CURRENT STATUS OF THE SPACE SHUTTLE

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The Gemini and Apollo programs demonstrated the need for a follow-on program that would employ a reusable vehicle for the economical transportation of cargo and passengers to and from orbit. The intent of this report is to present the current status of the Space Shuttle. It should be noted that the present configuration trade studies are a long way from the drawing board, much less the flight status to which this group —and all pilots—look forward. Because the limitation in funding levels can be expected to continue, the Space Shuttle represents an engineering and management challenge to NASA and American Industry exceeding the Lunar Landing.

The major functions envisioned by an economical reusable shuttle are logistical support of a Space Station by carrying passengers, expendables and hardware, to and from orbit, and also a platform for special manned scientific missions of up to one month duration. It would serve as a launcher for a variety of scientific and application satellites, a recovery vehicle for repairable satellites that are profitable to relaunch, a launcher for interplanetary probes and other high energy missions where the propulsive stage is part of the payload, and would provide the capability for a variety of military missions.

The objectives of a low cost, economical space transportation system were further defined to provide:

1. An operating mode geared to reduce costs at least an order of magnitude below present operating costs.
2. A flexible capability to support a variety of payloads and missions.
3. An airline type operation for passengers and cargo.
4. A reusable system with a high launch rate capability, short turn-around and reaction times compatible with rescue missions.
5. A development mode balanced to minimize total program cost.

The Space Task Group investigated the feasibility of an economical space transportation system. This Group's Space Shuttle System Characteristics Report presented a summary analysis of 23 mandatory and 19 desired shuttle characteristics. Some of these were: shirtsleeve operation, two week turn-around, 10,000 foot runway operations, and landing characteristics and handling qualities comparable to operational land based aircraft. The design mission from this report was a logistics mission to a

270 nautical mile orbit at 55° inclination with the vehicle carrying 10 passengers and expendables to and from orbit plus 50,000 pounds of cargo.

It can be seen from Figure 1 that this proposed capability and a 15' x 60' cargo bay size would serve as a replacement vehicle for all boosters currently in operation, excluding the Saturn V. The payload in a 100 nautical mile polar orbit compares almost identically with the payload in the shuttle reference orbit.

The payload and cargo bay volume, coupled with the reduced transportation costs afforded by the shuttle will change the character of satellite payloads. Preliminary estimates indicate that, for shuttle launched satellites, the reduction in complexity and miniaturization requirements could yield a satellite cost reduction of approximately 30%.

There are four phases to the Space Shuttle Program:

Phase A consists of an analysis of a proposed objective or mission in terms of alternate approaches or concepts and the conduct of that research and technology.

Phase B objectives are detail study, analysis, and preliminary design directed toward the selection of a single design, prediction of the scope, timing and cost of program, and identification of technology requirements.

Phase C consists of detail definition of the final project concept including system design and bread boarding of critical systems and subsystems. In this phase, reasonable assurance is provided that technical milestone schedules and resource estimates for the next phase are valid, and definitive contracts for Phase D can be negotiated.

In *Phase D*, final hardware design and development, fabrication, test and project operations take place.

Phase A studies consisted of four $450,000 and one $100,000 contracts and examined 1½ stage, triamese, and 2 stage fully reusable vehicles. These studies reflected 8 months of analyses plus a reporting period and commenced in March 1969.

The Phase B period, our current phase of activity, consists of two separate technical efforts monitored by individual NASA centers and a unique joint management of the 2 stage reusable vehicle study.

The Phase B engine selection is being monitored by MSFC and conducted concurrently with the vehicle effort. Three $6 million, 12 month study contracts were awarded in June 1970 to Pratt and Whitney Aircraft, Rocketdyne, and Aerojet General for design and cost studies on the high chamber pressure, LH/LOX, rocket engine for the shuttle's main propulsion system.

The objectives, in addition to engine requirements definition, are to provide data in support of vehicle studies and development plans, generate prototype engine design, and conduct analyses and component testing to demonstrate feasibility of design.

While the Phase B baseline engine is 400 K thrust, results of parametric studies for 250 K, 400 K, and 600 K engines in performance, weight, cost and schedule effects will be presented to the contractor. The engines must be throttleable between 50% and 100% of rated thrust to prevent exceeding the maximum allowable launch acceleration limit of three *g*.

Paralleling Phase B is a $4 million, 12 month Phase A type study contract, investigating alternate shuttle concepts being conducted by Grumman Aircraft and monitored by MSC.

NASA desires that the shuttle provide the optimum earth to orbit logistic system in terms of total cost, development, and operational factors. Since there is no absolute assurance that the 2 stage fully reusable configuration under study would meet this optimum, NASA-MSC let a Phase A type study contract to Grumman to investigate further some of the most promising alternate concepts from preliminary studies already conducted. This study will examine these alternate concepts in sufficient depth to allow meaningful technological, operational, and cost comparisons between these alternates and the concept being investigated in the Phase B study. The results of these alternate studies in conjunction with the Phase B study will provide NASA with the economic and technological information needed to formulate further plans for proceeding with the development of a low cost space transportation system.

The three basic concepts and key issues for each, being evaluated in depth in this study, are shown in Figure 2.

Concept A: A single reusable stage with propellant tanks and/or strap-on engines jettisoned during the flight. Does the cost of development and replacement of expendable tanks and/or engines or the cost of development, refurbishment, and maintenance of recoverable tanks and/or engines show an economic advantage over the other types of booster stages?

Concept B: A reusable orbiter stage with an expendable lower stage. For current boosters, is a reusable orbiter sized for use with a reusable booster compatible with the performance capability of existing boosters? For new booster designs, is the reduction in development cost coupled with the increase in replacement costs effective relative to a reusable booster for the traffic models considered?

Concept C: A two stage reusable system utilizing low thrust/low pressure existing engines (J2S) and strap-on jettisonable engines on the booster with eventual growth to a high thrust/high pressure engine system to eliminate the strap-ons. Will the use of an engine in advanced state of development reduce the funding rate requirement sufficiently to achieve early operational status? And if this is demonstrated, does the configuration have the flexibility and growth capability to yield future payload improvements?

Within each concept, many configurations will be explored to cover the widest spectrum of possibilities. The configurations within each concept will be compared for yearly and total costs, technological risk, and operational availability.

Guidelines, generally consistent with Phase B, are defined by the Study Control Document. A 1972 technological base and a 1977 IOC are to be used. Program costs are to be calculated on a traffic model of 10–75 flights/year while performing the Design Reference Mission–space station resupply in a 270 nautical mile orbit at 55° inclination–and to be exclusive of the payload cost. These guidelines specify a reusable orbiter, with a 200 nautical mile cross range and horizontal landing capability without airbreathing engines and sized for a 30,000 pound payload capability and a 15′ x 60′ cargo bay. The booster must be able to return to the launch site and possess go-around capability. Both stages must be ferryable and have intact abort capability.

One and one-half months after contract inception a configuration screening review was held in which 9 out of 29 configurations were recommended for additional study. Three of these were from Concept A, four from Concept B, and two from Concept C. Three months after contract inception another configuration screening review will be held, reducing the number of configurations for further study to four. At five months, a concept selection will be made and then, during the remainder of the study, a detailed preliminary design of the selected concept will be made.

The Statement of Work by NASA's Office of Manned Space Flight defines the depth of the present Phase B study effort being undertaken by the contractors on a 2 stage, fully reusable space shuttle with orbiters having both a 200 and 1500 nautical mile cross range capability.

The Study Control Document normalizes requirements to be applied by the contractors in the conduct of the Space Shuttle Phase B studies. These requirements are broken down into three levels, consistent with their priorities and related areas.

Level I Requirements are established by the Director of the Space Shuttle Program as necessary to achieve the objectives of the Phase B study. These requirements include those innumerated previously from the Space Task Group's Systems Characteristics Report and also:

1. GLOW–3.5 million pounds.
2. At least 1500 FPS usable Delta V in excess of injection orbit (50 x 100 nm) shall be provided.
3. Cargo range: zero to maximum–to and from orbit.
4. Mission duration: 7–30 days.
5. Two man flight crew but flyable under emergency conditions by one man.
6. 400 K SL thrust engines for MPS.
7. Booster/orbiter–100 mission lifetime.
8. Vehicle trajectory design load factors shall be 4 *g*, with 3 *g* capability for passenger-carrying missions.
9. Subsystems shall be designed to fail operational after failure of most critical component and to fail safe for crew survival after second failure.
10. Electronic subsystems shall fail operational after failure of two most critical components and to fail safe for crew survival after third failure.

Level II Requirements are established by joint approval of the Space Shuttle Task Team Managers at MSC and MSFC, and are those which affect both booster and orbiter. Examples of Level II Requirements are: series burning of the main propulsion system of the booster and orbiter; and no propellant crossfeed between stages.

Level III Requirements are established by the particular Shuttle Task Team Manager for the vehicle element within his area of responsibility. Examples of Level III Requirements are docking contact conditions, EVA provisions, cargo systems and delivery methods. These are established solely by MSC for the orbiter, with similar requirements generated by MSFC for the booster.

Two contractor teams were each awarded $8 million, 12 month contracts commencing June 1970 to study the two stage, fully reusable vehicle.

MSFC has technical monitoring responsibility of the contractor team headed by McDonnell Douglas. Martin Marietta, TRW, Pan American

Aviation, Sperry, Raytheon, and Norden are supporting subcontractors in the areas shown in Figure 3.

North American Rockwell is the prime contractor of the second contractor team for which MSC has the technical monitoring responsibility. General Dynamics, IBM, Honeywell, and American Airlines furnish subcontracting support in the areas depicted in Figure 4.

The overall Phase B Shuttle Management Plan can be seen in Figure 5. The joint NASA/USAF Space Transportation System Committee has the responsibility of resolving conflicts in requirements that arise between DOD and NASA.

While contract performance monitoring of the contractor teams rests with the appropriate NASA center, program integration is the responsibility of the Office of Manned Space Flight (OMSF) through the Vehicle Systems Integration Activity (VSIA), an intercenter body charged with implementing integration of program requirements in the Statement of Work. These requirements are defined in further detail by intercenter panels which have been chartered in representative areas (structures, flight control, etc.) and report to the VSIA board.

In addition, technical direction is given to the other contractor team by each center in the vehicle element that it has a particular competence (i.e., MSC gives this technical direction to MDAC for the orbiter, and MSFC provides direction to NR for the booster). KSC will provide technological inputs to the contract monitoring centers in the areas of assembly, checkout, launch, refurbishment, safety logistics, resources and ground support equipment, as well as serviceability and maintainability.

Changes to Level I Requirements rest with OMSF Shuttle Program Office or the STS panel in the event the proposed change conflicts with DOD requirements. An example of a Level I change recently made is the deletion of the 3.5 million pound GLOW limit and the establishment instead of a 25,000 pound payload objective in the reference orbit.

Level II Requirements changes may be made with the concurrence of the VSIA board. In the event no agreement can be reached by this board, the proposed change becomes a Level I change.

Level III Requirements changes may be made within the respective NASA center.

The 12 month Phase B study is divided into three major segments as seen in Figure 6. The initial three months of the study consist of operations and mission analysis and trade studies leading to a configuration selection. Preliminary subsystem definition is also conducted. The second three months of activity are composed of subsystem evaluation and selection. System analysis and trade studies continue leading to an update of the baseline configuration. In the final period of the study, system design and integration is conducted, detailed program plans generated, and resource requirements defined.

Examples of trade studies currently in work in this first segment of the study are:

1. *Vehicle Propellant Distribution and Main Propulsion Sizing.
2. *H_2 vs JP4 for Booster Air Breathing Engines.
3. *Booster Cruise Back or Down Range Landing.
4. Manned vs Unmanned Booster.
5. PU System Requirements.

6. *Integral vs Suspended Main Tanks (Orbiter).
7. Radiation Survivability (Orbiter).
8. *Integral Passenger Cabin vs Cargo Bay Personnel Module (Orbiter).
9. Powered vs Unpowered Landing (Orbiter).
10. Launch Site Location.
11. Integrated vs Conventional Avionics.
12. Shuttle/Ground Communication Interfaces.

*Trade studies having a major configuration influence.

Recommendations of the Astronaut Office are made in some of these trade studies. In consideration of the impact of adverse public reaction and review board design recommendations in the event an orbiter were lost on the initial flight, we strongly recommended the retention of air breathing engines until the demonstration of unpowered landings eliminated the unknowns presented by a new guidance system, aerodynamic characteristics, and transition maneuver in a new vehicle.

The Phase B contract will be supported by a substantial test program throughout the major period of the study. These tests will provide supporting data that will assist in overall configuration selection and design. Further, the tests will guide the detailed definition in critical technology areas such as:

1. Establishing high temperature insulation material properties.
2. Establishing the characteristics of long life, high temperature materials suitable for external surfaces of the vehicle.
3. Developing design details, weight and performance capabilities of the integrated thermal protection system.
4. Predicting the thermal environment for vehicle design.
5. Verifying the aerodynamic characteristics of the vehicles.
6. Evaluating the flight control systems.

More than 1500 hours of wind tunnel testing was completed prior to Phase B by the two contractors in demonstrating the feasibility of their configurations. During the Phase B contract period, each contractor plans an additional 1500 to 1800 hours of wind tunnel testing in both contractor and government facilities. Aerodynamics and thermal testing are planned for Mach numbers ranging from .3 to 10.0 with Reynolds numbers from 30,000 to 10 million, and this data will be used to refine baseline configurations.

The shuttle system of Phase B consists of vehicles and all supporting equipment to accomplish the variety of previously mentioned missions at a rate of 25 to 75 per year.

The mission profile is depicted in Figure 7. Major events include the boost flight phase, on-orbit operations, booster and orbiter entry phase, and the ground operations cycle. All elements and events of this profile must be taken into account if a system is to be designed that is consistent with cost and operational objectives.

One of the first steps in the vehicle and system evaluation process is the actual sizing of the vehicles–i.e., determining boost/payload performance capability, optimum staging velocity, thrust to weight ratio, number of engines, etc.

This optimization process was performed by the contractors and resulted in the configurations shown in Figure 8. It is expected that the baseline configurations will change at the first quarterly reporting period, which is almost here, as a result of the completion of trade studies previously mentioned. GLOW approximates 3.3 million pounds for the low cross range and 3.7 million pounds for the high cross range configuration.

Booster configuration is dictated in a large measure by its operating range. The booster is designed to be an efficient rocket powered vehicle for some three minutes, an unpowered hypersonic glider for about 10 minutes, and a subsonic aircraft for approximately one hour and a half. A high angle of attack entry ($\alpha \simeq 55-60°$) and consequently a lower hypersonic L/D of 0.5 is satisfactory since cross range capability is not a criterion. Attitude control system thrusters provide maneuver and stabilization capability until aerodynamic surface are effective. Subsonic cruiseback, with L/D ratios between 6 and 7 is obtained by deployable or buried airbreathing engines. Propellant mass fraction for the booster configuration under consideration is approximately .80 to .82. While size is comparable to 747, liftoff weights average about 2,600,000 pounds.

Shuttle orbiter designs, as noted previously, are being developed to meet two entry cross range requirements. At this time, both contractors have adopted a straight wing configuration for low cross range and a delta wing configuration for high cross range.

The low cross range orbiter is at a very high angle of attack during entry with a L/D ratio of approximately 0.5. This is a hypersonic stable trim point, and there are subsonic stable trim points at both high and low angles of attack.

A typical low cross range entry trajectory is shown in Figure 9. With the vehicle trimmed near maximum lift coefficient, the altitude of entry is near maximum, thereby minimizing heating rates and radiation equilibrium temperature. At the same time, the high drag which has developed shortens the duration of the heat pulse. Thus both temperature of the skin of the vehicle and amount of insulation under the skin are kept small. Subsonic L/D's range between 6.3 and 8.2 with touchdown speeds between 150 and 180 knots.

The necessity to meet the high cross range requirement means that the orbiter must be flown at a hypersonic L/D of >1.8 during the major portion of its entry maneuver. Substantial surface areas are thus exposed to higher heating rates and consequently the high cross range orbiter must be provided with greater thermal protection. This requirement and associated structure accounts for a significant portion of the 50,000 pound difference in the gross weights of the two orbiter configurations—and the 300,000 pound difference in GLOWS. Subsonic L/D's range between 6.0 and 7.0 with landing speeds between 120 and 180 knots.

Both contractors' baseline Flight Control system is fly by wire. Consequently, failure detection and redundancy techniques have a strong flight safety influence. Hardwired vs multiplexing will be traded—with a comparison of failure detection and isolation, technical risks and costs.

Since cost is a major driver in the shuttle program, significant economics can result from considering the electro mechanical and avionics systems as an integrated system. Centralization of computations, standardized digital interfaces, and multiplexed data buses can offer significant weight and hardware savings and flexibility but must be evaluated against increased software and interface complexity and added cost.

Orbiter/booster commonality promises significant savings due to the reduced number of independent developments. Areas of commonality exist in many subsystems: in the environmental control and lift support (water boilers, heat exchangers, pumps, blowers and cold plates); in the main propulsion system (engines, prepressure valves, propellant feed and check valves); power system (transformer-rectifiers, generator control units, APU's, hydraulic pumps, valves, switching networks, AC generators); attitude control propulsion system (engines, regulators, gas generators, heat exchangers, propellant valves).

The use of an advanced approach might permit almost complete commonality in cockpit design between orbiter and booster. Since these vehicles must function both as spacecraft and aircraft, early participation by astronaut personnel is important to achieve idealized cockpit design.

Heads-up and multi-format CRT displays are a solution to the presentation of the increased informational requirements of the shuttle, as shown in Figure 10. If current approaches to controls and displays are used, the cockpit might be larger and more complex, requiring more than the two man crew now planned. Whether or not common booster and orbiter cockpits are possible, the avionics system is an area where savings can be made through commonality: data storage units, electronic display units, caution and warning systems, alpha-numeric message panels, IMU, communications equipment, antennas VOR/DME, ILS, and marker beacon equipment, etc.

In programs that lower total costs by reusing basic hardware, maintainability design is essential because operations and maintenance constitute a relatively large proportion of the total cost per flight.

Using cost data from the Saturn IB, let us develop a hypothetical case and assume the launch vehicle could have been recovered and used for 100 flights as proposed for the shuttle. As seen in Figure 11, the first bar represents 100%, equivalent to the total 123 million dollar IB mission cost. If the cost of the IB hardware were amortized over 100 flights and the same operations techniques maintained, we see, in the second bar of this chart a 60% improvement in total cost. It is interesting to note that operations now make up 99% of the total cost.

The next step is to demonstrate what happens when a vehicle is developed with refurbishment and operations in mind. Propellants costs are a function of total impulse and are relatively fixed. Consequently potential operations cost reductions must come from vehicle preparation and checkout time, and personnel involved in refurbishment, checkout, and operations. If operations costs could be reduced an order of magnitude with the same amortized hardware costs, the total mission cost, depicted by the third bar, has been reduced by 95%. While these numbers are purely hypothetical (except for the IB program), they do indicate a point. The goals for the space shuttle require that both hardware and operations costs be considered in realizing cost reductions of an order of magnitude in payload delivery. Consequently ground and flight support operations as well as maintainability features in design will receive considerable attention in the Phase B study.

The objectives of Phase B are to develop the best shuttle system by confidence in our designs and performance in our cost and schedule projections. The three most critical issues faced in Phase B and throughout the shuttle development program are:

1. Maintaining the vehicle weight targets and thus predicted performance.
2. Achieving the projected total program, production and operational costs.
3. Developing the system to meet the initial operation capability goals.

Through recent space program achievements, American Industry and NASA have demonstrated the ability to meet performance and schedule goals despite technological and management hurdles. Now we must devote equal energy to improving our cost performance. I am confident we shall meet this objective as well and that the space shuttle will develop into the space transportation system of the 70's and 80's.

If this country is to have a role in manned space flight after 1973 and not concede a major capability to those who might someday be our enemies.... if we are going to pursue a course that accrues the benefits to *all* people of forced technological advancement.... then the Space Shuttle is our only hope.

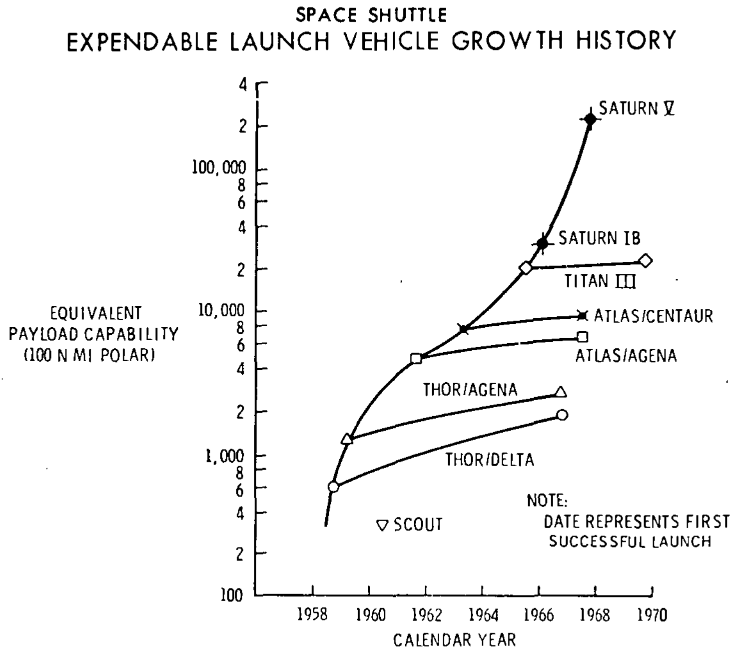

FIGURE 1
BOOSTER PAYLOAD CAPABILITIES

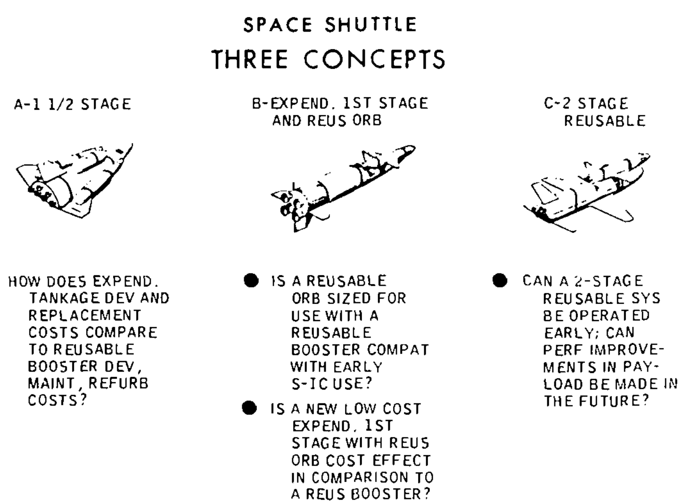

FIGURE 2
GRUMMAN PHASE A TYPE SHUTTLE STUDY

SPACE SHUTTLE

MCDONNELL DOUGLAS - PRIME CONTRACTOR

OVERALL BOOSTER AND ORBITER DEFINITION AND INTEGRATION

● SUBCONTRACTORS	● AREAS OF SUPPORT
MARTIN MARIETTA CORPORATION	BOOSTER AND ORBITER SUPPORT PROGRAM INTEGRATION
TRW	INTEGRATED AVIONICS MISSION OPERATIONS, ANALYSIS AND PLANNING
PAN AMERICAN AVIATION	MAINTENANCE AND TURNAROUND FACILITY AND TRAINING REQUIREMENTS
SPERRY	FLIGHT CONTROL SYSTEMS
RAYTHEON	ONBOARD COMPUTER
NORDEN	DISPLAYS

FIGURE 3
PHASE B CONTRACTOR TEAM MONITORED BY MSFC

SPACE SHUTTLE

NORTH AMERICAN ROCKWELL CORPORATION PRIME CONTRACTOR

PROGRAM AND SYSTEM INTEGRATION AND ORBITER DEFINITION

● SUBCONTRACTORS	● AREAS OF SUPPORT
GENERAL DYNAMICS CORPORATION	BOOSTER DEFINITION AND GROUND OPERATIONS
IBM	DATA MANAGEMENT - INTEGRATED AVIONICS
HONEYWELL, INC	GUIDANCE, NAVIGATION AND FLIGHT CONTROLS - INTEGRATED AVIONICS
AMERICAN AIRLINES	GROUND OPERATIONS AND MAINTENANCE

FIGURE 4
PHASE B CONTRACTOR TEAM MONITORED BY MSC

SPACE SHUTTLE

PHASE B SHUTTLE MANAGEMENT PLAN

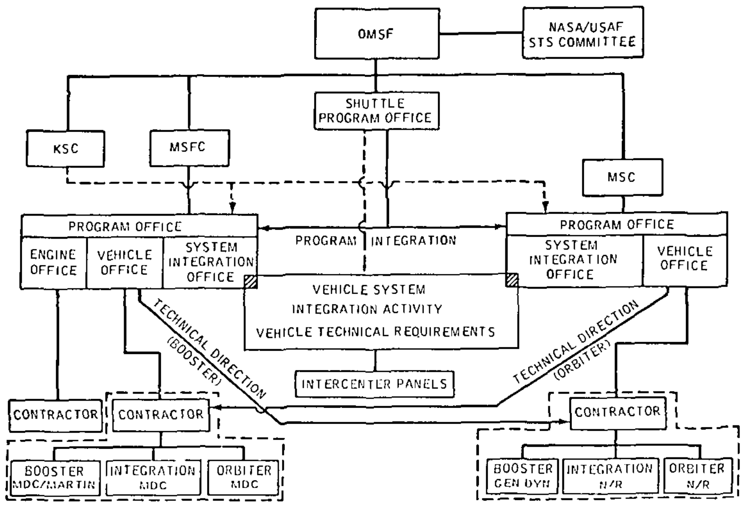

FIGURE 5
PHASE B SHUTTLE MANAGEMENT PLAN

SPACE SHUTTLE

PHASE B CONTRACT PLAN

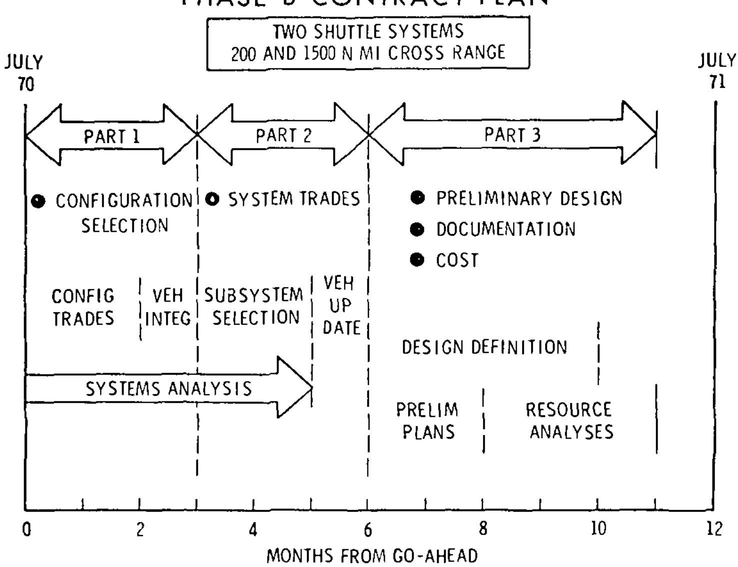

FIGURE 6
PHASE B CONTRACT PLAN

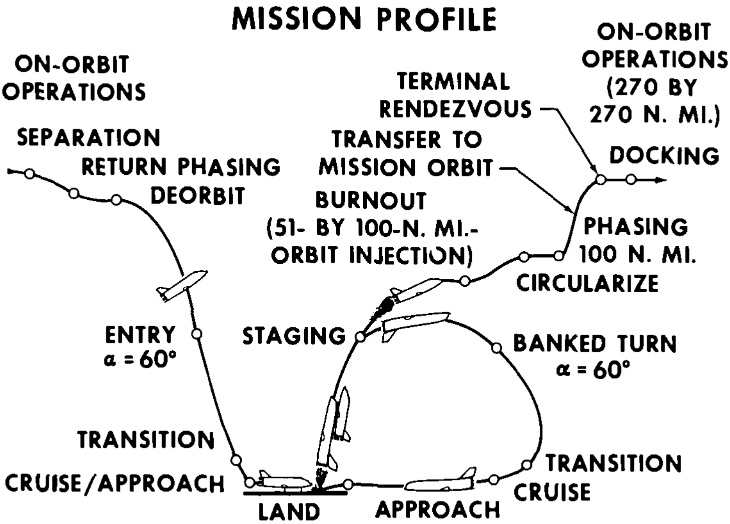

FIGURE 7
MISSION PROFILE

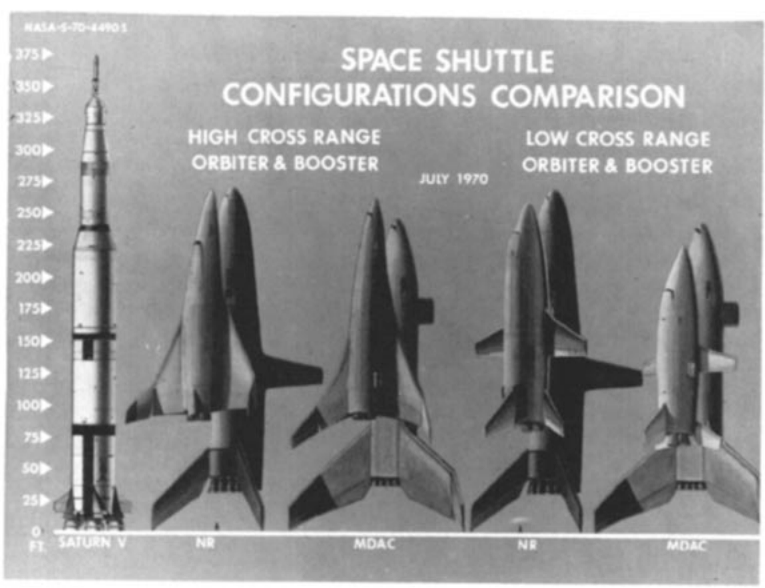

FIGURE 8
SPACE SHUTTLE CONFIGURATION COMPARISON

ENTRY TRAJECTORY

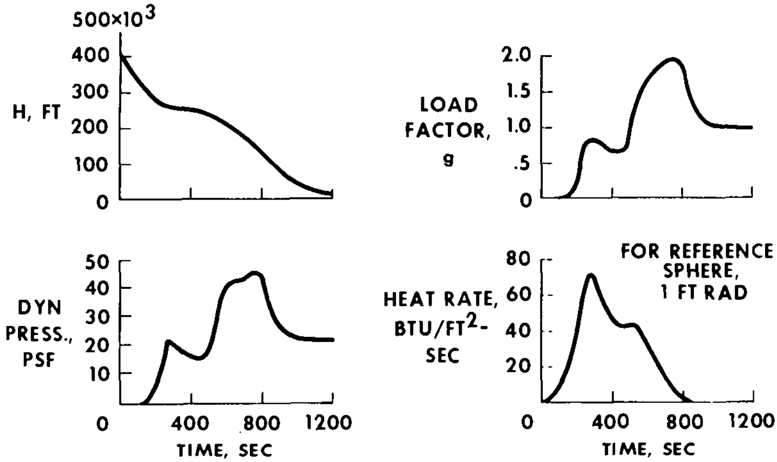

FIGURE 9
ENTRY TRAJECTORY

BASELINE ORBITER CREW STATION

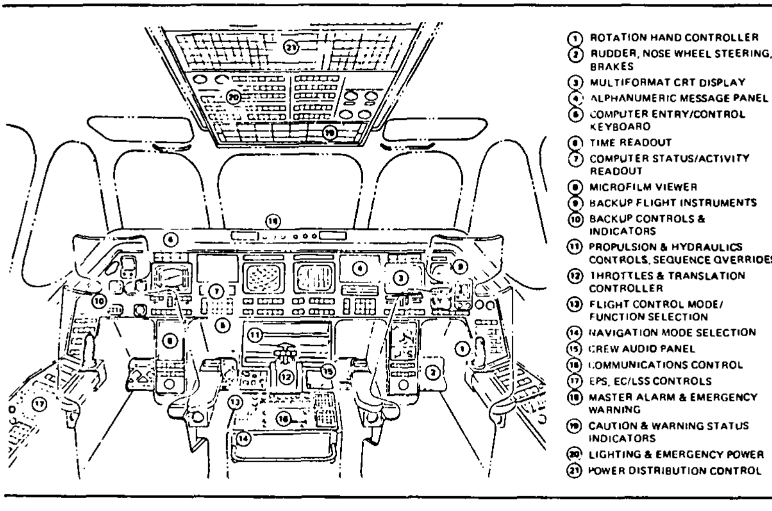

FIGURE 10
BASELINE ORBITER CREW STATION

SPACE SHUTTLE

SATURN IB TO SHUTTLE COST DEVELOPMENT

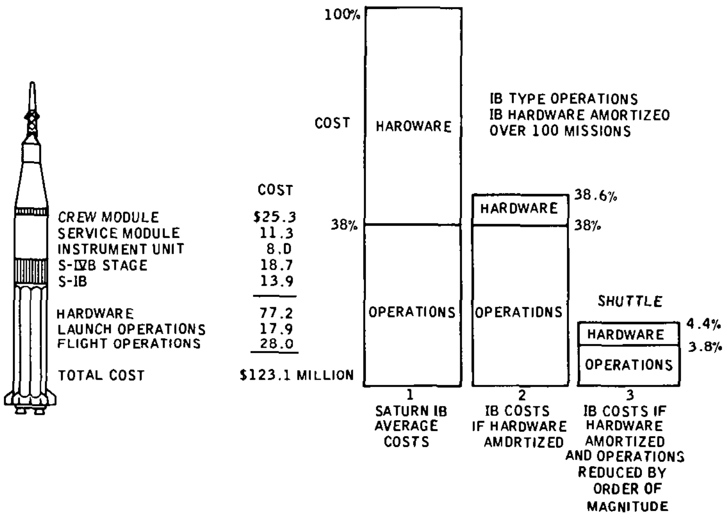

FIGURE 11

SATURN IB TO SHUTTLE COST DEVELOPMENT