AEROSPACE ENGINEERING
AE449 Senior Design Project III
Auburn University, Alabama

FINAL STUDY REPORT FOR THE SPACE SHUTTLE II ADVANCED SPACE TRANSPORTATION SYSTEM

Volume I: Executive Summary

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1.0 Project Summary

This report summarizes an investigation into the feasibility of establishing a second generation space transportation system. Incorporating successful systems from the Space Shuttle and technological advances made since its conception, the second generation shuttle presented here was designed to be a lower-cost, more reliable system which would guarantee access to space well into the next century. A fully reusable, all-liquid propellant booster/orbiter combination using parallel burn was selected as the base configuration. Vehicle characteristics were determined from NASA ground rules and optimization evaluations. The launch profile was constructed from particulars of the vehicle design and known orbital requirements. A stability and control analysis was performed for the landing phase of the orbiter's flight. Finally, a preliminary safety analysis was performed to indicate possible failure modes and consequences.

2.0 Review

The Advanced Space Transportation System (ASTS) is a program designed to initially supplement and later replace the current Space Transportation System (STS). Problems characteristic of the current system include a 1970's base technology level, high operational cost per launch, excessive turn-around time, and a low level of reliability.

An Advanced Space Transportation System, designed to enter service at the beginning of the twenty-first century, is the next logical step in the evolution of the space transportation program. Designed as a high-technology replacement to the STS, the Shuttle II offers the promise of lower operational costs and greater efficiency in both manned missions and cargo deployment. Its design will take advantage of industrial advances made since the original design of the current Space Shuttle. These advantages include, but are not limited to, composite materials, automated control systems, propulsion systems, hypersonic aerodynamics, and the experience gained from the present STS.

A number of factors deemed critical to its operational success and technical feasibility influenced the design of the Shuttle II. Among these were: decreased turnaround time, a lower cost per launch, emphasis on reliability over performance, maintaining a reusable system, low cost engines, pre-processed payloads, STS-developed technology, the presence of a permanently-manned space station, development of a Heavy Lift Launch Vehicle (HLLV) to off-load payload requirements, and compatibility of cargo/passenger transport with systems already operational.

To select the most practical and efficient configuration, a number of design classification parameters were examined. These included reusability of the system, the possibility of a manned booster system, the number of vehicle stages, the type of propellant used, and the type of burn staging. These five considerations were varied to determine all potential designs. These configurations were then subjected to primary evaluation criteria to select the optimum design. These criteria included the overall safety of the system, the performance of the system, the expense involved for the total ASTS program (including the cost per flight), and the operation and support of the system, including turnaround time, overhauls, and reliability.

The final design was required to meet National Aeronautics and Space Administration (NASA) ground rules for the ASTS. The proposed configuration was evaluated on its ability to deliver payload into the two standard orbits currently employed by NASA: a due-east launch from Kennedy Space Center into a 270 nautical mile orbit with an inclination of 28.5 degrees, and a launch from Vandenberg Air Force Base into a 150 nautical mile orbit with an inclination of 98 degrees. The proposed design was based on an anticipated 1992 technology level. Other ground rules included the ability to be transported by air from the landing site to the launch site, the ability to abort to orbit if an engine is lost during flight (engine-out capability), and an initial (sea level) thrust-to-weight ratio of 1.3.

After subjecting the potential configurations to the weighted criteria, the optimum ASTS design was determined to be a fully reusable system with an unmanned fly-back booster and a two-stage parallel burn of all-liquid propellants.

3.0 Proposed System Configuration Description

From the preliminary design studies, a fully-reusable system employing parallel burn from a manned orbiter and an unmanned flyback booster was determined to be the most efficient and economically feasible arrangement for extended life-cycles. It was further decided that the orbiter and booster would be designed to be as similar as possible to reduce development and production costs. The ultimate result of these decisions is the configuration presented here (See Figures 3.0.1 and 3.0.2).

The booster and orbiter will have a common fuselage, wing, vertical tail, and avionics and control systems. They will differ in the size and number of fuel and oxidizer tanks, number and arrangement of engines, payload, and passenger compartment. Design and construction costs will be minimized by having a common structure in which components can fit for either the booster or the orbiter.

3.1 Changes In Preliminary Configuration

The most dramatic change in the system concept involved the ascent propulsion system. Propulsion was originally divided equally between booster and orbiter vehicles. Subsequently, however, one of the STMEs from the orbiter was shifted to the booster, leaving the orbiter with a total of four engines and the booster with a total of six engines. This change was made for three principal reasons:

- to reduce the dry weight of the orbiter;
- to give the booster a larger thrust/weight ratio, thus making it more suitable as a general purpose booster that is not necessarily restricted to the Shuttle II system;
- to allow the booster to carry more propellant, lowering the gross lift-off weight of the orbiter and giving the booster a longer burn duration.

The fuselage was expanded by increasing the radius of curvature of the fuselage ceiling. This alteration allowed oxygen tanks on both vehicles to be increased from 26 feet to 28 feet in diameter. The hydrogen tank on the booster, which is similar in design to its oxygen tank, was also enlarged to 28 feet in diameter.

The crew compartment, originally envisioned as being two-storied (as in the present Shuttle Orbiter), was changed to a single-level facility to provide room for hydrogen tanks underneath the flight deck and forward of the cargo bay. The cargo bay was expanded, from the 60 feet x 15 feet size employed on the present shuttle, to encompassing all available volume (an irregularly-shaped section having 165% of the volume of the 60 feet x 15 feet section) in the sixty feet under the cargo bay doors.

Since the booster does not require a crew compartment and support facilities, cargo bay doors, its dry weight is some 20,000 pounds less than that of the orbiter. This figure includes the additional weight incurred by two extra engines and corresponding pumping facilities.

3.2 Wing

A delta wing configuration was chosen for its significant advantages over conventional constant-taper wings in terms of both heat shielding during re-entry and static stability.

The horizontal tail may be eliminated by using a delta wing which is both swept and twisted. Furthermore, flight experience gained from the STS can be incorporated into anticipated Shuttle II wing performance.

The wings on both the orbiter and booster are similar to that used on the current STS, but larger to accommodate the greater weight and fuselage length of the ASTS. The wing-loading does not significantly differ from that of the Shuttle Orbiter.

The following table lists the wing data used in aerodynamic analysis.

Table 3.2.1: Delta Wing Physical Characteristics

Root Chord	87.00 feet
Tip Chord	18.00 feet
Mean Aerodynamic Chord	51.12 feet
Aspect Ratio	2.800
Taper Ratio	0.246
Leading Edge Sweep	47°
Quarter Chord Sweep	42°
Trailing Edge Sweep	13°
Planform Area	5818 feet^2
Wetted Area	9738 feet^2
Body Width at Wing	30.0 feet
Body Height at Wing	28.0 feet

The wing mass is estimated as that of an aluminum wing sized to the same wing loading. The wing mass includes the box body section and main gear installation provisions. A constant thickness/chord ratio of 6% was assumed. Also, the wing will incorporate a control surface on each half-wing for lateral control of the orbiter vehicle.

3.3 Vertical Tail

A simple constant-taper vertical tail was chosen for both the orbiter and the booster. The only control surface incorporated into the tail is a combination rudder and speed brake. This design reduces both complexity and component weight, while not significantly impairing performance.

The following table lists the vertical tail data used in aerodynamic analysis.

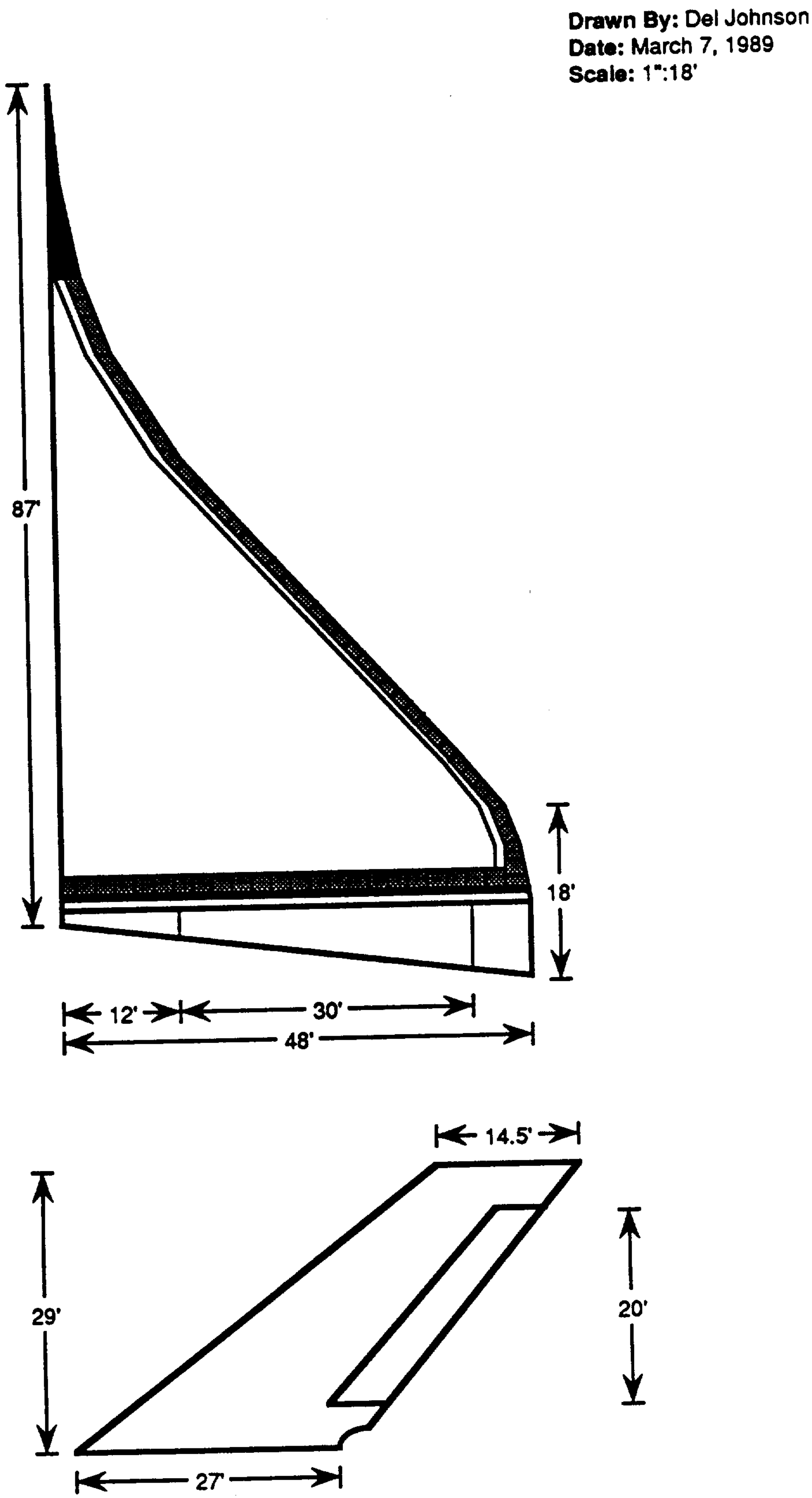

Figure 3.2.1: Top View of the Obriter/Booster Delta Wing and Side View of the Orbiter/Booster Vertical Tail

Table 3.3.1: Vertical Tail Physical Characteristics

Root Chord	29.00 feet
Tip Chord	14.50 feet
Mean Aerodynamic Chord	21.40 feet
Aspect Ratio	5.580
Taper Ratio	0.500
Leading Edge Sweep	52°
Quarter Chord Sweep	49°
Trailing Edge Sweep	41°
Planform Area	603 $feet^2$
Wetted Area	1206 $feet^2$
Z_F: Vertical distance between aircraft CG and AC_F	41.0 feet
l_f: Horizontal distance between aircraft CG and AC_F	48.0 feet

The vertical tail is a composite design with an estimated 80% of the unit mass of the aluminum tail on the Shuttle Orbiter.

A schematic of the vertical tail is shown in Figure 3.2.1.

3.4 Forward Fuselage

The first 50 feet of the fuselage is designated as the forward section of the fuselage. The forward section of the orbiter and booster are the most dissimilar parts of the two vehicles. The forward section on the booster is a shroud covering the upper section of the hydrogen tank. It is designed to be aerodynamically suitable for re-entry, and it contains the avionics and forward reaction control systems. On the orbiter, the forward fuselage houses most of the complex mechanisms not related to propulsion. It contains the flight deck, crew compartment, life support systems, external access mechanism, cargo bay access mechanism, all flight avionics, forward reaction control systems, and the most heavily thermally shielded section of the orbiter. The weight and number of components present in the forward section moves the center of gravity forward of the aerodynamic center.

The nose section consists of a semimonocoque shell structure with provisions for nose landing gear and items associated with crew support. The unit mass of this structure is 80% that of the aluminum design shell structure used on the Shuttle Orbiter. Crew module particular items contributing to this weight include thermal windshield, observation stations, access panels, and external and cargo bay access.

A schematic of the fuselage is shown in Figure 3.4.1.

3.5 Mid Fuselage

The mid section is designated as the sixty feet of fuselage behind the forward fuselage. This section has a constant cross-sectional area. On the booster, it is featureless. On the orbiter, it exclusively consists of the cargo bay compartment, external doors to the cargo bay, and room for the hydrogen tanks and their associated plumbing. The cargo bay doors are located across the top of the section for its entire length of sixty feet.

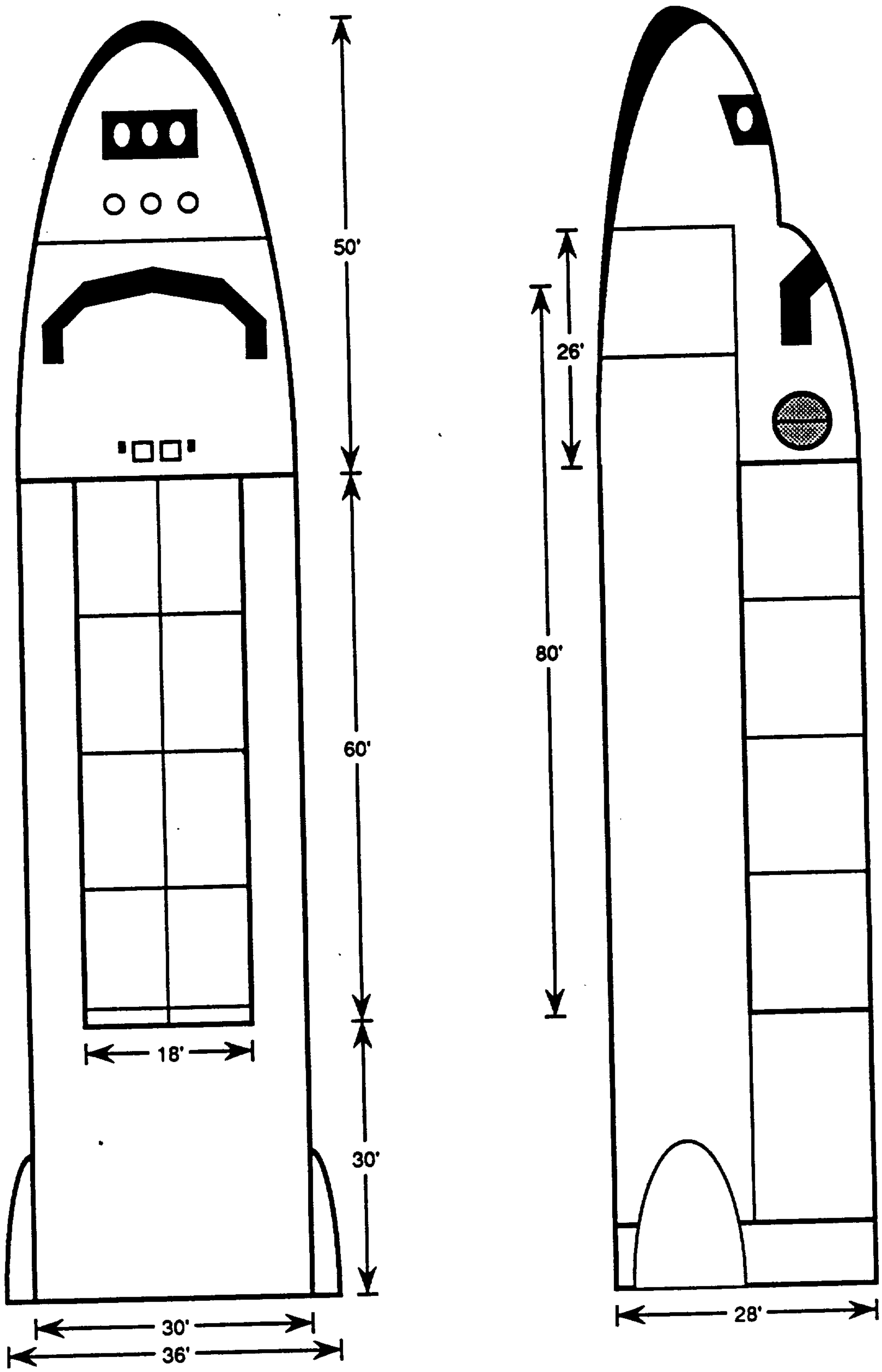

Figure 3.4.1: Top and Side Views of the Orbiter Fuselage

Drawn By: Del Johnson
Date: March 7, 1989
Scale: 1":18'

This section has a constant width of 30 feet and height of 28 feet. Only the mechanisms for opening and closing the cargo bay doors, structural reinforcements for the bay, and the doors themselves raise the weight above that of a simple hollow structure. The section is composed of an aluminum skin structure with aluminum honeycomb panels. Its unit weight is estimated at 80% that of the Shuttle Orbiter cargo area.

3.6 Aft Fuselage

The aft fuselage is the section which contains the oxygen tank and most of the plumbing for the main engines on both the booster and the orbiter. Structurally, it has constant area except for the fairings on either side to house the auxiliary propulsion. Since the number of engines on the booster differs from that on the orbiter, the rear panel is completely different between the two vehicles.

This section consists of a semimonocoque shell extending from the rear of the cargo bay to the engine support plane. It includes a 4 foot fairing on either side to house the orbital maneuvering system, a base heat shield support structure located at the engine support plane, and the body flap. Its weight is estimated at 80% that of the Shuttle Orbiter rear fuselage.

3.7 Fuel and Oxidizer Tanks

The fuel and oxidizer tanks for the booster and the orbiter differ in both shape and size. In the booster, which has a largely uniform cross-section available for its entire length, simple cylindrical tanks are used. In the orbiter, a more complicated arrangement is necessary to accommodate personnel and cargo. The location of the cargo bay immediately behind the flight deck and along the top of the fuselage leaves a large volume directly under the flight deck and cargo bay empty. The hydrogen tanks of the orbiter are located here to use this space most efficiently. These tanks are arranged symmetrically to insure proper weight distribution during ascent and landing maneuvers. The oxygen tank is located immediately aft of this section and just before the engine housing.

The liquid hydrogen tanks are all-welded titanium honeycomb sandwich pressure vessels with ring stiffened sidewalls. They are designed by cryogenic temperature proof test conditions corresponding to 3g boost acceleration with a maximum pressure of 26 psia.

The liquid oxygen tanks are all-welded aluminum pressure vessels with stiffened sidewalls. The tanks are designed by room temperature proof tests conditions corresponding to 3g boost acceleration with a maximum pressure of 26 psia.

The following tables contain summaries of the design specifications for tanks used in both the orbiter and the booster vehicles.

Table 3.7.1: Orbiter Tank Characteristics

Hydrogen Tanks:	
Number	2
Weight of Hydrogen	135,964.29 lb
Total Volume	31,112.40 ft^3
Overall Length	92 ft
Overall Diameter	15 ft
Oxygen Tanks:	
Number	1
Weight of Oxygen	815,785.71 lb
Total Volume	11,372.68 ft^3
Overall Length	22 feet
Overall Diameter	28 feet

Table 3.7.2: Booster Tank Characteristics

Hydrogen Tanks:	
Number	1
Weight of Hydrogen	198,280.61 lb
Total Volume	45,372.10 ft^3
Overall Length	92 ft
Overall Diameter	28.00 ft
Oxygen Tanks:	
Number	1
Weight of Oxygen	1,189,683.67 lb
Total Volume	16,585.10 ft^3
Overall Length	31 feet
Overall Diameter	28 feet

3.8 Payload Bay and Payload Bay Doors

The payload bay is located immediately aft of the flight deck on the orbiter. It is sixty feet long and a minimum of fifteen feet in diameter. It is designed to hold removable payload modules which have been pre-processed for placement in the orbiter either in the vehicle assembly building or on the launch pad.

An access hatch to the cargo bay is located at the rear of the crew compartment on the flight deck. Since the crew compartment is located in the upper half of the orbiter, the access hatch can open to the center of its fifteen foot diameter.

The doors of the cargo bay are formed from a graphite/epoxy composite to reduce weight and thermal distortion. These factors are of chief importance when the doors are opened and closed in space. Here they serve as heat exchangers and solar panels. Through use of composites rather than aluminum, the doors were estimated as having a unit weight 70% that of the Shuttle Orbiter.

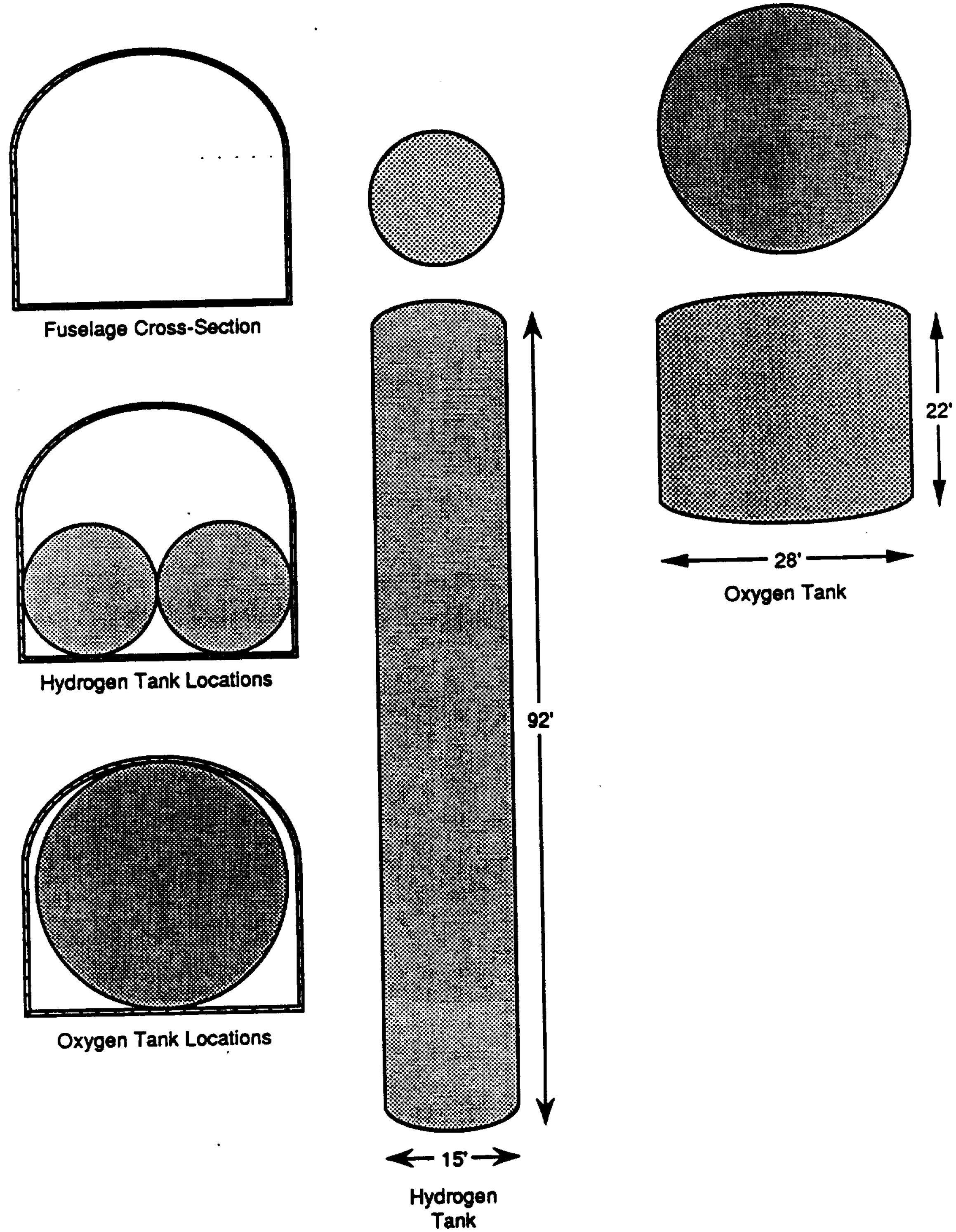

Figure 3.11.1: Schematic Diagrams of the Liquid Hydrogen and Liquid Oxygen Tanks for the Orbiter

Drawn By: Del Johnson
Date: March 7, 1989
Scale: 1":18'

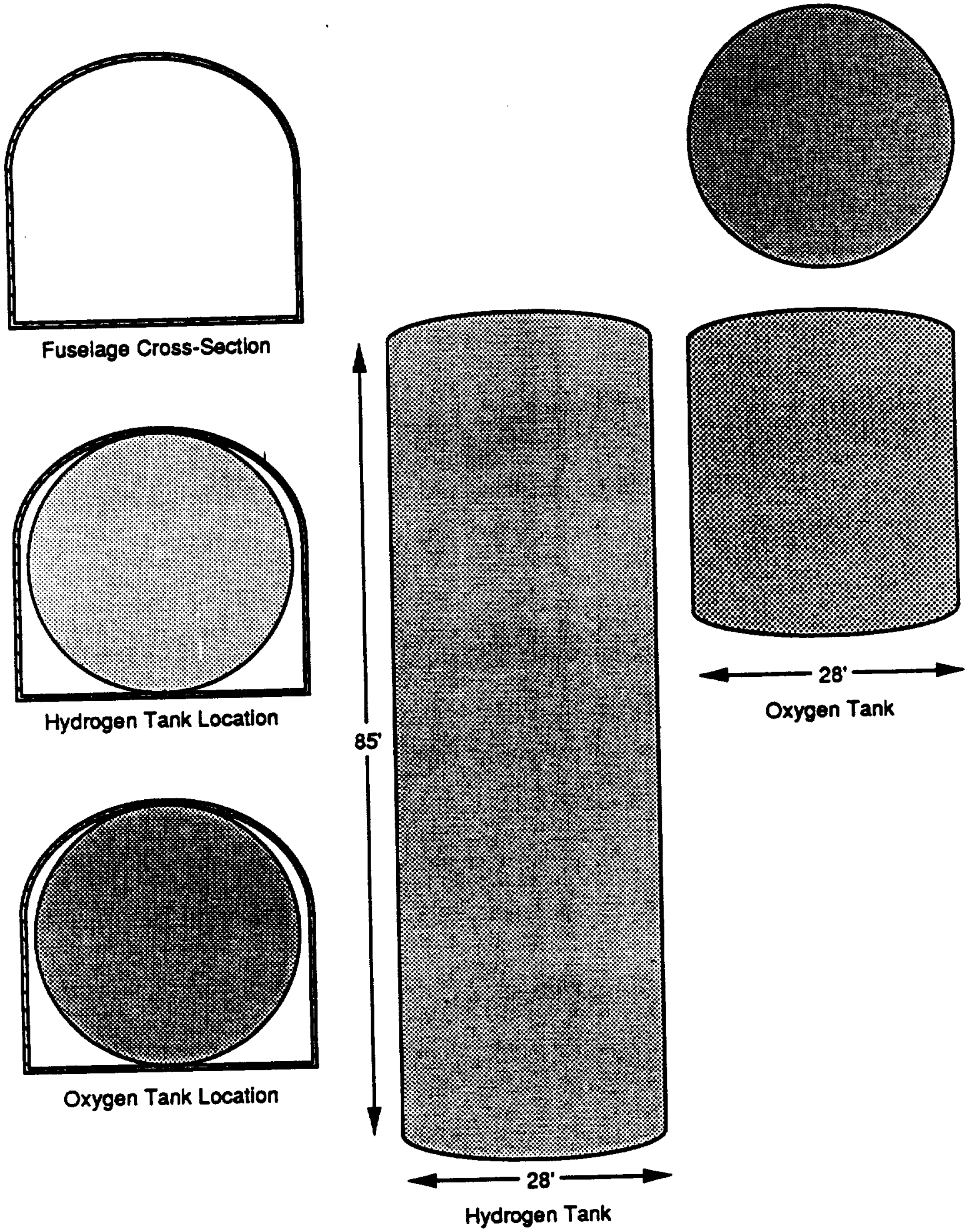

Figure 3.11.2: Schematic Diagrams of the Liquid Hydrogen and Liquid Oxygen Tanks for the Booster

Drawn By: Del Johnson
Date: March 7, 1989
Scale: 1":18'

The payload bay is simply a large, reinforced volume aft of the crew compartment designed to house payload canisters. Aluminum supports are provided to keep the cargo in position during ascent and landing.

3.9 Thrust Structure

The thrust structure is a beam system of composite design which transmits thrust loads from the STMEs, orbital maneuvering system, and reaction control system to the aft body section. The weight of these support structures was included in the design weight of the aft fuselage.

3.10 Ascent Propulsion

Ascent propulsion is provided by ten Space Transportation Main Engines (STMEs). These engines burn liquid hydrogen/liquid oxygen and are fully reusable. Four such engines are located on the rear of the orbiter vehicle, while the booster is equipped with six. This division of propulsion results in the booster having a thrust-to-weight ratio of 1.4 at sea level and provides 60% of total thrust. The orbiter therefore provides 40% of the total thrust and has a 1.2 thrust-to-weight ratio at sea level.

The arrangement of these engines as seen from the rear was determined to minimize complexity of the pumping systems and insure uniform thrust. However, fuselage cross-sectional area made certain arrangements more attractive than others. A diamond pattern was adopted for the orbiter to minimize asymmetrical thrust effects if an engine should be lost during ascent. A modified circular pattern was chosen for the booster to insure symmetry and compatibility with the orbiter burn pattern.

A schematic of the burn pattern for both the booster and the orbiter is shown in Figure 3.10.1.

3.11 Fuel/Oxidizer Feed System

A crossfeed mating system is used between the booster and orbiter to maximize the amount of fuel onboard the orbiter at the time of separation. Thus, ideally, when the booster separates from the orbiter its tanks are empty and the orbiter's tanks are full. With the STME configuration chosen, the mission closely approximates this ideal situation (while still leaving a safety margin).

Simple feed lines are used on the booster to connect the fuel tank and oxygen tank to the turbomachinery. This plumbing is located within the fuselage, to the side of the stacked tanks. In the orbiter, separate feed lines from the two hydrogen tanks proceed down either side of the oxygen tank to the aft fuselage, and the oxygen tank is connected by simple feed lines.

Propellant for the orbital maneuvering systems and reaction control system is self-contained. Thus the weight of the propellant and associated feed system is not considered as part of the fuel/oxidizer feed system of the main propellants.

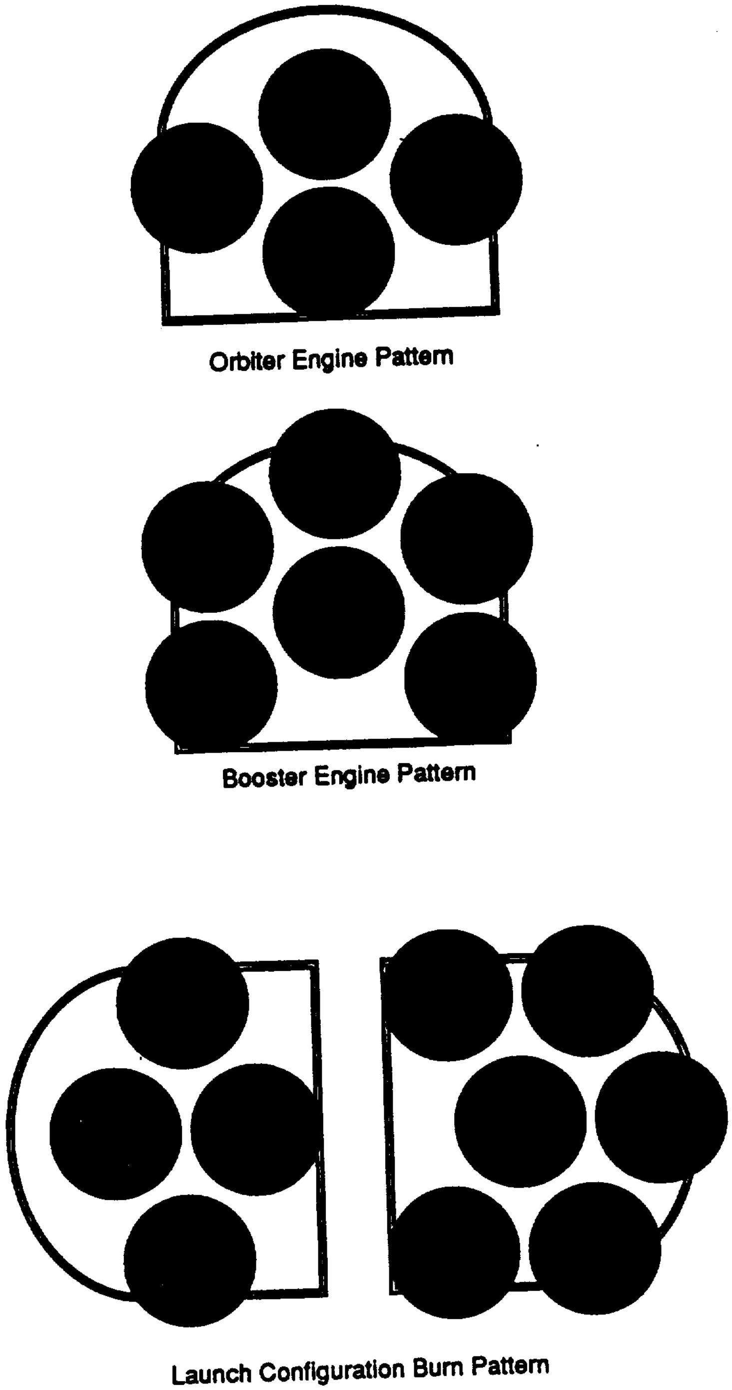

Figure 3.10.1: Engine Arrangement and Launch Configuration Burn Pattern

Drawn By: Del Johnson
Date: March 7, 1989
Scale: 1":18'

3.12 Orbital Maneuvering System/Reaction Control System

An orbital maneuvering system is provided for completion of orbital insertion, deceleration for the descent phase, and major orbital shifts during the mission. Two such systems are located in fairings affixed to the aft fuselage beside the thrust structure. Each OMS consists of a single 8,000 pound engine with approximately 10,000 pounds of propellant. Monomethylhydrazine was selected as the fuel, and nitrogen tetroxide was chosen as the oxidizer. Each has good storage properties and thrust efficiency. Furthermore, the Shuttle Orbiter OMS has used such a propellant system with great success in the past. The OMS consumes the majority of its fuel in boosting the orbiter vehicle from the elliptical orbit initially achieved with the main ascent thrust to a circular orbit coincident with the space station.

The reaction control system consists of more than thirty sets of vernier rockets. These engines have self-contained propellant and vary in thrust from 25 pounds to 600 pounds of thrust in a vacuum.

3.13 Landing Structures

The ASTS retains the conventional landing gear arrangement of one forward landing strut and two located under/inside the delta wing. Weight provisions for each of the landing gear assemblies have been considered in combination with the weights allocated to the fuselage.

4.0 Performance/Mission Analysis

The total mission performance of the Shuttle II can be easily broken down into five segments: the launch/ascent phase during which the booster and orbiter are connected, the flight of the booster following separation and subsequent landing, the flight and orbital insertion of the orbiter, the orbital mission of the orbiter, and the descent and landing of the orbiter. Each phase is very different from the other, and all five are described in detail below.

4.1 Launch Event Schedule

The Launch Event Schedule determines the sequence of occurrences following a decision to launch in a given window of opportunity. Although many important pre-flight preparations must be made for the launch to commence, this schedule details only those events that directly relate to the mission flight profile. Assuming a normal three-to four day countdown resulting in a delay immediately preceding the final countdown for launch, the following stages of the launch must be executed in series:

- After coming off the final hold, fuel and oxidizer will be released from the main tanks, conditioning the plumbing for the main engines on both the booster and orbiter. The tanks will be pressurized and sealed, and the external feed systems will be removed. At this point, the tower will be moved away from the booster-orbiter vehicle and stored in its final position. Onboard systems will be continually checked and maintained for launch readiness until the time of launch.
- When the countdown reaches 45 seconds remaining, fuel and oxidizer will be released into the turbomachinery to condition them for launch. At this point, a delay of more than approximately two hours will require the turbopumps to be bled, and the launch will have to be temporarily postponed.
- Assuming that all systems are functioning properly, a decision to launch will be made, and the main engines on both orbiter and booster will be fired 5 seconds before lift-off from the pad. During this time, the engines will be brought up to steady-state performance levels and checked for proper functioning. Even if one engine fails, the engine-out capability of the system will allow the launch to continue by throttling up the remaining engines that properly function.
- At 0:00 the booster-orbiter configuration will be released from the hold-down posts and allowed to accelerate. For the first twenty seconds of the launch, the shuttle will ascend vertically while rolling into proper alignment. After twenty seconds, the system will begin to pitch at a rate of 0.5 degrees/second. The booster will pitch nose down, while the orbiter will rotate onto its back. This pitching motion will continue until the booster is aligned at a 30 degree angle with the horizon, eight seconds before separation and 120 seconds following commencement of the maneuver.
- At 2:28 into the launch, the booster will separate from the orbiter vehicle. At this point, the booster/orbiter combination is approximately 37 miles downrange from the launch site at an altitude of roughly 40 miles. The booster will begin to execute its turnaround procedure for a flyback to the landing site, while the orbiter will continue its ascent into orbital insertion.
- The orbiter will continue in this 30 degree orientation until it has cleared the booster. Twelve seconds after separation, 160 seconds into the launch, the orbiter will begin a pitch maneuver of 0.5 degrees/second that will bring it into its final orientation of 12 degrees with respect to the horizon.

- At a time of 6:34 into the launch, the main engines of the orbiter will be shut down and initial orbital insertion will have taken place. At this time, the shuttle will be 635 miles downrange and at an altitude of 90 miles. The total velocity will be slightly greater than the local circular orbital speed, placing it in an elliptical orbit. Following this orbital insertion, the orbital maneuvering system will be fired at the apogee to minimize energy necessary to transfer between orbits. The shuttle will then be in a 270 nautical mile circular orbit, due east of Kennedy Space Center.

Table 4.1.1: System Launch Event Schedule

Ignition of Main Engines on Booster and Orbiter	-0:00:05.0
Release of Main Restraining Members/Launch	0:00:00.0
Optional throttle-down to 85% power during maximum q	0:00:48.0
Throttle-up to maximum power	0:01:20.0
Separation of orbiter and booster stages	0:02:28.0

Table 4.1.2: Orbiter Launch Event Schedule

Separation from booster	0:02:28.0
Shutoff of main engines	0:06:34.0
Initial Orbital insertion	0:06:34.0

4.2 Booster Launch/Landing Event Schedule

Following separation from the shuttle system, the booster will fall away in unpowered flight until it is clear of the orbiter. It will pull up to a 20-30 degree angle of attack to increase drag and slow down. When slowed sufficiently, the reaction control system will fire and begin a powered, high-g turn to re-orient the booster with the landing site. The booster will be slowed to a stop and allowed to fall back to the earth, pitching down to increase speed and reduce drag. The booster will then glide back to the landing site, using burns from the reaction control system if necessary for in-flight maneuvers requiring more than aerodynamic forces. At the end of its descent, it will flare and follow the same landing procedure detailed later for the orbiter vehicle.

Table 4.2.3: Booster Launch/Landing Event Schedule

Separation from orbiter	0:02:15.0
Shutoff of main engines	0:02:16.0
Increase in angle of attack to increase drag and reduce velocity	0:02:45.0
Beginning of high-speed turnaround	0:06:15.0
End of high-speed turnaround	0:07:15.0
Beginning of glide down to lower atmosphere	0:07:30.0
Beginning of landing approach	0:19:30.0
Landing	0:21:30.0

4.3 Orbiter Orbital Event Schedule

The initial burn sequence for the ASTS will place the orbiter at an altitude of 78.1 nautical miles, with a velocity of 25, 962 feet per second. Since this value is slightly greater than the circular velocity at this altitude, the orbiter will proceed in an elliptical orbit with an eccentricity of 0.02473.

At the apogee altitude of 257 nautical miles, the first of two burns designed to complete orbital insertion will be made. These burns will produce an elliptical orbit transfer, thus minimizing the energy necessary to accomplish the maneuver. The orbital maneuvering system (OMS) will be employed to increase the total velocity by 181 feet/second. This increase in velocity will place the orbiter into another elliptical orbit with a velocity at perigee of 24,890 feet per second.

At the apogee of this second orbit, an altitude of 270 nautical miles, a second burn of the OMS will be performed. This burn will increase the total velocity by 176 feet/second to the local circular speed of 24,975 feet/second. At this point, the orbiter will be in a 270 nautical mile circular orbit.

The total impulsive change in velocity necessary to accomplish these maneuvers is a ΔV of 357 feet/second. This value falls well within the capabilities of both the OMS employed on the current STS and the OMS designed for use on the Shuttle II orbiter.

The particulars of any given orbital mission are determined by the payload and crew carried into orbit. Missions will be designed for three day to one week periods, depending on its specific purposes. In general, enough provisions for sixteen man-weeks will be standard on all missions. Thus, even missions that visit the Space Station will have the luxury of operating independently from external sources. Typical mission profiles include: the launch and assembly of Space Station components, maintenance of and/or taking stores to the space station, performing experiments independently using the ESA Spacelab, shuttling personnel to and from the space station, launching satellites into both LEO and GEO, repair and/or retrieval of already-orbiting satellites, and rendezvous with other space facilities.

In general, mission times will be minimized to minimize turnaround times, therefore maximizing the number of annual missions.

4.4 Orbiter Landing Event Schedule

Once the orbital mission is completed, preparations must be made for re-entry. The desired landing location dictates the point where the actual de-orbit sequence is initiated. An OMS de-orbit burn, which slows the orbiter just enough to begin the re-entry process, is performed. Small, supplemental RCS burns are made to maintain the correct nose-up attitude for the orbiter as it continues on its re-entry course.

At an altitude of approximately 250,000 feet, attitude control is exercised by means of the reaction control system. These adjustments will continue to be made by the RCS until an altitude of approximately 80,000 feet. From 80,000 feet until touchdown, the orbiter is controlled with the large body flap, speed brake, and elevons.

To minimize the effects of drag on the control of the orbiter, the landing gear is not deployed until the orbiter is approximately 250 feet off the ground and the wheels do not lock into place until eleven seconds before touchdown. The Shuttle II touches down with a velocity of approximately 300 feet per second.

Accurate guidance to the landing site is currently provided by a microwave scanning beam landing system. This system sends the necessary signals to the orbiter so it can make the required adjustments on descent. A similar system will be used for the Shuttle II.

5.0 Stability and Control Analysis

Stability and Control parameters for the Advanced Space Transportation System were computed using methods given by Roskam, Etkin, and Smetana. These methods are based on previously compiled flight data so that the basic stability and control parameters of almost any configuration can be determined. Physical parameters for the Shuttle II can be found in Tables 3.2.1 and 3.3.1.

The longitudinal static stability of the Shuttle II was determined using the relationship:

$$C_{M\alpha} = C_{L\alpha} (h - hn)$$

where $C_{M\alpha}$ = change is pitching moment due to variation in angle of attack
$C_{L\alpha}$ = change in lift coefficient due to variation in angle of attack
h = non-dimensional center of gravity location
hn = non-dimensional location of the neutral point

The static stability/instability of a configuration is immediately known through the value of $C_{M\alpha}$. For an aircraft to be statically stable, it must have a negative value for $C_{M\alpha}$. Since $C_{L\alpha}$ is always positive, hn must be greater than h for static stability, i.e. the center of gravity must lie ahead of the neutral point.

Values of $C_{L\alpha}$ for the Shuttle II were found to vary greatly with Mach number and only slightly with Reynolds number. In fact, $C_{L\alpha}$ increased with increasing values of subsonic Mach numbers and decreased with increasing values of supersonic Mach numbers. For instance, at very low subsonic speeds, $C_{L\alpha}$ was found to have a value of approximately 2.7/rad; whereas, the value of $C_{L\alpha}$ at a Mach number of approximately 2.8 was 1.62/rad. $C_{L\alpha}$ for the Shuttle II was found to be maximum (4.42/rad) in the 1.0 - 1.3 Mach number range.

The value of the non-dimensional center of gravity (the location from the leading edge of the mean aerodynamic chord to the center of gravity divided by the value for the mean aerodynamic chord) was found by summing the moments due to the weight components for the Shuttle II orbiter and dividing by the total weight of the vehicle. Calculations reveal that the center of gravity location for the Shuttle II orbiter is approximately 91 feet from the nose along the body centerline. When non-dimensionalized by the mean aerodynamic chord, h has a value of 0.136.

The neutral point is the point where the total aircraft pitching moment is invariant with angle of attack. Studies show that at low subsonic cruise the value of hn is approximately 0.25 (i.e. it lies on the quarter-chord) and continues to increase towards a value of 0.5 for high supersonic cruise. Analysis of the Shuttle II configuration reveals that at low subsonic speeds, hn has a value of approximately 0.28 at a Mach number of approximately 0.49.

Hence, the Shuttle II proved to be statically stable for all flight regimes considered since its center of gravity was always located ahead of its neutral point.

In addition to static stability, a flight vehicle should also demonstrate dynamic stability. In actuality, neither static or dynamic stability is essential since fly-by-wire control systems could be implemented to account for the instabilites; nevertheless, dynamic stability is still considered an important part of the stability and control picture and will be considered.

In order to determine the dynamic properties of a system, the equations of motion must be written and analyzed. The non-dimensional, controls fixed, longitudinal and lateral equations of motion for the Shuttle II are written in matrix form. These equations are based on the values of numerous longitudinal and lateral stability derivatives for the Shuttle II. The actual determination of dynamic stability/instability at any chosen flight regime is carried out by examining the matrices. If the matrices have all negative real Eigen values then the system is said to longitudinally and laterally dynamically stable.

After determining the stability matrices for the Shuttle II during its landing/approach sequence and determining their respective Eigen values, it was found that the Shuttle II is both longitudinally and laterally dynamically unstable at landing. But, as stated earlier, this situation can be eliminated by employing a fly-by-wire control system.

6.0 Interface With Other Systems

An important technical and economic aspect is the ability of the ASTS to interface with both existing and future support systems and related facilities. Among the most important of these are: the current launch facilities and equipment, the space station, and the Boeing 747 transport aircraft.

- **Space Station:** A permanently manned space station will be constructed in low earth orbit during the mid 1990's. Among the components of the space station are the pressurized modules for habitation and work areas and a docking port for the Space Shuttle and Shuttle II. The transfer of crew, supplies, and equipment will require frequent docking of the orbiter to the space station. Therefore, a critical design point will be the interface of these two systems. A similar atmosphere will be used in the two, so there will be no need for extensive airlocks. The entry/exit path is the primary concern of docking compatibility and maneuvering. Engineers estimate that the closing velocity will be roughly between 0.5 and 1.5 feet per second, but the dynamic vibration on the highly flexible structure even at this low speed could be significant. Further investigations must be made into this problem before a suitable docking arrangement can be determined.
- **Launch Sites:** For operational and economical reasons, the existing launch facilities will be modified whenever possible to accommodate the ASTS fleet of orbiters and boosters. This includes the facilities at Kennedy Space Center and Vandenberg Air Force Base. At Kennedy, the orbiter and booster will be mated in the vehicle assembly building and transported to launch pads 39A and 39B via the crawler used on the Apollo and STS systems. Changes to the launch pad will include a slightly modified tower system and a modified flame trench for the orbiter/booster configuration. At Vandenberg, it is uncertain what modifications will be necessary. It would be necessary to construct a landing strip for the flyback booster and possibly the orbiter. At the present time the facility has been placed on permanent caretaker status. However, the base was nearly ready to begin Space Shuttle launches when it was mothballed in 1986.
- **Shuttle Rotating Service Structure:** The purpose of the Shuttle Rotating Service Structure in the STS is to position an environmentally controlled payload change-out room in a mated position with the orbiter cargo bay such that payloads can be inserted or removed without exposure to the outside environment. Once this task is complete the structure is moved away from the launch pad during the shuttle launch. This structure will be ideally suited for use with the ASTS, since it is designed to hoist a canister (containing the payload changing room) into a mated position with the orbiter cargo bay. For the ASTS, modifications will be made to the rotating structure to actually insert the payload canister into the mid-fuselage section of the orbiter.
- **Air Transportable (Boeing 747 Piggy-Back Configuration) :** By limiting the size of the orbiter to 180 feet, the ASTS will be fully compatible with the current NASA transportation system used with the STS. The Boeing 747 carrier aircraft will be used to deliver the Shuttle II from landing sites other than Kennedy to operation sites when needed. Since the booster and orbiters have similar construction, the boosters will also be transportable in a similar fashion.

7.0 Safety Analysis

When operating a complex vehicle consisting of many integrated systems, such as the ASTS, the chances for mechanical failure are great. The proper development of an effective safety system is governed by the identification of hazards associated with each operating subsystem, the proper elimination of unnecessary hazards, and the minimization of hazards which cannot be dismissed. Management and personnel officials must have an equal awareness of the hazards and risks to practice sound engineering judgment when crises arise.

The following system of hazard classification was developed to aid in just such a decision-making process by familiarizing those associated with the project with the potential dangers of the system. This system of classification is based on the model set forth by the Aerojet Corporation in their technical proposal for the STME. In it, severity categories are used to determine the risk level for system components. Hazardous conditions could arise due to influences of the environment, personnel error, design characteristics, procedural deficiencies, or subsystem malfunction. Each of these may result in personnel or entire system loss. The hazards are categorized as follows:

Table 7.0.1: Hazard Severity Categories

- **Catastrophic (CA):** No time or means are available for corrective action.
- **Critical (CR):** May be counteracted by emergency action performed in a timely manner.
- **Controlled (CO):** Has been counteracted by appropriate design, safety devices, caution and warning devices, or special automatic/manual procedures. Time is not a significant factor. Control has been verified by appropriate test, analysis, etc.
- **Conditionally Controlled (CC):** The hazard has been eliminated or reduced to an acceptable level (controlled hazard) and project or program commitments have been made to verify this elimination or reduction by way of required test programs, analytical studies, and/or training programs.
- **Residual Hazard:** A hazard for which safety or warning devices and/or special procedures have not been developed or provided for effectively counteracting the hazard. Residual hazards (catastrophic and critical) are specifically identified to NASA. Continuation of effort to eliminate or reduce such hazards is accomplished throughout the program by maintaining awareness of new safety technology or devices being developed and their application to the residual hazards. Rationale for residual hazards is documented.
- **Accepted Risk:** After thorough evaluation and assessment of those open hazards and safety concerns which have not been eliminated or controlled (residual hazards) program management accepts the induced risk.
- **Open Safety Item:** A hazard for which effective hazard controls have not been provided; action assignment has been made to implement effective hazard control.
- **Eliminated (EL):** Completely eliminated by design; energy source cannot cause a hazard. Eliminated hazards are not listed in the hazard analysis.

These failure modes correspond to those laid out in the STME handbook. The failures of the Shuttle II have been broken down into three main divisions: ascent propulsion, structures, and control systems. These subsystems have the most significant impact on the mission during its two most critical phases, ascent and landing.

7.1 Ascent Propulsion Failure Modes

The extent of damage caused by propulsion will vary with the particular system components involved, but ascent propulsion failures range from nearly 100% catastrophic internal fuel leakages to relatively minor ignition failures. These failures are given as described in the STME handbook.

- **Thrust Chamber Assembly Injector:**
  - Function: Atomizes propellant for efficient, stable combustion
  - Failure Mode: Internal leakage
  - Effects: Engine failure due to explosion
  - Consequence: *Catastrophic*
- **Combustion Chamber:**
  - Function: Contains, contracts, and expands combustion gases; directs hot gases to nozzle coolant manifold
  - Failure Mode: Fails to contain and direct hot gases
  - Effects: Engine failure
  - Consequence: *Controlled*
- **Nozzle:**
  - Function: Provides controlled expansion to increase thrust
  - Failure Mode: Fails to properly contract hot gasses
  - Effects: Reduced engine performance
  - Consequence: *Controlled*
- **Deployable Nozzle:**
  - Function: Extends to provide additional expansion of chamber gasses
  - Failure Mode: Fails to properly direct hot gasses
  - Effects: Reduced engine performance
  - Consequence: *Controlled*
- **Main Fuel Valve:**
  - Function: Controls liquid hydrogen flow to the thrust chamber
  - Failure Mode: Fails to open; no propellant flow
  - Effects: Engine fails to start
  - Consequence: *Controlled*
  - Failure Mode: External leakage
  - Effects: Reduced engine performance; fire/explosion
  - Consequence: *Catastrophic*
- **Main Oxidizer Valve:**
  - Function: Controls liquid oxygen propellant to the combustion chamber
  - Failure Mode: Fails to open; no oxidizer flow
  - Effects: Engine fails to start
  - Consequence: *Controlled*
- **Low Pressure Oxidizer Turbopump Assembly:**
  - Function: Controls and directs oxidizer flow
  - Failure Mode: internal leakage of liquid oxygen
  - Effects: Possible pump failure or liquid oxygen fire/explosion
  - Consequence: *Controlled*

- **High Pressure Fuel Turbopump Assembly:**
  Function: Converts energy from hot gasses to rotational energy for driving the fuel pump
  Failure Mode: Fails to rotate properly and pump liquid hydrogen as required
  Effects: Engine failure due to lack of liquid hydrogen propellant
  Consequence: *Catastrophic*
- **Gas Generator:**
  Function: Provides hot gas to drive turbine and pressurize propellants
  Failure Mode: Internal leakage
  Effects: Engine failure due to deformation
  Consequence: *Catastrophic*
- **Gas Generator Ignition Assembly:**
  Function: Provides spark ignition to the gas generator
  Failure Mode: Fails to provide ignition energy for the gas generator
  Effects: Engine fails to start
  Consequence: *Controlled*
- **Gas Generator Ignition Assembly:**
  Function: Provides spark ignition to the gas generator
  Failure Mode: Fails to provide ignition energy for the gas generator
  Effects: Engine fails to start
  Consequence: *Controlled*
- **STME Structural Components:**
  Function: Provides support and attachment of engine components
  Failure Mode: Fails to maintain supports and contain liquid propellants
  Effects: Engine failure due to explosion or fragmentation damage
  Consequence: *Catastrophic*

7.2 Structural Failure Modes

Structural failures are another critical category which must be analyzed in the total risk assessment. This category of failures is generally associated with damage to structural components of the vehicle body, but also includes the cargo bay doors, the landing gear system, and the thermal protection system.

- **Fuselage Structure:**
  Function: Provides main support structure for orbiter/booster vehicle
  Failure Mode: Crack, rupture, or metal failure
  Effects: Depressurization of crew cabin or cargo bay; fragmentation damage to adjacent structural components
  Consequence: *Critical*
- **Wing:**
  Function: Generate lift and provide stability
  Failure Mode: Shearing or stress fractures during ascent
  Effects: Asymmetrical instability; incapable of reentry
  Consequence: *Critical*
- **Vertical Tail:**
  Function: Provides lateral stability
  Failure Mode: Shearing or stress fractures during ascent
  Effects: Severe problems during landing and approach
  Consequence: *Critical*

- **Thermal Protection System:**
  Function: Protects vehicle against extreme re-entry temperatures
  Failure Mode: High re-entry temperatures yield thermal penetration of fuselage
  Effects: Localized disintegration of aluminum skin structure; potential crew/cargo damage
  Consequence: *Critical*
- **Thrust Structure:**
  Function: Transmits thrust loads from the STMEs, OMS, and RCS to aft fuselage
  Failure Mode: Rupture in feed lines; exposure of engine compartment
  Effects: Explosion damage; loss of (multiple) engine power; thrust deflection
  Consequence: *Critical*
- **Landing Gear:**
  Function: Allows successful landing maneuvers
  Failure Mode: Fails to extend fully
  Effects: Shearing on touchdown; severe damage to orbiter/booster structure
  Consequence: *Critical*
- **Cargo Bay Doors:**
  Function: Provides a sealed access to and enclosure for the cargo bay and cargo
  Failure Mode: Shearing during ascent
  Effects: Exposure of cargo to environment; loss of unsecured cargo
  Consequence: *Critical*
- **Windows:**
  Function: Provides visibility during landing and orbital maneuvers
  Failure Mode: Cracking, shattering
  Effects: Loss of visibility; depressurization
  Consequence: *Critical*
- **Control Surfaces:**
  Function: Maintain longitudinal and lateral stability
  Failure Mode: Shearing or stress fractures
  Effects: Loss of stability during atmospheric re-entry and landing
  Consequence: *Critical*

7.3 Electronic Controls Failure Modes

Any movable component of the ASTS controlled by electrically operated servos would become useless in the event of electrical failure. Included in this group are the control surfaces, cargo bay doors, engine components and flight deck controls.

- **Rudder:**
  Function: Provides lateral stability
  Failure Mode: Fails to respond to input signals
  Effects: Landing hazardous if crosswinds are prevalent
  Consequence: *Controlled*
- **Elevons/Ailerons:**
  Function: Pitch-down and landing maneuvers
  Failure Mode: Fails to respond to input signals
  Effects: Cannot perform maneuvers necessary for landing
  Consequence: *Critical*

- **Cargo Bay Doors:**
  - Function: Provides a sealed access to and enclosure for the cargo bay and cargo
  - Failure Mode: Fails to close during orbit
  - Effects: Prevents landing due to temperatures encountered by the exposed doors
  - Consequence: *Controlled*
- **Orbital Maneuvering System:**
  - Function: Provides thrust to achieve desired orbit and begin re-entry
  - Failure Mode: Fails to fire; fails to shut down
  - Effects: Prevents reaching desired orbital altitude; radically changes orbit
  - Consequence: *Controlled* to *Critical*
- **Reaction Control System:**
  - Function: Provides thrust to maintain desired orbit, maneuver while in orbit
  - Failure Mode: Fails to fire; fails to shut down
  - Effects: Prevents proper orientation during orbital and re-entry maneuvers
  - Consequence: *Controlled* to *Critical*
- **Flight Deck Controls:**
  - Function: Provides means for direct control of the orbiter vehicle by pilot
  - Failure Mode: Fails to respond to pilot commands
  - Effects: Systems controlled by pilot input become unoperational
  - Consequence: *Controlled to Critical* depending upon the condition of automatic flight controls system

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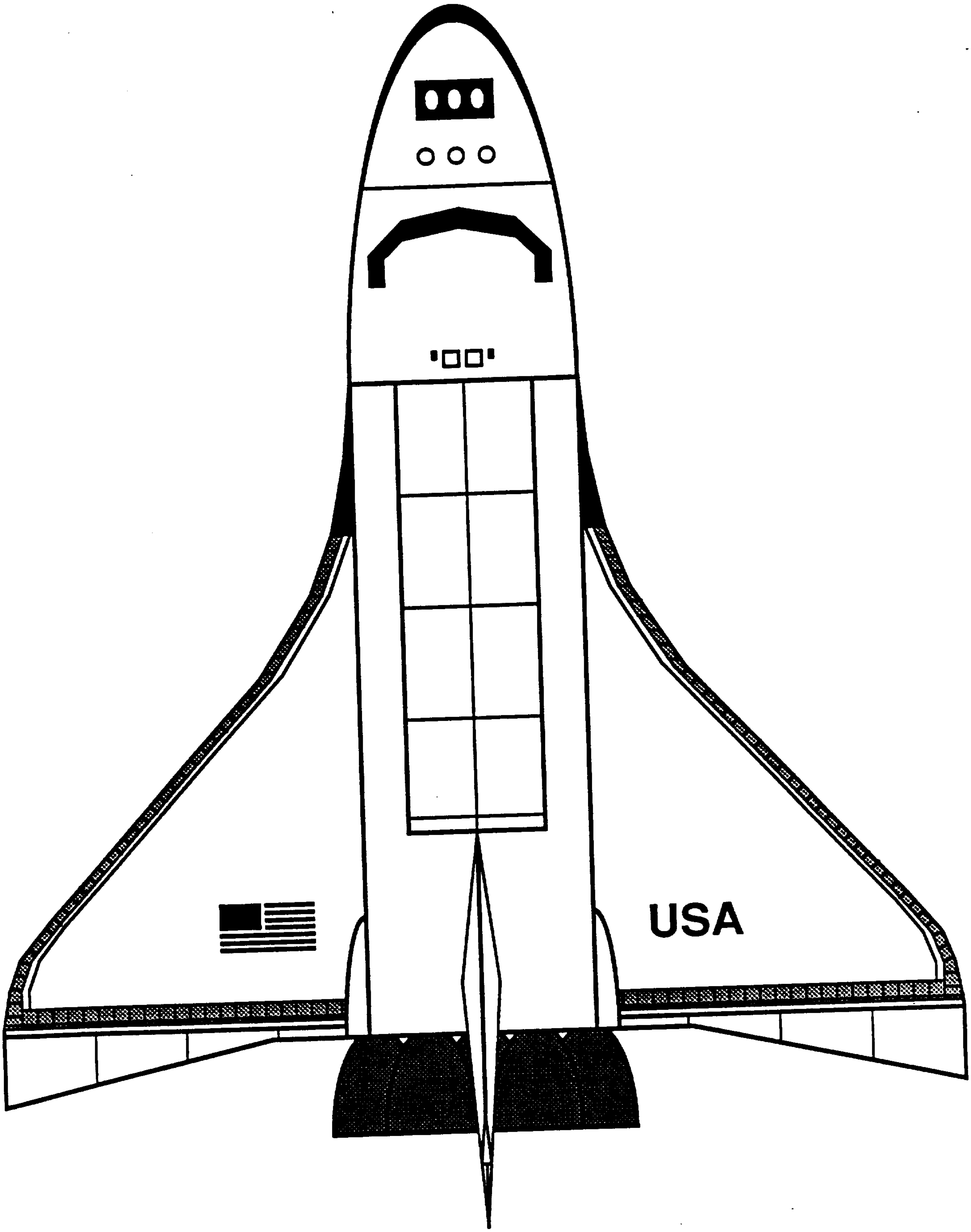

Figure 3.0.1: Shuttle II Orbiter

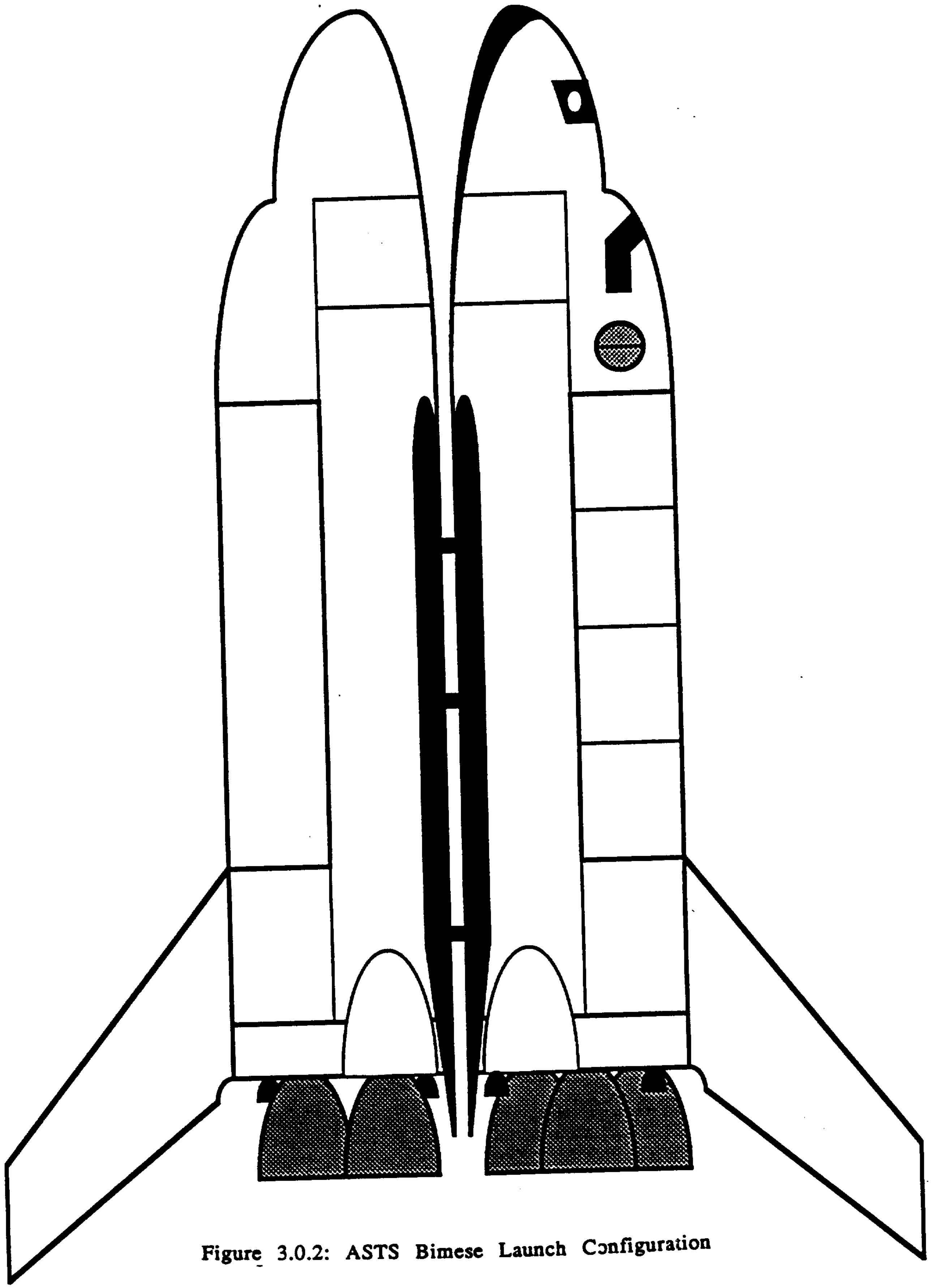

Figure 3.0.2: ASTS Bimese Launch Configuration