine are now inherent in the Shuttle vehicle, and on balance the choice of main engine configuration was very good. The technology was available to support this development, and the overall system benefits should be recognized as we work out the residual issues of qualification, lifetime, and cost.

Stacking Arrangement/Parallel Burn

Another major configuration decision faced early in the Shuttle Program concerned the launch element arrangement. The willingness to employ an expendable tank combined with high efficiency in the Orbiter main engines led naturally to the consideration of a stacking arrangement somewhat different from previous flight experience. This launch configuration (See Figure 5) gave the advantage of using the high performance Orbiter engines throughout the launch phase including the benefit of engine start and thrust verification prior to booster ignition, and enabled the system to accept with reasonable sizing the simple low-performance booster rockets that were relatively easy to develop, recover and reuse. Of primary concern with this arrangement was the very large number of natural modes of vibration in a frequency range of possible interaction concern to the flight control and propulsion systems. Also, the Orbiter was located low on the stack near the main thrust exit plane and was, therefore, subjected to high plume heating and vibro-acoustic forcing functions. Of secondary concern with this stacking arrangement were such issues as interference effects on aerodynamics and heating, controllability (with fixed SRB nozzles), center of gravity management, load paths, etc. The decision was made to accept the challenges of this stacking arrangement and gain the benefits of parallel burn and solid propellant boosters. Interference effects were reacted to with a comprehensive wind tunnel test program and design conservatism. The controllability concerns were eliminated by gimballing the solid rocket motors as a part of the active flight control system, and accepting the higher development and operating costs. The heavy propellant (liquid oxygen) was located forward in the expendable tank for center of gravity control and, to improve load path efficiency, the principal thrust from the boosters was brought in through the forward attach points. In order to deal with the structural dynamics concerns, a very comprehensive program of analysis, model testing, full-scale element testing, and full-scale mated vehicle testing was established and directed toward an accurate understanding of the vehicle vibration characteristics (See Figure 6). Stability criteria were established, and as the digital flight control design evolved, gains and filters were developed that met these stability criteria with reasonable error margin applied to the structural response characteristics of the vehicle. A comprehensive pogo stability analysis and prevention plan was established early in the program, and when a stable but marginal interaction between the structure and the Orbiter main engine was detected analytically, pogo suppressors were added to the engines in order to establish a comfortable margin. During the main propulsion test program, pressure pulses were introduced into the propellant fuel lines in order to verify the pogo analysis program. The high thermal and vibro-acoustic environment was accommodated by detailed Orbiter design and the willingness to live with relatively high vibro-acoustic levels during launch.

What can we learn from a review of the stacking arrangement decision? First was a willingness to accept the challenge of a previously untried stacking arrangement in order to gain the attendant overall system advantages described. However, the program was implemented by relatively conservative decisions in an effort to avoid detail problems in flight control or pogo. The message here is that the technology must exist in order to deal in detail with the consequences of major configuration decisions, and when developing a new configuration, one must be willing to expend the resources (analysis, test or weight) to assure effective implementation. For example, a major pogo or flight control problem must be avoided if at all possible when one moves into the flight phase of a complex manned vehicle like the Space Shuttle. The consequences of cutting the margins too thin are just unacceptable.

Control Configured Vehicle

Another significant but relatively easy configuration decision involved how to insert the pilot into the control loop of the Shuttle. For years, designers of aircraft have struggled with the desire to give the crews direct mechanical access to the primary flight controls and to provide a basic airframe capability that was stable and controllable for all flight regimes with minimum system augmentation. For a vehicle that must traverse the extremely broad flight envelope involved in orbital operations, it was clear that this desire was outdated, and if pursued, would lead to very complex development paths with questionable probability of success. Much time and effort could have been spent working with variable geometry, complex vehicle contouring, tricky piloting tasks, and even with our best efforts, significant augmentation techniques would have probably been required. Instead, it was decided to simplify the vehicle geometry and provide for adequate vehicle stability and control through a highly reliable avionics system. A major effort in the program was spent in developing a guidance, navigation, and control system having a high tolerance to failure in the primary system and protection against a generic software problem by the incorporation of a backup system having a different software program (Figure 7). Significant ground testing was carried out in software and hardware laboratories built to closely replicate the flight system. The resultant development path was long and tedious, also one of the critical paths in the program. However, results with the flight control system have been very satisfactory. Stability and control characteristics during launch, orbital, entry, and terminal phase (down to flare) operations have been very satisfactory. The auto land system has not been sufficiently utilized all the way to touchdown to have a good evaluation at this time, and the "control stick steering mode," wherein the pilot provides steering commands to the control computer, appears to provide acceptable touchdown handling qualities, though not optimum. Any practical considerations to provide significant improvement in vehicle touchdown control (such as deployable or fixed cannards) resulted in unacceptable system compromises, and the handling qualities at landing are considered adequate for a vehicle of this nature.

In retrospect, it appears that a complex, highly reliable stability and control system is a must, and the technology is available for a vehicle like the Space Shuttle. With this in mind, and the recognition that in the hands of good designers, a properly engineered digital flight control system can overcome significant shortcomings in aerodynamics, then one should not get the basic airframe shape too involved in complex contouring or variable geometry. Keep the shape relatively simple for attaching thermal protection systems and to minimize weight.

External Reusable Surface Insulation (Non-Metallic TPS)

Very early in the basic design evaluation, it was recognized that the option of building the Orbiter with conventional aircraft materials (aluminum, titanium, and composites) and protecting this basic airframe from the heat of entry by external reusable surface insulation had considerable merit. One could proceed along conventional lines and develop the basic structural airframe while working out and adjusting the details of the external non-metallic thermal protection system. The alternate choice available to the program was the so called "hot structure" approach wherein metals having the characteristics of strength at very high temperature would be developed and utilized in the basic structural airframe. This "hot structure" approach involved a more highly integrated structure and TPS and gave concern due to complex program interactions. This approach also required the development of new metals and coatings at least as complex and risky as the external TPS materials. When these tradeoffs were considered, the decision to follow the non-metallic, external TPS path became easy.

The early non-metallic TPS concerns were with the weight and insulation properties of the silica-fiber based tiles which were to be utilized over a large portion of the external surface area. These silica tiles were to be used in combination with carbon material for the very hot areas and cloth blankets in the cooler payload bay area (Figure 8). This total system was recognized as another critical program development path. The technology associated with the silica fiber tiles was evolving rapidly as the Shuttle development program started, and the weight and insulation characteristics of the tiles fell into place very nicely. Development of the carbon material and the cloth blankets was essentially straightforward. However, the structural characteristics of the silica tiles, together with the attachment details, were not sufficiently recognized as a potential development problem, and therefore resulted in a late program scramble to achieve structural certification. The need for detailed design and analysis of each tile was late in receiving proper program attention. Some unique stress concentrations brought about by the nature of the strain isolation material and the need to characterize the ceramic (silica) tile material structural properties in a more formal statistical sense all contributed to the late program effort required for tile testing and flight certification. Despite these development difficulties and the fragile nature of the tiles as they relate to daily operations, the choice of basic airframe construction and external non-metallic TPS remains, in my view, a proper configuration choice. I feel that the development progress of the program was considerably enhanced by the decision to separate the basic airframe structure from the TPS, and future improvements and refinements in TPS can be readily incorporated onto the flight system.

The lesson to be remembered here is that, when dealing with new materials, a thorough understanding of material characterization and careful attention to material applications is very important. However, it is a fact of life that many detailed problems cannot be recognized prior to actual application. In other words, until it came time to tile an actual full scale Orbiter, many issues were difficult to anticipate.

Unpowered Landings/Piggyback Transport

When one considers the overall system penalty to an earth orbital vehicle associated with carrying turbojet engines and their associated fuel all the way to orbit and back, it becomes very clear why the unpowered landing approach was desirable. However, a 200,000 lb. glider with a very low lift-to-drag ratio at the end of a landing strip many miles from its normal operating base presents some interesting logistics problems. In considering the various configuration choices during the early design phase of Shuttle, considerable unpowered landing research work had been previously accomplished, and the energy management and handling quality requirements for a safe unpowered landing appeared achievable. However, little attention had been given to the logistics issues. Glider-type towing and turbojet engine ferry kits were considered as possible solutions; however, a space shuttle optimized for the orbital task does not readily adapt to horizontal takeoffs and cross-country atmospheric flight. The penalty involved in providing for a reasonable ferry capability was found to be very undesirable. Fortunately, we had in existence in this country at this decision time in the Shuttle Program at least two large aircraft (C-5 and 747) suitable for carrying an unpowered Orbiter in a piggyback configuration. In the history books were several examples of aircraft that had been operated successfully in this flight mode, and some exploratory wind tunnel work assured that a very reasonable flight transport mode could be developed. In addition, this configuration approach provided the capability for some early approach and landing tests prior to first orbital flight. The 747 was ultimately selected as the Shuttle carrier aircraft, the required modifications were carried out in a very straightforward manner, and the operation has proven very successful (Figure 9).

Unpowered landings of the Orbiter have gone well to date (Figure 10). Energy management during entry and in the terminal approach phase has consistently placed the Orbiter in a favorable position relative to the runway, and vehicle handling qualities have been satisfactory for flare and touchdown control in the limited range of landing conditions encountered to date. As mentioned previously, Orbiter handling qualities during landing, while perhaps not optimum, are considered to be reasonable for a vehicle that must operate over a very broad range of flight conditions and any modifications that appear to offer significant improvements introduce unwarranted system penalties or complexities.

The piggyback transport mode has been very successful and was used to air launch the Orbiter in support of the approach and landing tests conducted during the development phase. These tests highlighted some shortcomings in the Orbiter flight control system that were corrected prior to first orbital flight and, in addition, provided experience and confidence prior to the first orbital flight.

In reviewing this configuration choice, the unpowered landing/piggyback transport mode of operation has proven to be very satisfactory. The development paths that resulted have been relatively trouble free, and the Orbiter design has been optimized for the orbital mission with minimum impact from the landing and post-landing requirements.

Manned First Orbital Flight

Previous manned spaceflight programs (Mercury, Gemini and Apollo) all utilized unmanned test flight vehicles to explore the flight envelope prior to committing to manned operations. Considering the experience base available at the time of these early development programs and the characteristics of the systems being developed, these unmanned tests were a very rational approach. However, unmanned flights introduce additional configurations and costly development steps into the overall process, and when the Shuttle development approach was being established, two important factors appeared significant. First, the Shuttle Orbiter was a considerably more complex vehicle when operating in the entry and landing phase than the capsule-type, parachute landing vehicles of the earlier programs and would, therefore, benefit significantly from having a man onboard to manage systems and control the landing.

Second, there was a much higher experience base in the government/industry complex than existed at the time the development approach was established for the previous manned spaceflight programs. The approximately 14 year span of these programs gave good insight into launch, orbit and entry issues. The wealth of aircraft and lifting body experience gave a good understanding of the terminal approach and landing phase requirements. This total background of technology development and experience base gave a feeling of confidence toward direct commitment to manned first flight.

Therefore, when one considered the significant benefit of having man on a Shuttle-type vehicle and the experience base available to support the development program, the option of manning the first orbital flight proved reasonable (Figure 11).

Based on experience gained from previous programs, a formal certification process was established and rigidly followed in the preparation for first flight. This certification activity included development testing, qualification testing, analysis, and a broad management review and concurrence at all program levels. This process established the reasonableness of a manned first flight baseline. Shuttle flight experience to date has been very satisfactory and, in retrospect, the approach of manning the initial flights appears justified.

Future Technology

I have discussed a small sample of the typical program configuration decisions that must be faced when a new complex vehicle development is undertaken. When it came time to develop the logic and make these choices for the Space Shuttle, in most cases a good foundation of technology and experience was available, and a satisfactory development program ensued. This technology and experience base was due mainly to the research and developments that had been pursued in this country during the previous 25 years:

- The research airplane programs from the X-1 thru the X-15 including lifting body vehicles;
- The high speed wind tunnels and the unmanned rocket assisted test techniques developed in the post-1945 era and the test and analysis programs which they fostered;

- Rocket engine and launch vehicle developments;
- The focused developments of manned space systems starting with Mercury and continuing thru Apollo and Skylab;
- Numerous advanced technology efforts without focused program objectives.

This composite activity provided the experienced people and the knowledge necessary for a successful Space Shuttle undertaking.

As one projects into the future and speculates on a second generation Space Shuttle development, one could expect to see a continuing spectrum of research similar to that listed above if a solid base of technology and experience is to be maintained. One would also rightly expect the second Shuttle to evolve on a solid base of knowledge developed as a result of building and flying the first Shuttle. If one examines the above listing of past research activities, it becomes apparent that the Shuttle vehicle represents our principal ongoing activity in the first, third and fourth items listed. With this in mind, it becomes apparent that in addition to its primary mission of transportation, a comprehensive flight research program should be a Shuttle program objective. The basic operational experience to be gained while flying the Shuttle and understanding its operational boundaries will be invaluable when it comes time to consider what characteristics or improvements the follow-on vehicle should have. However, if proper design refinements are to be made, then detailed design-type data must also be developed and recorded so that the next design team can be confident in their improved approaches. To this end, I would suggest the establishment of a research advisory committee charged with the responsibility of focusing Shuttle flight research objectives with a view toward developing better detailed design data for use as the technology base for future vehicle developments. This approach could draw on the combined skills of government, industry, and university groups in the best NACA tradition. The group, to be effective, must have adequate influence on program priorities and funding. They must also produce well thought out flight research objectives and compliment these flight data with other ongoing research activities. The Shuttle today routinely operates over a range of flight conditions that were impossible to achieve with research tools of only a few years ago. Let's not miss the opportunity of piggybacking this research effort as the Shuttle moves into routine operations.

Closing Remarks

As a result of reviewing the evolution of the Space Shuttle design and the logic of the configuration choices that were made, I would like to leave these two thoughts.

FIRST: The requirements for the Space Shuttle could, of course, have been met by any one of several design approaches. The logic behind any group of design choices depends to a large extent on the experience base and judgement of those charged with the responsibility; the technology base that exists at the time the choices must be made; and such practical considerations as funding and overall program support. For the Space Shuttle, the technology base was very adequate, and the resulting vehicle appears to be performing well. It remains to be seen whether the nation will fully utilize the vehicle in the very broad transportation mode for which it was conceived. I have high hopes that this will, in fact, be the case.

SECOND: The technology base that was so helpful at the time of the Shuttle design was primarily the product of earlier flight and advanced research programs. The Shuttle is today routinely operating over a range of flight conditions impossible to achieve with conventional research tools. The Shuttle program should, therefore, take steps to effectively contribute to the detailed technology base of future Shuttle designs.

REFERENCE

1) Love, Eugene S., "Advanced Technology and the Space Shuttle, Theodore Von Karman Lecture," AIAA 9th Annual Meeting and Technical Display, Washington, D. C., January 8-10, 1973.

FUNDING GUIDELINE EFFECT ON SYSTEM CONCEPTS

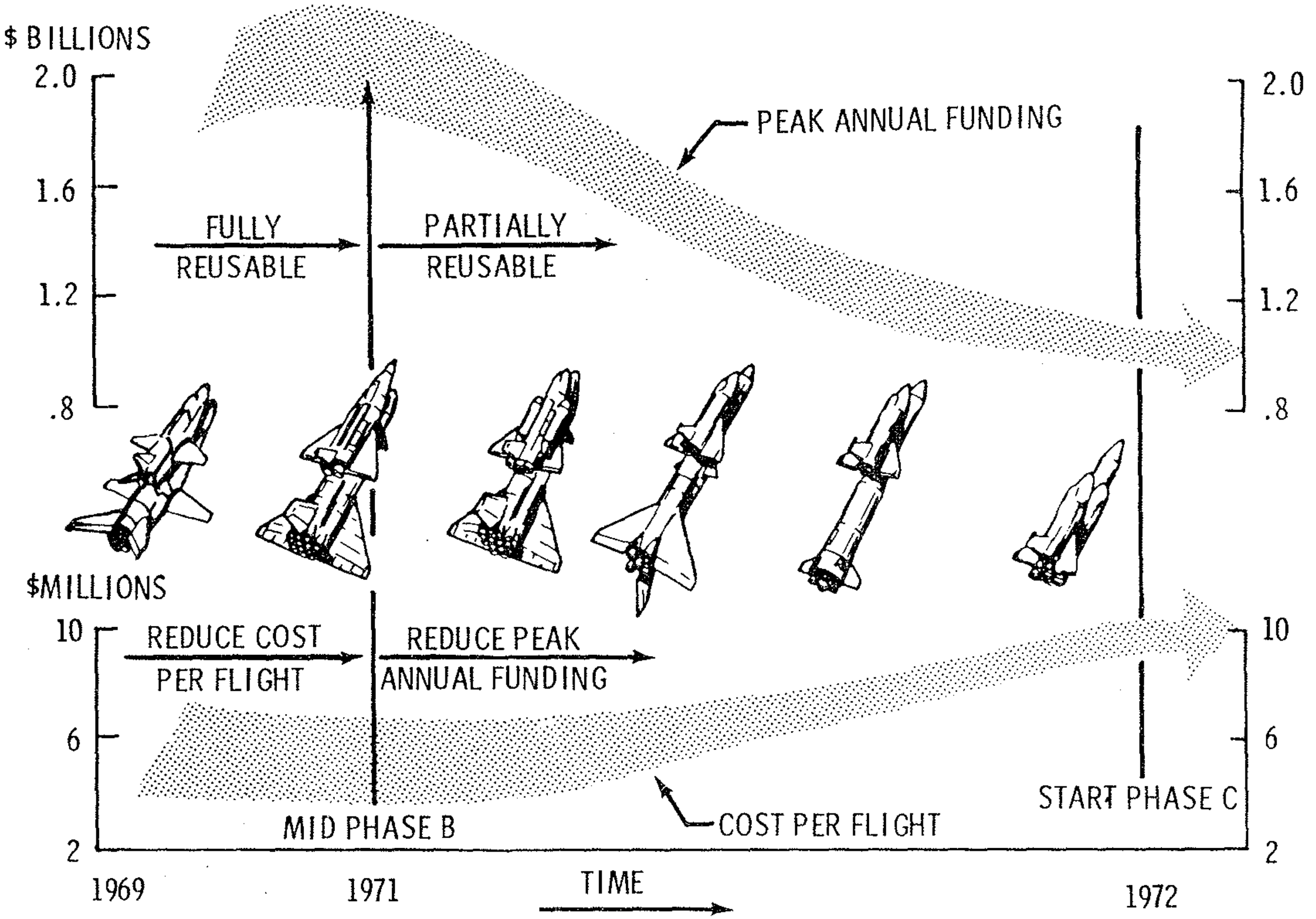


FIGURE 1.

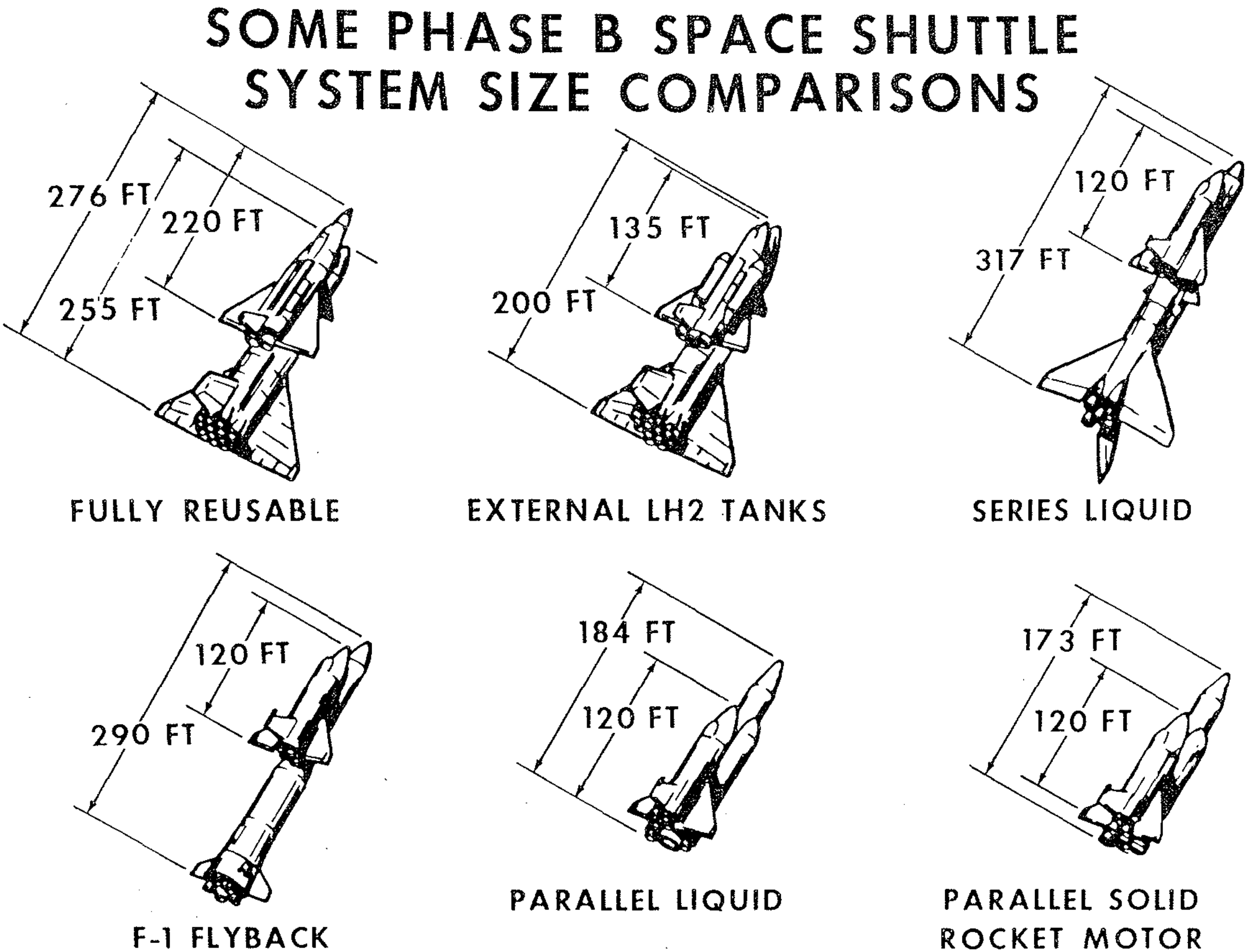

SOME PHASE B SPACE SHUTTLE
SYSTEM SIZE COMPARISONS
276 FT
220 FT
255 FT
FULLY REUSABLE
135 FT
200 FT
EXTERNAL LH2 TANKS
120 FT
317 FT
SERIES LIQUID
120 FT
290 FT
F-1 FLYBACK
184 FT
120 FT
PARALLEL LIQUID
173 FT
120 FT
PARALLEL SOLID
ROCKET MOTOR

FIGURE 2.

SPACE SHUTTLE COST COMPARISON

65,000 LB P/L - DUE EAST LAUNCH

15 FT DIA × 60 FT PAYLOAD BAY

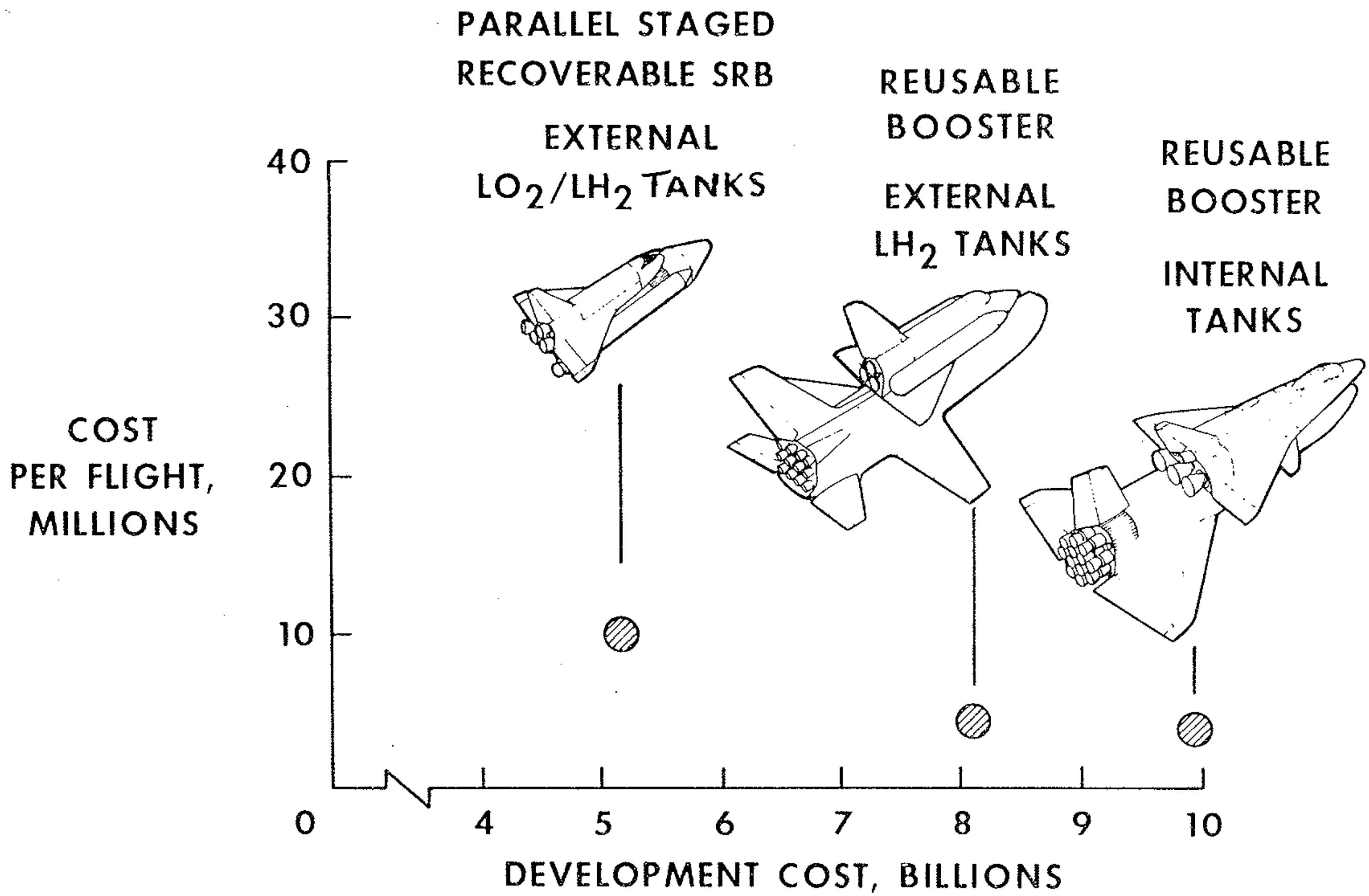
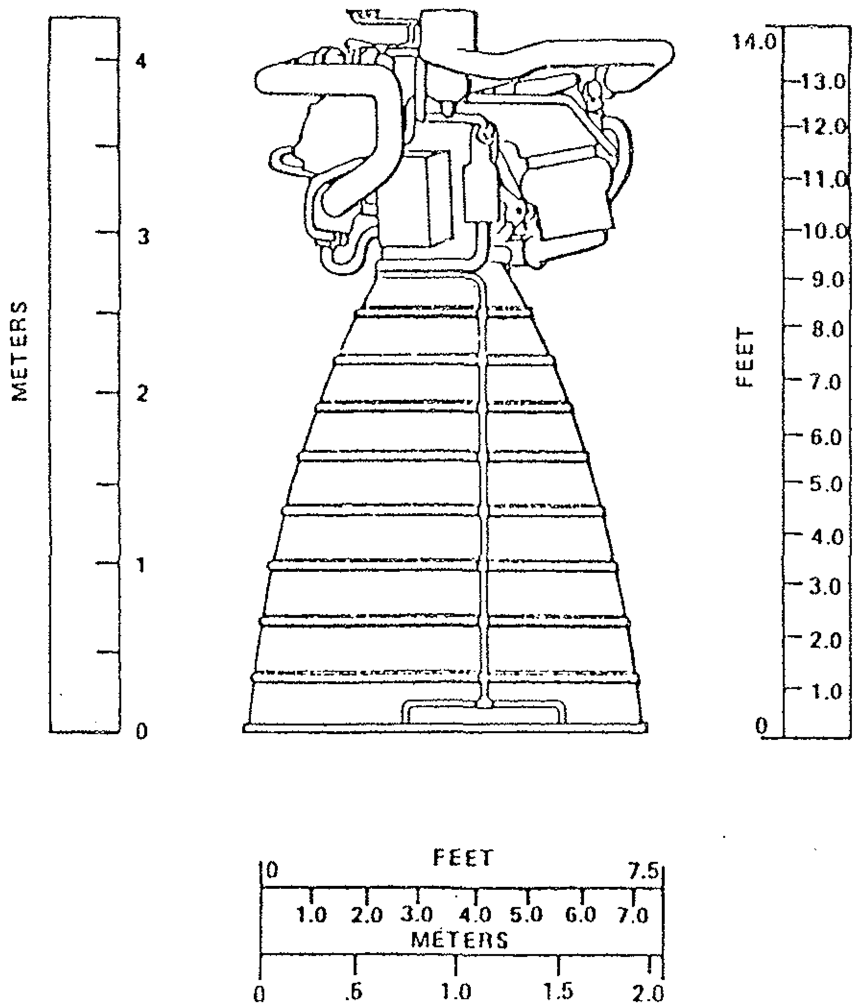


FIGURE 3.

SPACE SHUTTLE MAIN ENGINE CHARACTERISTICS



CURRENT ENGINE WEIGHT~7000 LB

THRUST		
• SEA LEVEL	375K	(1,668,080 N)
• VACUUM	470K	(2,090,660 N)
FPL	109%	109%
CHAMBER PRESSURE	2970 PSIA	2048 N/cm^2
AREA RATIO	77.5	77.5
SPECIFIC IMPULSE (NOM)		
• SEA LEVEL	363.2	3562 $\frac{N\ sec}{kg}$
• VACUUM	455.2	4464 $\frac{N\ sec}{kg}$
MIXTURE RATIO	6.0	6.0
LENGTH	167"	424 cm
DIAMETER		
• POWERHEAD	105" x 95"	267 x 240 cm
• NOZZLE EXIT	94"	239 cm
LIFE	7.5 HRS	7.5 HRS
	55 STARTS	55 STARTS

FIGURE 4.

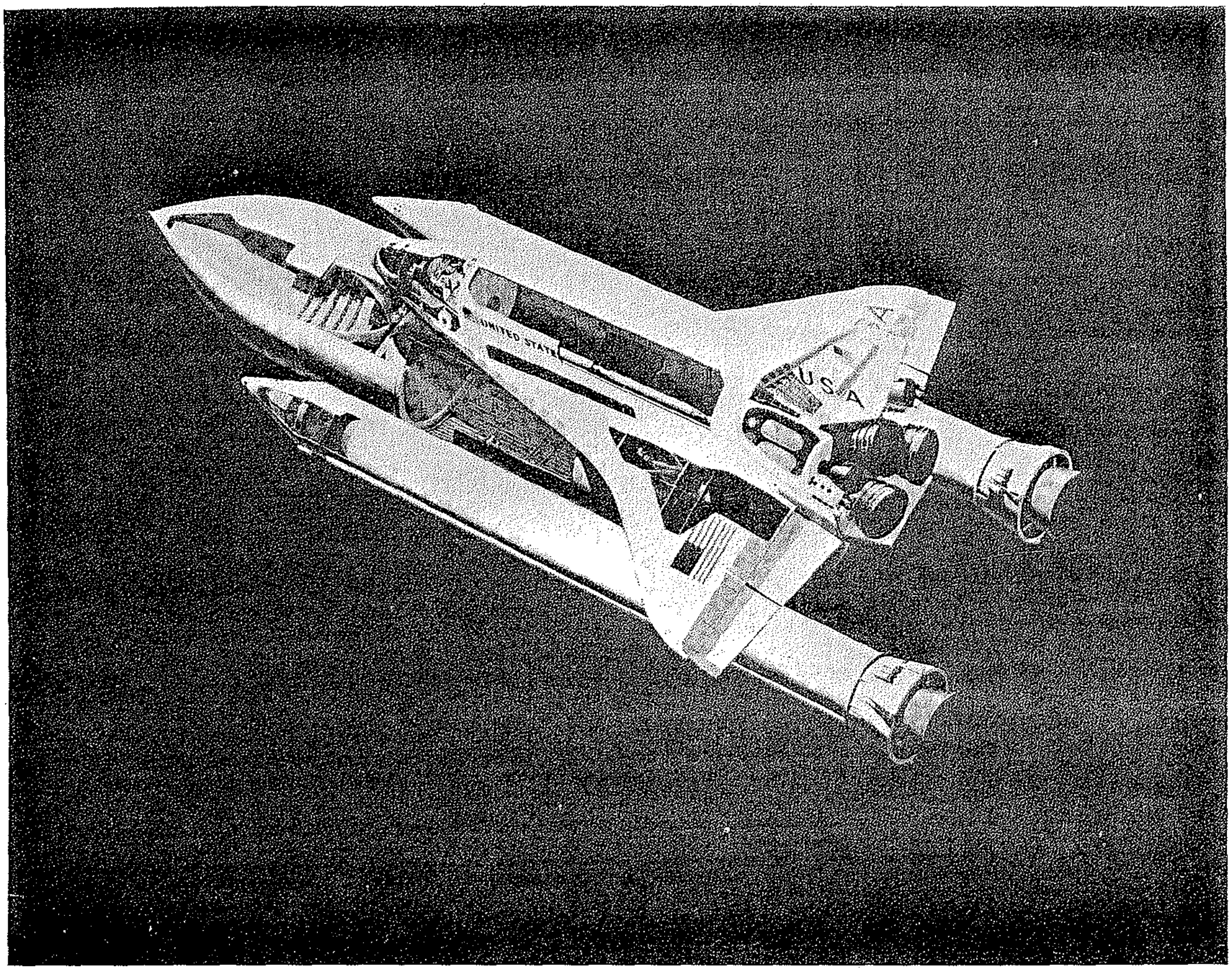


FIGURE 5. SPACE SHUTTLE LAUNCH CONFIGURATION

'BUILDING BLOCK' APPROACH
UNDERSTANDING OF SHUTTLE STRUCTURAL DYNAMICS

- EXAMPLE - VERIFICATION OF SHUTTLE STRUCTURAL DYNAMIC CHARACTERISTICS USED IN DYNAMIC STABILITY AND LOADS ANALYSES

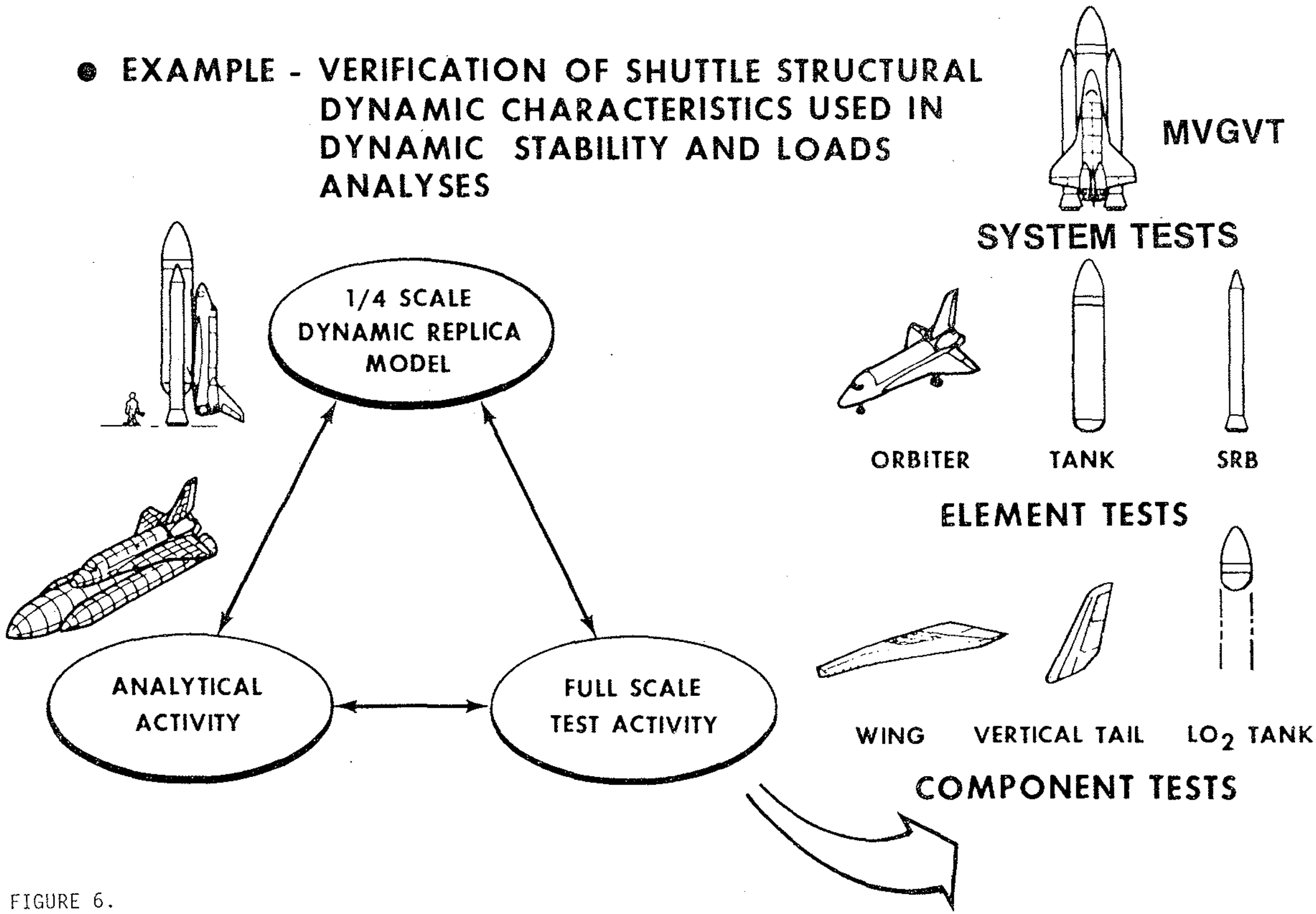


FIGURE 6.

SPACE SHUTTLE PROGRAM
GUIDANCE, NAVIGATION, AND CONTROL SUBSYSTEM
FUNCTIONAL BLOCK DIAGRAM

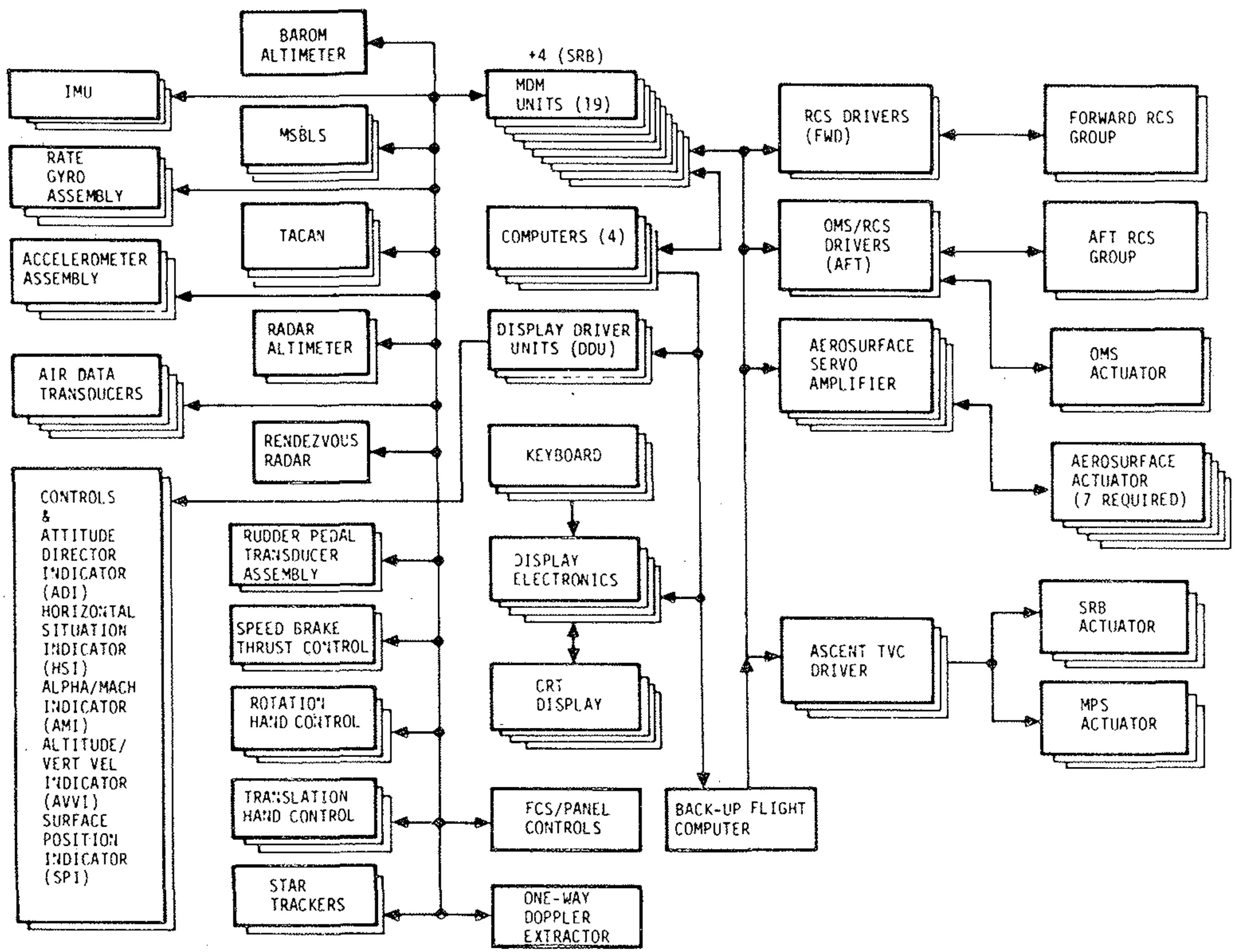


FIGURE 7.

THERMAL PROTECTION SUBSYSTEM

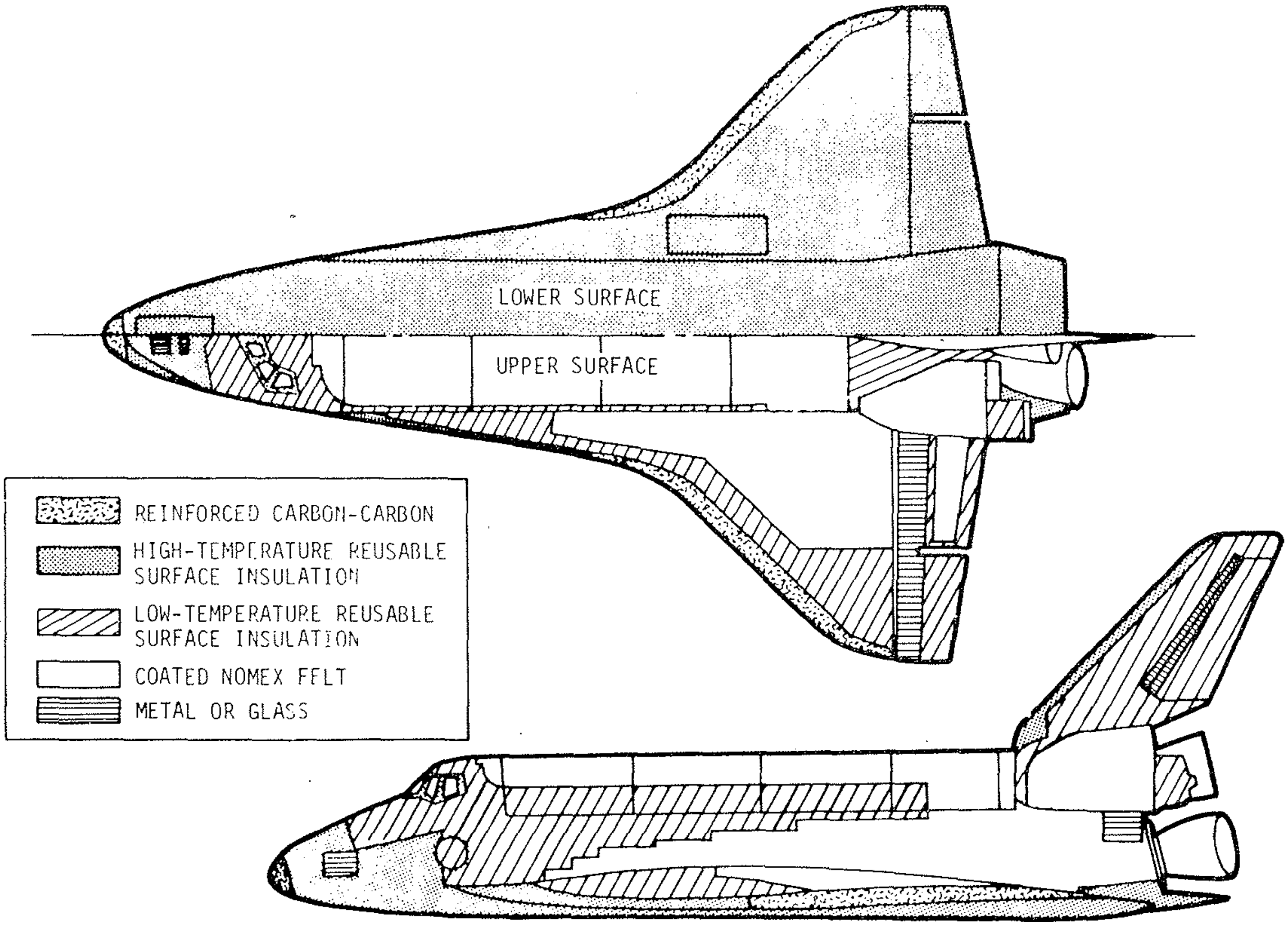


FIGURE 8.

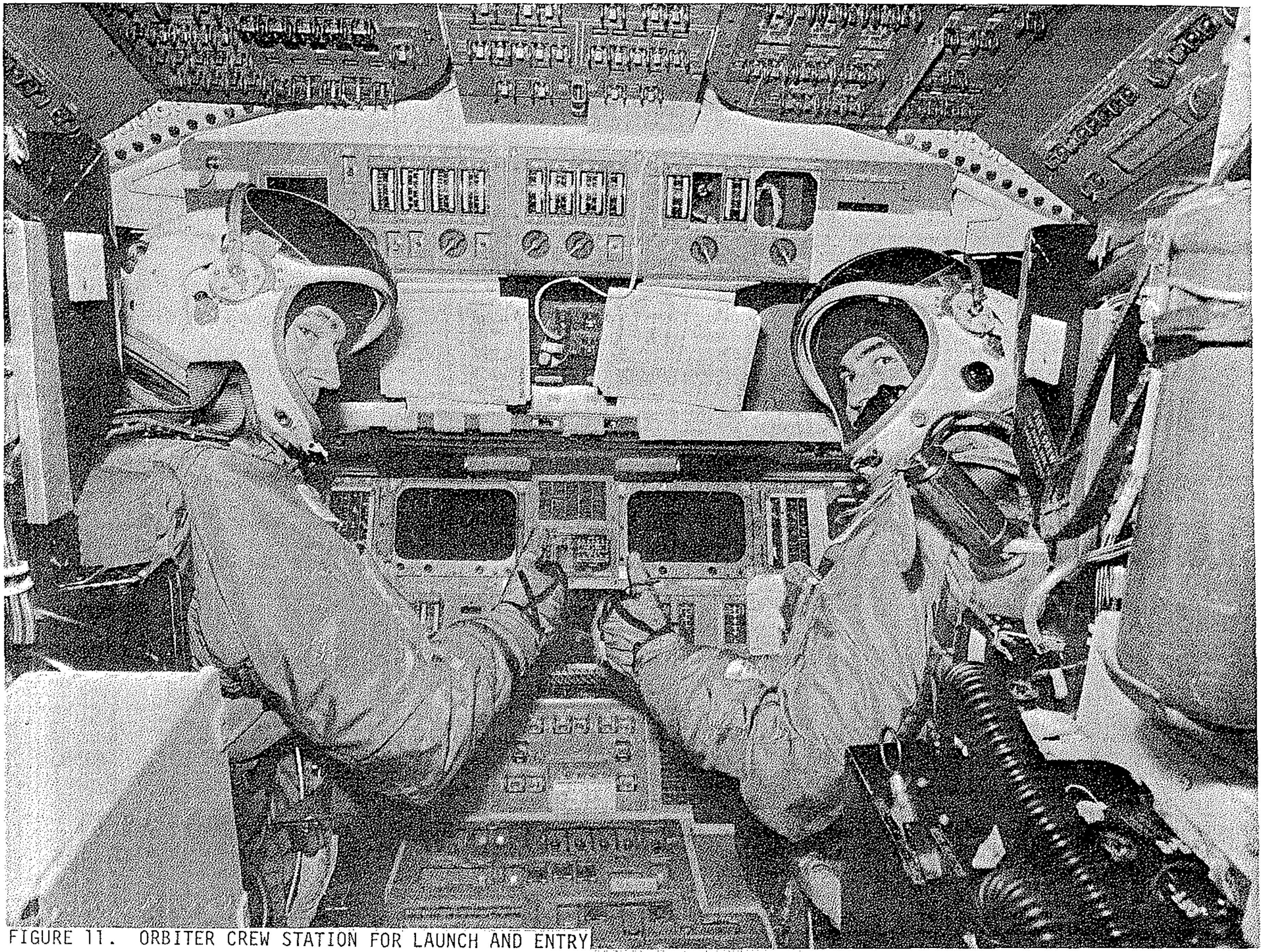


FIGURE 11. ORBITER CREW STATION FOR LAUNCH AND ENTRY