NASA Contractor Report 2878

Technology Requirements for Advanced Earth Orbital Transportation Systems

Volume 1: Executive Summary

A. K. Hepler and E. L. Bangsund

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Seattle, Washington

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FOREWORD

This report presents the detailed results of a study of Technology Requirements for Advanced Earth Orbital Transportation Systems conducted by The Boeing Company under Contract NAS1-13944 from June 1975 through March 1976.

The work was performed by the Advanced High Speed Transportation group of the Space Systems Division, Boeing Aerospace Company, at its Kent Space Center.

Study Manager was Mr. E. L. Bangsund under the administration of Mr. A. K. Hepler. A listing of the Boeing personnel who contributed directly in the studies and preparation of the report is as follows:

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H. N. Johnson	Configuration
R. T. Savage	Aerothermal Analysis
A. R. Swegle	Stress
W. H. Walker	Subsystems/Ground Accelerator
H. Zeck	Aerodynamics and Performance

Mr. F. Kirby of Rocketdyne provided support for the main propulsion subcontract.

Contract documentation is provided as follows:

	Document	Boeing No.	NASA No.
Volume 1:	Executive Summary	D180-19168-3	CR-2878 Vol. 1
Volume 2:	Summary Report	D180-19168-4	CR-2879 Vol. 2
Volume 3:	Summary Report-Dual Mode Propulsion	D180-19168-5	CR-3037 Vol. 3

TABLE OF CONTENTS

SUMMARY

Presented briefly in this report are the results of a four task effort to identify the technology requirements associated with advanced earth orbital transportation systems. Task I was directed at providing assessments of current technology and normal growth to 1986 in key system and subsystem technology areas as applied to future advanced earth orbital transportation systems. The projected technology level increases based on normal growth in structures and subsystems were found to be 17% and 12.5%, respectively.

Task II consisted of the design and definition of performance potential of three different types of vehicle concepts resulting in four configurations. These concepts were a ground sled launched horizontal take-off (HTO) mode, a vertical take-off (VTO) mode, and an inflight fueled (IFF) mode consisting of both aerial refuel and air launch.

The sled assisted, horizontal take-off (HTO) vehicle appears to offer the lowest practically attainable GLOW, 1.0×10^6 kg (2.2 million lb), and life cycle cost of 8.1 billion dollars. Operational costs of 1.35 million dollars per flight resulted in a transportation cost of 45.64 dollars/kg (20.7 dollars/lb) based on a payload of 29.5×10^3 kg (65,000 lb). Estimated c.g. loacation and aerodynamic characteristics indicate a stable and trimmable vehicle both at hypersonic and subsonic speeds.

The vertical take-off (VTO) vehicle GLOW is estimated at 2.01×10^6 kg (4.4 million lb). The primary increase in weight was caused by the difference in propulsion thrust to weight ratios (.77 for the HTO versus 1.31

for the VTO) and associated scaling effects. Since the VTO vehicle design concept was based on generic association with the HTO vehicle which utilized LO_2 in the wing during ascent for inertial load relief, this generic commonality of fuel location might have unduly penalized the VTO configuration. Resultant life cycle cost for this vehicle was 12.6 billion dollars. The 2.3 million dollar cost per flight results in transportation cost of 16.1 dollars/kg (35.4 dollars/lb).

The inflight fueled and air launch vehicle reduced take-off weights of .771 X 10^6 kg (1.7 million lb) for each vehicle result from launching at altitudes of 6096 - 9144 m (20 - 30,000 ft). Overall life cycle costs for this concept are about one billion dollars more, due mostly to the tanker development and unit costs, but the cost per flight approaches that of the horizontal take-off concept. As a result of the size and cost differences and the technical development difficulties affecting concept feasibility and associated with the inflight fueled concept, the sled assisted horizontal take-off vehicle was selected with Government concurrence for the advanced technology assessment in Task III.

The Task III activity consisted of defining advanced subsystems and technology areas where performance advancements reap the large payload gains for the R&D dollars invested. Structures and propulsion were determined as critical areas for eventual development of an all-metallic, completely reusable, cost effective earth orbital transportation system. This includes the nickel brazed Rene'41 and aluminum brazed titanium honeycomb thermal/structural concept which accomplishes the dual function of providing adequate cryogenic insulation properties during ascent while operating within the temperature capabilities of the materials during reentry.

The two-position nozzle for the Space Shuttle Main Engine (SSME) also has a significant impact on Single Stage to Orbit (SSTO) vehicle performance. Aerodynamic heating, trajectory optimization, operations, cost analysis, and certain configuration/systems programs are also recommended for future study.

The Task IV extended performance vehicle GLOW was reduced to .856 X 10^3 kg (1.886 million lb) when updated with selected advanced technology programs. Overall program cost was reduced by approximately 600 million dollars resulting in a cost per flight of 42.8 dollars/kg (19.4 dollars/lb).

INTRODUCTION

The Space Shuttle program is currently in the final development stages and hardware is being fabricated. It is anticipated that this vehicle system, together with the planned space tug, will provide the space transportation capability for most of the requirements to transport men and material between earth and earth orbit at least until the 1990 time frame and, more probably, for several years to follow. This program has provided a significant technology base (and will continue to do so throughout its lifetime) upon which to build for future aerospace transportation systems. For long range planning purposes, consideration of the lead times associated with major vehicle system programs and the assumption of a nominal fifteen year operational lifetime for the Space Shuttle gives a clue to the possible schedule for the development of more advanced systems. The lead time from an "Authority to Proceed" to an operational system is of the order of eight to ten years, based on both Apollo and Space Shuttle experience.

For study purposes, the assumption was made that a follow-on system to be available in the 1995 time frame based on a nominal schedule would require that the planning for and development of the necessary technology base must be accomplished within the next ten years. A fundamental assumption underlies any consideration of these more advanced systems: any new system must offer clear and significant cost/performance advantages over current systems.

Three operational concepts (resulting in four configurations) of a Single Stage to Orbit system using advanced hydrogen fueled rocket engines for the main propulsion system were examined under this contract. A detailed examination of these systems in light of both normal technology growth anticipated for the time frame of interest and focused growth in selected areas have provided clues as to which technology areas should and must be pursued on a cost/performance basis.

Results of the study provide a basis for management decisions relative to the selective support of future development programs.

NORMAL TECHNOLOGY GROWTH - TASK 1

This task consists of providing assessments of current technology and normal growth to 1986 in key system and subsystem technology areas as applied to advanced earth-orbital transportation systems. Data for this effort were obtained from recent literature, subcontractors, government and industry sources and in-house field specialists. For this purpose it was first necessary to define the required systems together with their operational environments and performance requirements generated in the course of the configuration development activities of Task II.

System Weight Relationships

In order to determine the leverage of the various vehicle elements and subsystems, it was necessary to determine their weight relationship with respect to the overall vehicle systems.

Figure 1 uses the horizontal takeoff vehicle as an example to illustrate the various vehicle weight breakdowns.

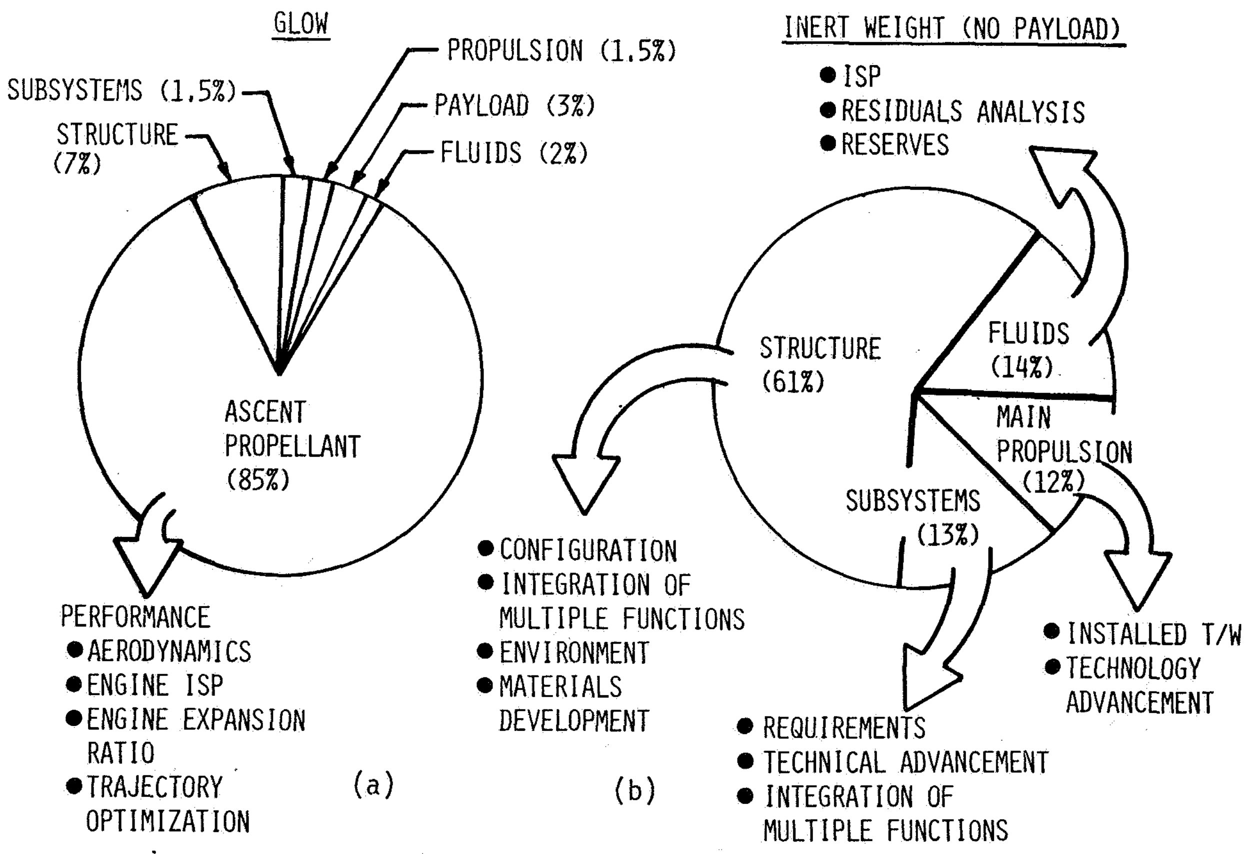


FIGURE 1 - TYPICAL SSTO VEHICLE WEIGHT DISTRIBUTION

The most significant item of Gross Lift-Off Weight (GLOW) shown in Figure 1a is the usable ascent propellant, which makes up 85% of the total. Several areas associated with performance show potential for reducing the propellant weight, which in turn reduces the structures weight and GLOW.

Figure 1b details the breakout of vehicle inert weight to determine what elements are drivers. Structures is a key element at 61% of the total inert weight. Subsystems, main propulsion and fluids share nearly equally in making up the remaining weight.

Technology Projections

The 1986 technology projections thus reflect the results of detailed examinations of relative potential for advance in the various technology and subsystem areas as well as the leverage on vehicle performance that such advances provide.

Table 1 summarizes the "normal technology projections" for the structures subsystems of a Single Stage to Orbit vehicle. The illustration lists the

TABLE 1 - STRUCTURES TECHNOLOGY NORMAL GROWTH SUMMARY

Structural elements	Technology growth area	Result
Surface panels Rene' 41 honeycomb	Basic braze alloy/process dev.	Decrease cost, improve braze toughness
	Allowables development Panels/joints/dev. & test Assemblies/dev. & test	Low density/insulative structure with 20 K (-423°F) to 1,144 K (1600°F) operational capability
Titanium honeycomb	Basic braze alloy/process dev.	Improve temp cap. from 699 K (800°F) to 811 K(1000°F)
	Allowables development Panels/joints/assy dev. & test Assemblies (see above)	Provide low density/insulative structure with 20 K (-423°F) to 811 K (1000°F) operational capability
Truss/frames/thrust structure Metal matrix composites	Process/manufacture dev. Allowables development Design/joints/assys dev. & test	Provide low density/high strength structure Provide structure with significant weight savings over metallic structure for temperature of 33 K (-400°F) to 755 K (900°F)
Leading edges Refractory & super-alloy metals	Design/analysis development Assembly dev. & test	Provide lightweight, long life leading edges with temp capability to 1,589 K (2400°F)
Components	Tooling, joining and inspection	Capability to manufacture advanced structural system for cryogenic fuel containment

various structural elements, the technology growth area or program which will drive the technology improvement and the result in terms of weight and/or performance capability. The main criterion used to determine if a technology would be available by 1986 without special funding was: "Would the program exist if an SSTO type program were not available?" In-house structural programs at Boeing and other aerospace and aircraft companies as well as supplemental Government funding indicate the application of the structural concepts to areas outside the interest of an SSTO vehicle (i.e. SST, Space Shuttle improvements, hypersonic research vehicle, etc.).

Table 2 summarizes the "normal technology projections" for the subsystem elements of a single-stage-to-orbit vehicle. As indicated, several subsystems utilize the existing technology because perturbed or special funding would be required so that the subsystem program presently projected would not be weight competitive with the present performance requirements.

TABLE 2 - SUBSYSTEMS TECHNOLOGY NORMAL GROWTH SUMMARY

Subsystem	Technology growth area	Result
● Landing gear	● 2.4×10^9 Pa (350 ksi) maraging steel ● Boron/aluminum composites ● 2.7×10^7 Pa (4,000 psi) hydraulics	● System weight reduced from 3.5 to 2.8% landed weight
● Main propulsion	● Nozzle extension ● 2.4×10^7 Pa (3,500 psi) chamber pressure ● Zero NPSH pumps	● Increased performance with improved T/W ● Reduced ullage pressures
● Surface controls	● 3.45×10^7 Pa (5,000 psi) hydraulics ● Composite materials	● Reduced system weight in actuators
● Hydraulic conversion and distribution	● 3.45×10^7 Pa (5,000 psi) operating pressure ● Composite materials	● Reduced system weight in lines and fluids
● Propellant feed and repressurization	● Composite materials	● Reduced system weight in lines and tanks
● Avionics	● LSI circuitry ● Laser radars ● Micro processors ● Solid state displays ● Bubble memories	● Reduced system weight in all areas
● Electrical power conversion and distribution	● Solid state power conditioning and switching equipment	● Reduced system weight
● RCS, OMS, prime power, ECS & crew provisioning	● Existing technology	● No impact

Figures 2 and 3 show significant projected weight reductions on the basis of "normal technology projections" (bottom of shaded area) for SSTO - HTO structures and subsystems respectively as compared with a vehicle using current technology (top of shaded area). Weight reductions range from 0 to 45% for structures and from 0 to 27.3% for subsystems. The P/L doors and crew compartment reflect existing Space Shuttle technology. The total structural reduction is 17.1%. In Figure 3 the RCS and OMS system weights reflect the existing technology of the Space Shuttle and RL-10 engine, respectively. The total overall subsystem reduction is 12.5%. This combined with the structures reduction is a projected weight improvement of 15.8%.

It is important to understand that generally, when considering potential weight reductions, these may reflect the impact of two factors. These are changes in requirements and improvement in technology. The requirement differences alone can have a significant impact in several areas. Examples are the lower entry temperatures which affect materials usage and the 12-hour mission duration which reduces the overall subsystem loads. The weights reductions illustrated in Figures 2 and 3 show only the impact of the normal technology improvements because of the lack of a confirmed data base from the Space Shuttle program.

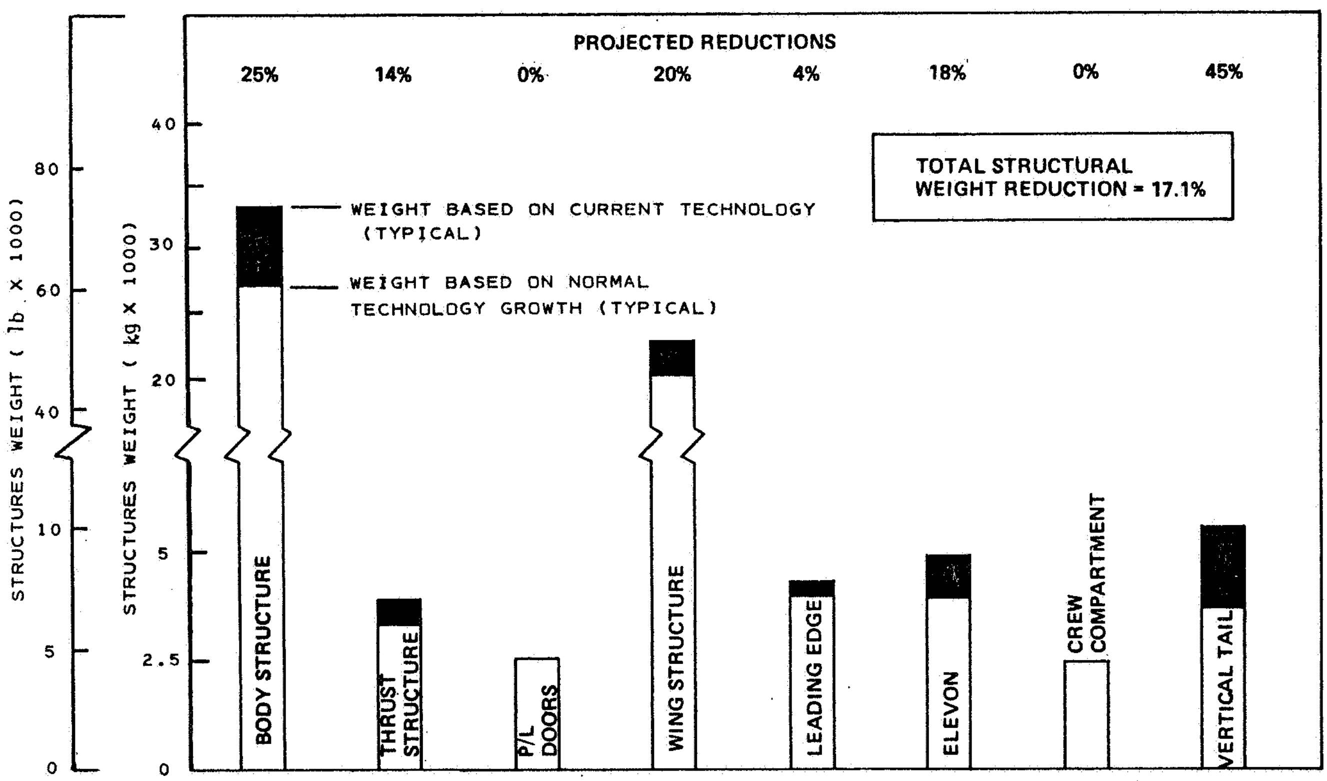


FIGURE 2. STRUCTURES WEIGHT REDUCTION SUMMARY

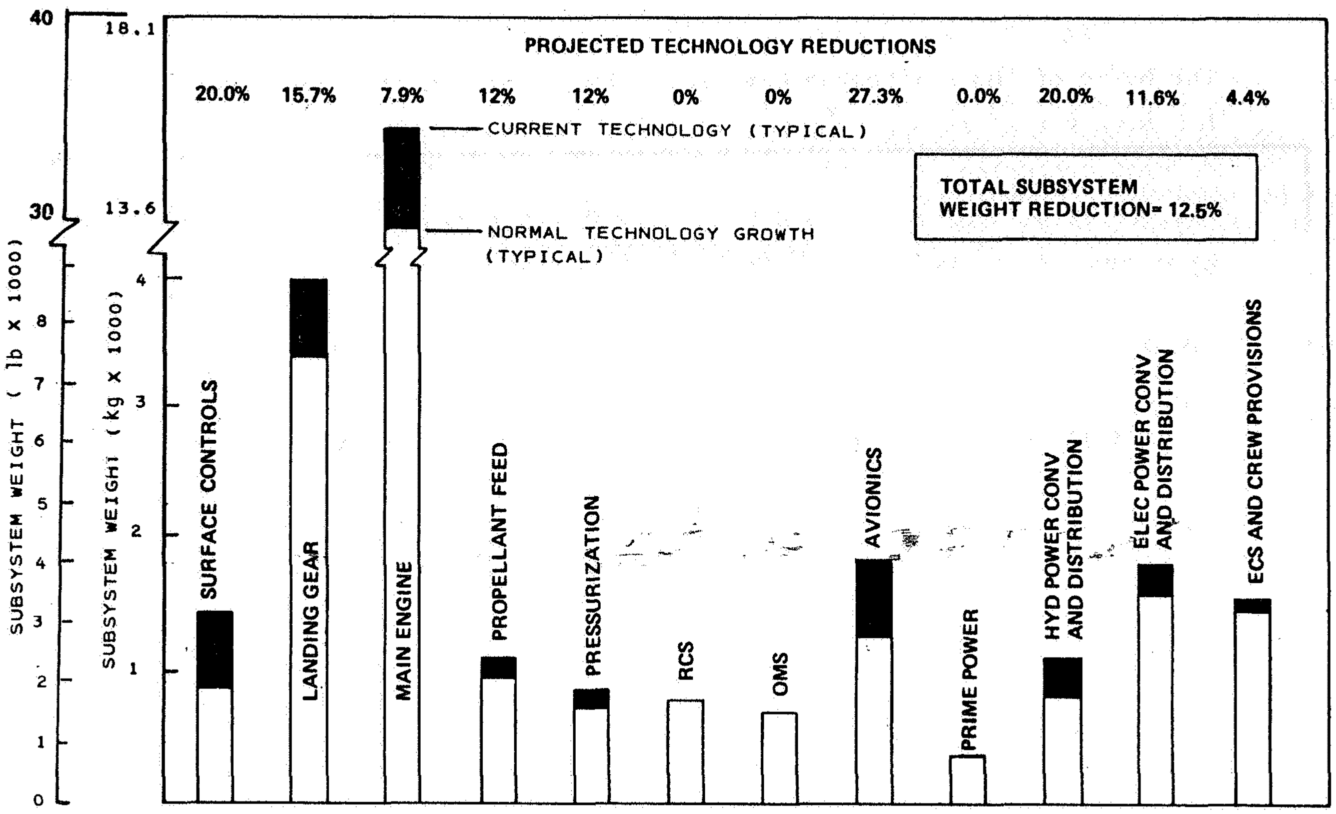


FIGURE 3, SUBSYSTEMS WEIGHT REDUCTION SUMMARY

DESIGN AND DEFINITION OF PERFORMANCE POTENTIAL OF VEHICLE SYSTEMS - TASK II

This task consisted of defining four SSTO configurations, obtaining subsystem design data from Task I, defining subsystem performance requirements and environments, selecting subsystem concepts, analyzing and sizing subsystems and calculating total configuration weights. In addition, guidelines were established which provided a consistent set of ground rules to permit a valid comparison of the three vehicle system concepts developed in the study. These requirements were grouped into mission, subsystems, and performance require ments. Performance requirements included aerodynamics, loads, thermal, and structural analysis and design criteria. Table 3 summarizes the top level mission requirements. Both NASA directed and Boeing proposed requirements are included.

Three different system concepts were analyzed during Task II. The four resulting configurations, all having horizontal landing capability but different ascent operating modes, are: (1) sled assist - horizontal take-off - Concept 1 (HTO); (2) sled assist - horizontal take-off-aerial refuel and

TABLE 3 STUDY REQUIREMENTS SUMMARY

- Lifetime: 500 missions (low cost refurbishment and maintenance as design goal).
- Mission duration: 12 hours of self-sustaining lifetime from lift-off to landing.
- Eastern launch from KSC @ 28.5° inclination (Reference energy orbit 93 x 185 km (50 x 100 n.mi.)
- Payload: 29,484 kg (65,000 lb) (Payload volume 18.29 m (60 ft) long; 4.57 m (15 ft) diameter)
- Orbital maneuvering system: ΔV = 198 m/s (650 fps)
- Reaction control system: ΔV = 30.5 m/s (100 fps)
- TPS design mission (reentry): Entry from due east 28.5° inclination
  371 km (200 n.mi.) altitude orbit
  Return payload 29.484 kg (65,000 lb)
  2,038 km (1,100 n.mi.) cross range capability.
- Fuel: LO_2/LH_2. Main Engine: High pressure bell (SSME type) or linear rocket engine.
- Load: n_x = 3g ascent; n_z = 2.2g entry; n_z = 2.5g subsonic maneuver
- Aerodynamic heating: Boundary layer transition onset - RI/SD correlation.
- Subsonic aerodynamics: Minimum landing speed = 84.8 m/s @ $\alpha = 15^\circ$
  Minimum static margin = 2% $\bar{c}$ (non CCV design)
  Static directional stability $\geq$ .002 (non CCV design)
- Hypersonic aerodynamics: Trimmable α range = 20° min. to 40° or greater.
  Trimmable through entry with control surfaces and RCS.

(3) air carry - horizontal take-off-air launch - Concept 2; and (4) vertical take-off (VTO) - Concept 3. These vehicles would have a first operational flight in 1995. A generic configuration was used by all three concepts. Design differences between concepts reflect consistent design approaches, philosophy and technology levels. Due to this approach, it was possible to avoid repetition in the analysis of the various configurations and to apply analysis results to more than one configuration.

Configuration 1 - Sled Assisted Horizontal Take-Off - Concept 1 (HTO)

A typical mission profile for the SSTO-HTO vehicle is shown in Figure 4. It includes a ground accelerator assisted take-off at 182.9 m/s (600 fps) followed by a climb limited to a 1.25 g normal load factor. Take-off thrust to weight is .77. The acceleration phase is a lifting type ascent trajectory to orbit injection. After delivery of payload the vehicle uses its OMS engine to deorbit, entering at a planform loading of 1245 Pa (26 psf). The vehicle glides back and performs its final maneuvers to a power off horizontal landing.

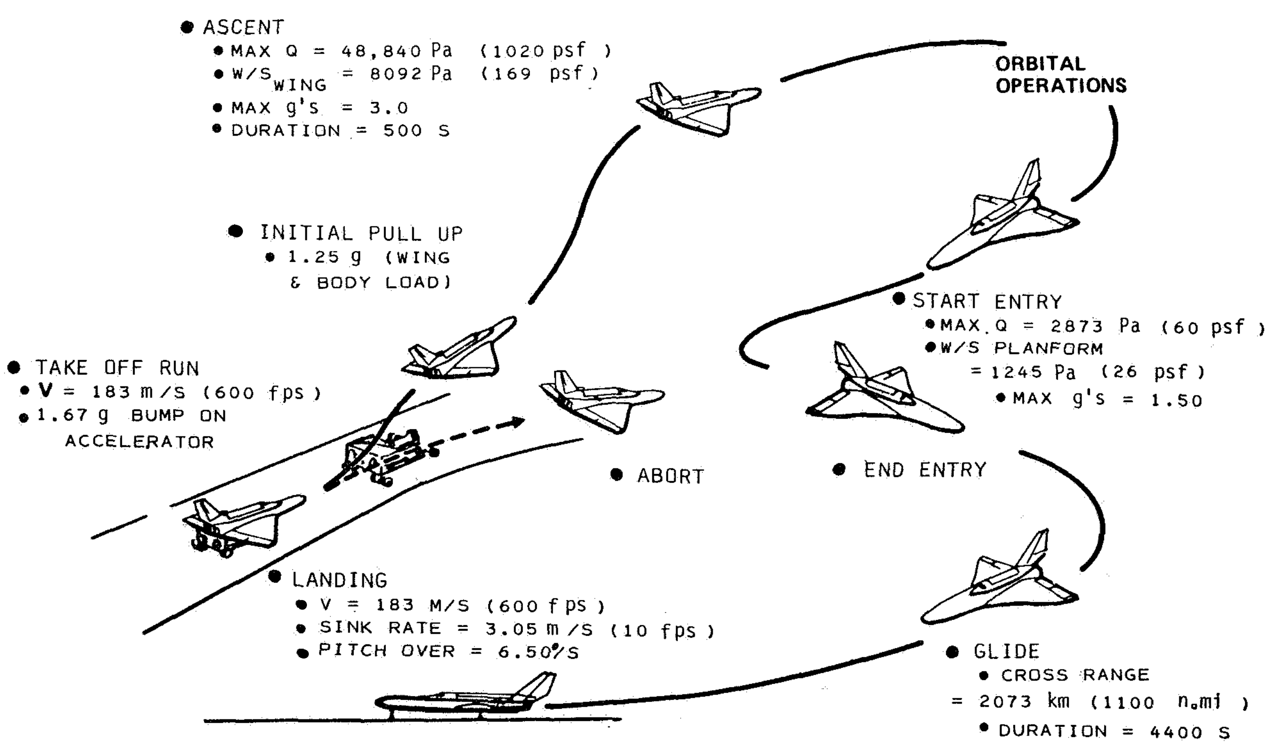


FIGURE 4. - HTO-SSTO MISSION PROFILE.

Configurations 2 & 3 - Aerial Refuel and Air Launch - Concept 2 (IFF)

As originally conceived, it was assumed that a ground accelerator launch vehicle would be configured. However, investigation during the study indicated that a lightly loaded vehicle realized very little benefit from a ground accelerator. Several options of Concept 2 were studied which include: (1) SSTO-sled assist - aerial LO_2/LH_2 transfer; (2) SSTO-sled assist - aerial LO_2 transfer; (3) SSTO-sled assist - aerial LH_2 transfer; (4) SSTO-sled assist - aerial slush propellant transfer; (5) SSTO air carry - aerial launch total fuel transfer; and (6) SSTO air carry - aerial launch partial fuel transfer.

Figure 5 is illustrative of the aerial refuel of LH_2 and LO_2 at 9144m (30,000 ft.) after vehicle rendezvous, fueling, and separation at a velocity of M = .6. Once separated, the refueled vehicle follows an ascent trajectory similar to that of the HTO SSTO vehicle.

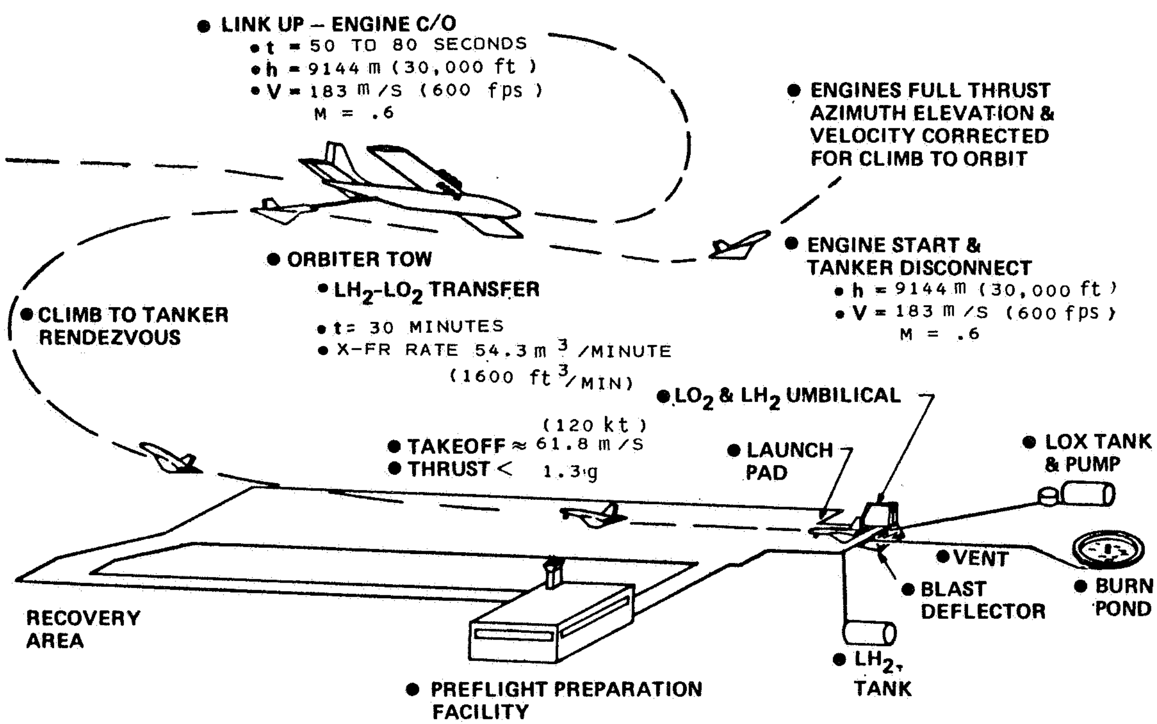


FIGURE 5. AERIAL REFUEL SSTO MISSION PROFILE

Configuration 4 - Vertical Take-Off - Concept 3 (VTO)

A typical mission profile for the VTO SSTO vehicle is shown on Figure 6. Initial T/W at take-off is 1.31. The acceleration phase is a vertical rise until M = .4 and then utilizes a pitch-over to gain some lift after gravity losses are minimized. After delivery of payload, the vehicle uses its OMS engine to deorbit, entering at a planform loading of 1389 Pa (29 psf). The vehicle glides back and performs its final maneuvers to a power off horizontal landing similar to the other study vehicles.

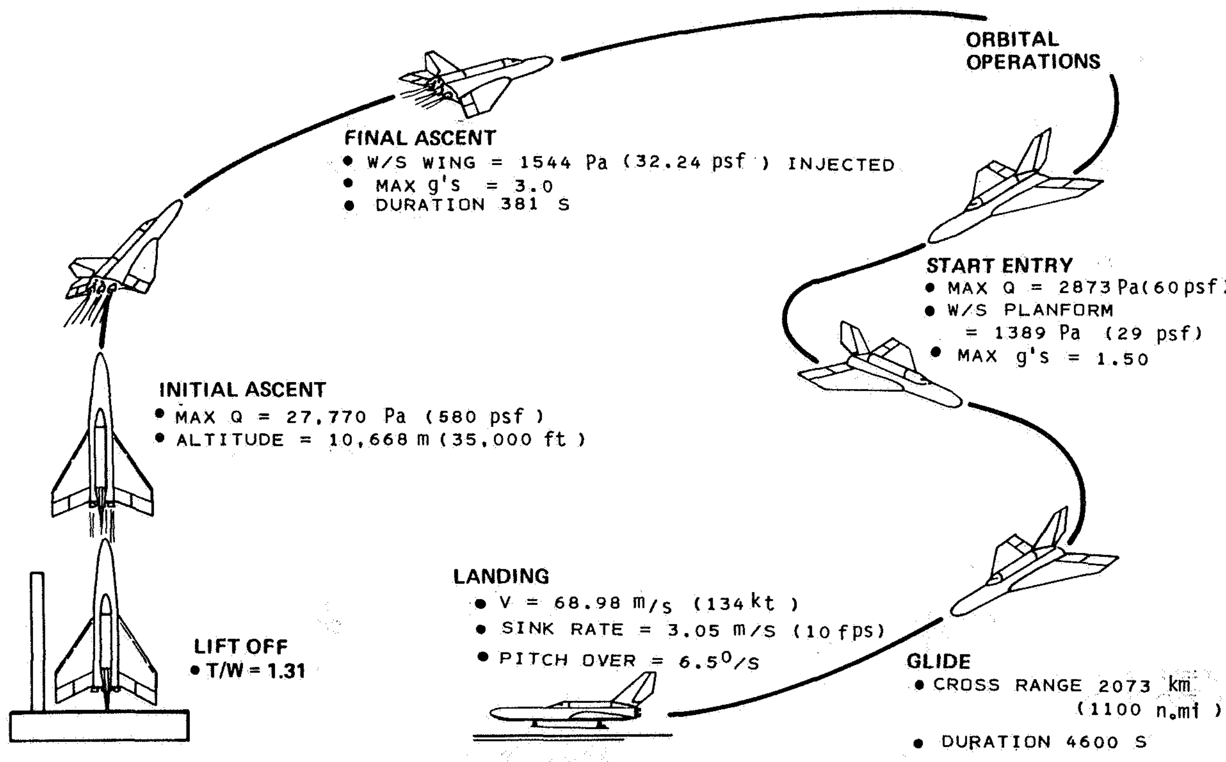


FIGURE 6. VTO-SSTO MISSION PROFILE

Baseline Configuration - Concept 1 (HTO)

It is important to note that the basis for generic scaling of structural concepts was the horizontal take-off SSTO vehicle which Boeing had been working on for over four years. The company's interest is based on the belief that the reusable, airplane type operation of earth orbit transportation vehicles will allow considerable improvement in cost per flight and flexibility. Earlier studies indicated that to provide a useful payload to orbit with a Single Stage to Orbit concept, operating in any launch mode, structural weight must be significantly reduced. Consequently, the study baseline concept uses a single structural system to serve functions which previously required four separate systems: thermal protection, airframe, cryogenic tankage, and cryogenic insulation.

In keeping with the foregoing, and noted in Figure 7, the structure can be thought of as being fuel and oxygen tankage with integrated instructure and required addendums. The present baseline configuration is a delta wing vehicle that takes off and lands horizontally. The wings are liquid oxygen tanks capped by a high temperature leading edge fairing at the front, control surfaces and their actuators at the back, and only a main landing gear intrusion in the lower surface. The liquid oxygen in the wings provides relief for the aerodynamic lifting loads during ascent. The

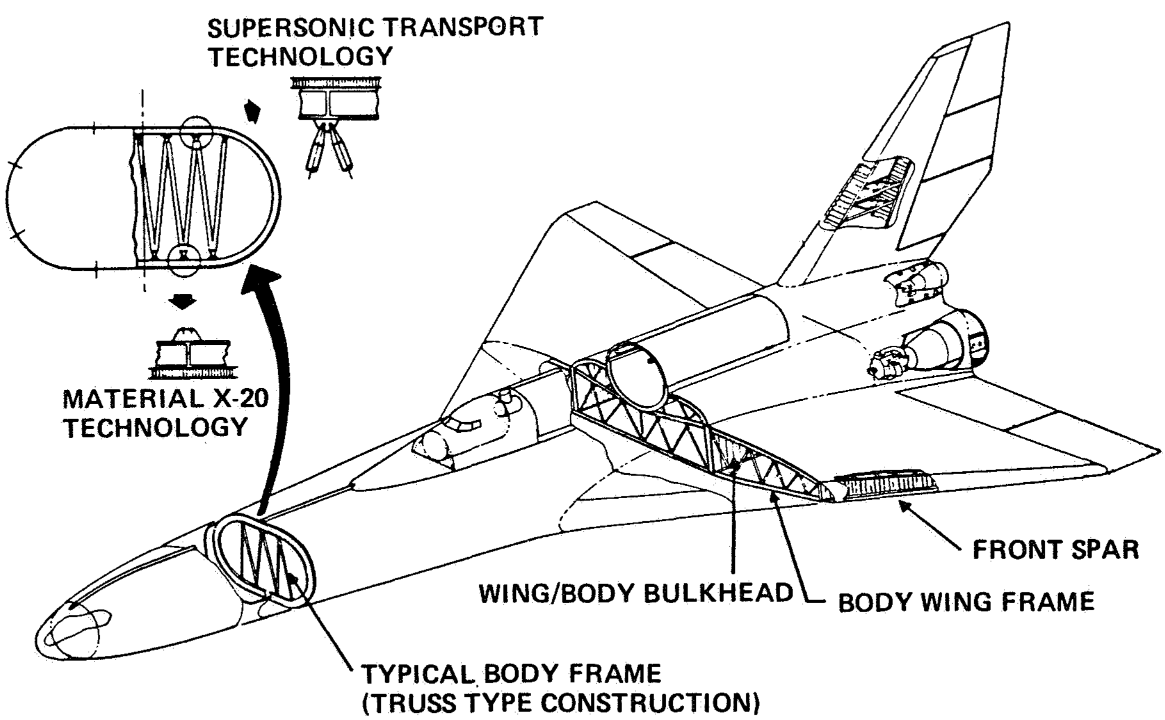


FIGURE 7. SSTO VEHICLE STRUCTURAL CONCEPT

oxygen's weight is sled supported during take-off, then aerodynamically supported until expended. As a result, wing bending, landing gear punch and the resulting weight required by a conventional landing gear supported take-off are eliminated. At the same time, the weight savings associated with the low thrust-to-weight ratio of a landing-gear-supported take-off is retained. The vertical tail is mounted on and ties into both the body tank and aft body. Control surfaces in the vertical fin and wings are used for atmospheric vehicle control.

A liquid hydrogen tank forms the major portion of the main body with a high temperature nose fairing at the front; a propulsion system and housing at the back; crew, payload, and equipment accommodations on top and only a nose wheel intrusion in the lower surface. The wing root bulkhead forms the interface between the body hydrogen tank and the liquid oxygen wing tanks.

One of the key issues regarding feasibility of this type of vehicle is the ability to integrate the propellant tankage with load carrying structure. Thus, the propellant is contained by aerodynamically shaped structure rather than the more conventional cylindrical pressure vessels used on current space boosters. The resultant primary structure consists of an outer shell of load bearing honeycomb panels stabilized by ring frames with truss type internal tension struts.

The exterior surface of the vehicle is made from Rene'41 and titanium honeycomb sandwich. Material selection is based upon the temperature attained during ascent or reentry. The Rene'41 material was developed for use on the X-20 program. The aluminum brazed titanium honeycomb panel development was sponsored by the Department of Transportation on the Supersonic Transport program.

By reshaping the typical cylindrical cryogenic tankage in the form of an aerodynamic type airframe, the vehicle can reenter the earth's atmosphere with a planform loading which allows the use of proven materials technology. Reentry equilibrium isotherms for this type of reentry are shown on Figure 8.

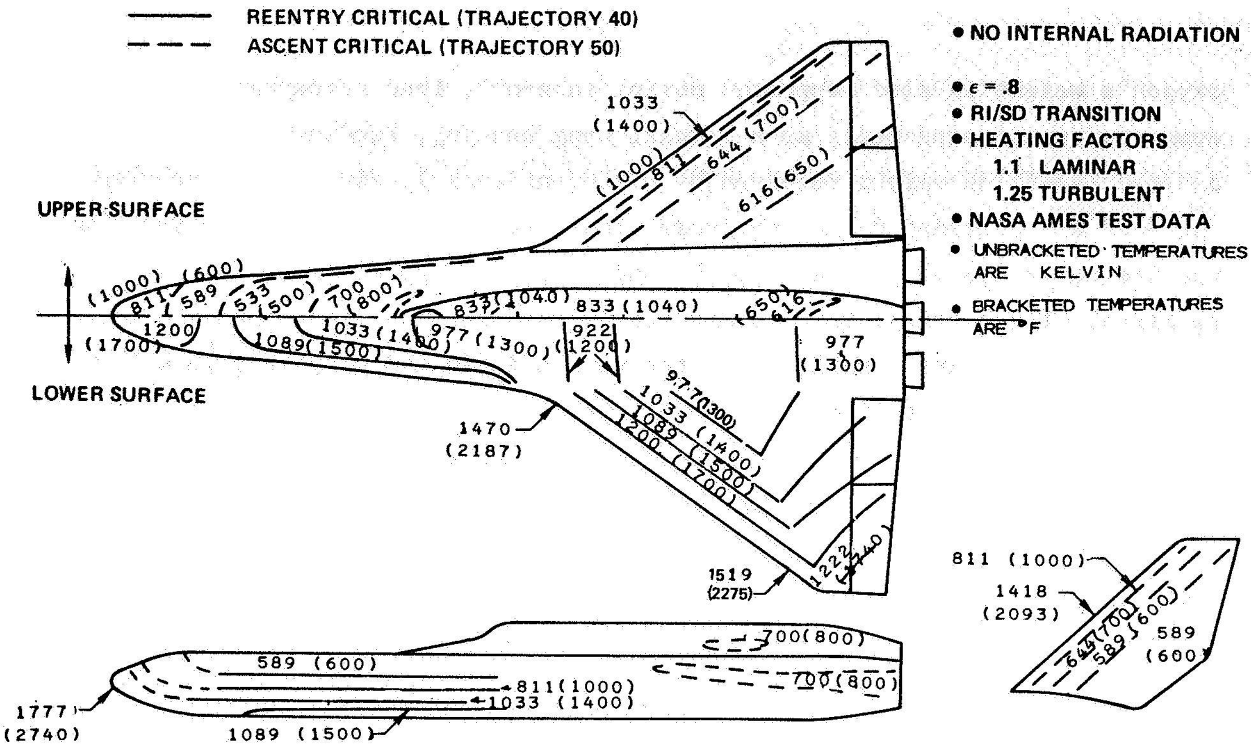


FIGURE 8. HTO SSTO PEAK EQUILIBRIUM TEMPERATURE DISTRIBUTION

The resultant temperature distribution and structural details for a typical body section are shown on Figure 9. The honeycomb body skins are stabilized by internal circumferential frames at approximately .76m (30-inch) spacing. The frames are made from Rene'41 at the lower surface and titanium at the upper surface, spliced mechanically at the halfway waterline. The flat sections of the frames have high bending moments caused by internal tank pressure. These bending loads are reacted by tubes between the upper and lower surfaces. All of the internal body frames are truss and ring types except for the solid bulkheads at the forward and aft ends of the tank.

The wing, which is not shown, contains LO_2, and uses the same structural system as the body, with Rene'41 honeycomb for the lower surface and titanium honeycomb for the upper surfaces. The wing bending loads are carried by a series of truss wing spars located at the same body station as the body frames. The wing bending loads are carried through the body by beams, stabilized by the body frame struts. The wing leading edge temperatures exceed the capability of Rene'41 and so a combination of Inconel, Haynes 188, and Columbium is used. The relative low thermal conductivity of the sealed core honeycomb prevents formation of liquid air on the outside of the vehicle and prevents excessive boil-off of the LH_2 and LO_2.

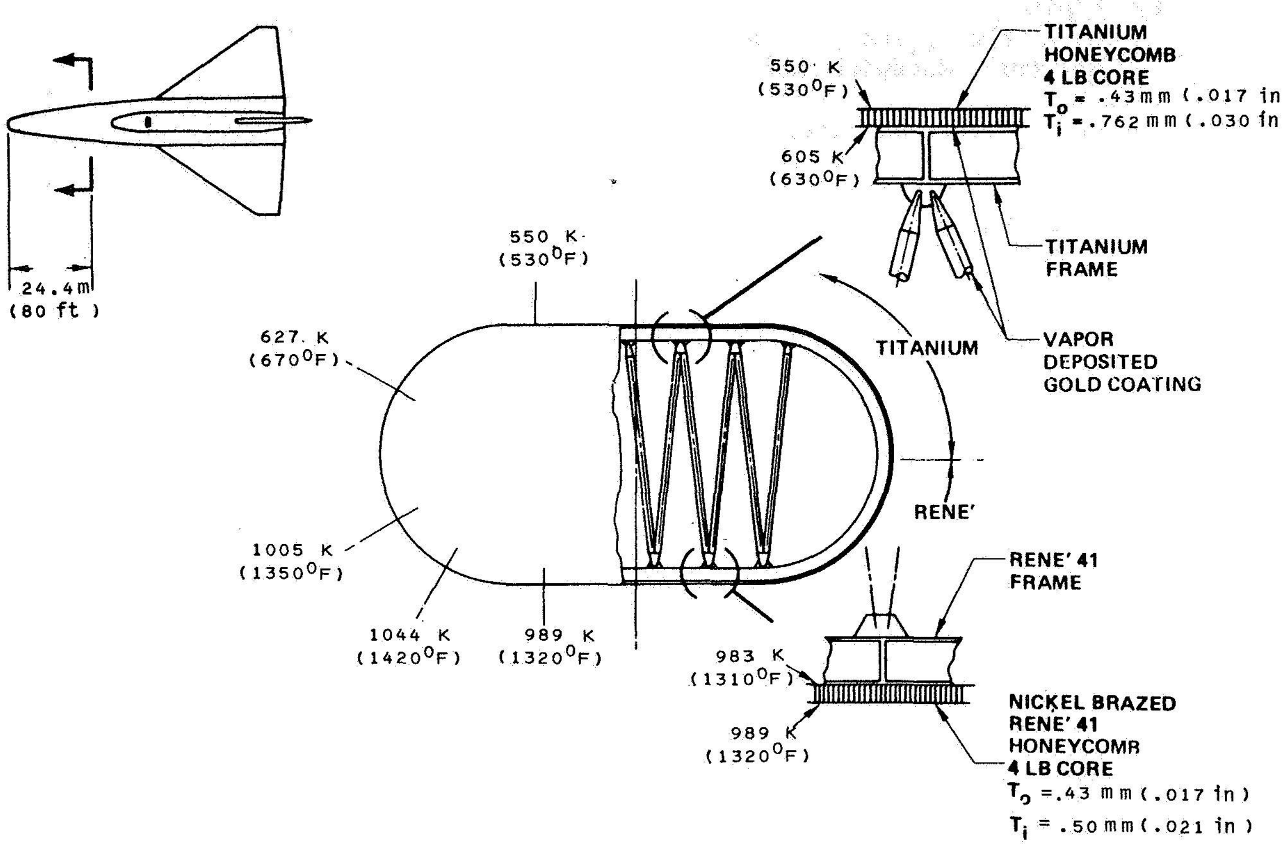


FIGURE 9. TYPICAL BODY SECTION TEMPERATURE DISTRIBUTION AND STRUCTURAL DETAILS

Vehicle Design Analysis

A detailed analysis of the horizontal take-off vehicle was accomplished and included:

1) Peak equilibrium radiation temperatures for ascent and reentry;

2) Temperature distribution accounting for internal radiation, conduction and heat storage;

3) Body and wing bending moment, shear and axial loads for all conditions making up the design envelope;

4) Surface hinge moments and engine gimbal requirements for flight controls and auxillary power analysis;

5) Structural sections representative of all portions of the vehicle structure including forward, mid and aft body, wing loading edge, elevon, payload bay and thrust structure;

6) Finite element model of typical body frame including inner and outer chords and webs of a frame, frame support struts, inner and outer sandwich skin and honeycomb core;

7) Reentry thermal stresses at maximum reentry thermal gradient and at maximum temperature;

8) Main engine and subsystem detailed definition including feed system, pressurization systems, reserves and residual analysis;

9) Aerodynamics; and

10) Performance.

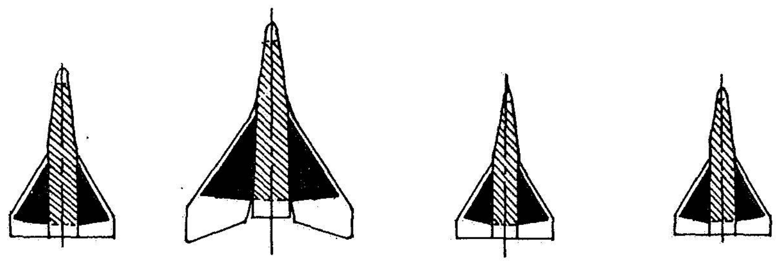
In addition, subsystems were defined, sized consistent with their respective performance requirements and located within the vehicle. This served as the basis for scaling several of the analyses for the vertical take-off and the in-flight fueled configurations.

Configuration Summary

As a result of this type of analyis, the vehicles were sized as shown by the summary of characteristics on Table 4.

The sled assisted, horizontal take-off vehicle appears to offer the lowest practically attainable GLOW, 1.00 X 10^6 kg (2.2 million lb). Estimated c.g. location and aerodynamic characteristics indicate a stable and trimmable vehicle both at hypersonic and subsonic speeds. The vertical take-off vehicle GLOW is estimated at 2.01 X 10^6 kg (4.4 million lb). The primary increase in weight was caused by the difference in propulsion thrust to weight ratios (.77 for the HTO versus 1.31 for the VTO and associated scaling effects. In addition, the VTO vehicle design concept was based on generic association with the HTO vehicle which utilized LO_2 in the wing during ascent for inertial load relief. This generic integration of fuel location might have unduly penalized the VTO configuration. However, additional analysis and study indicate that the overall GLOW could not be reduced below 1.8 X 10^6kg (4.0 million lb) even on an optimistic basis. The inflight fueled and air launch vehicle show reduced take-off weights of .77 X 10^6 kg - (1.7 million lb) for each vehicle results from launching at altitudes of 6096 - 9144 m (20 - 30,000 ft). However, the technical difficulties associated with cryogenic refueling, fuel transfer, balance and stability and large tanker design indicate operational difficulties and complexities and potential for high development and recurring costs.

TABLE 4. SSTO VEHICLE CONFIGURATION SUMMARY



	CONCEPT 1	CONCEPT 3	CONCEPT 2	
ITEM	HTO ♦ (HORIZONTAL TAKE OFF)	VTO (VERTICAL TAKE OFF)	IN-FLIGHT FUELED	AIR LAUNCH ♦♦
● WEIGHT GLOW	1.00 x 10^6 kg (2,203,500 lb)	2.01 x 10^6 kg (4,421,000 lb)	.77 x 10^6 kg (1,700,000 lb)	.77 x 10^6 kg (1,700,000 lb)
DRY WEIGHT	10.0 x 10^4 kg (218,880 lb)	20.6 x 10^4 kg (455,050 lb)	8.2 x 10^4 kg (180,393 lb)	8.2 x 10^4 kg (189,393 lb)
● LENGTH	62.9 m (206 ft 4 in)	71.6 m (235 ft)	55.4 m (181 ft 8 in)	55.4 m (181 ft 8 in)
● SPAN	42.6 m (139 ft 8 in)	61 m (200 ft)	37.1 m (121 ft 10 in)	37.1 m (121 ft 10 in)
● AREA REFERENCE WING	881 m^2 (9484 ft^2)	1,709 m^2 (18,400 ft^2)	747 m^2 (8,040 ft^2)	747 m^2 (8,040 ft^2)

♦ SLED ASSISTED ♦♦ CARRIER AIRPLANE ASSISTED TO 9144 m (30,000 ft)

Cost Analysis

Cost Ground Rules and Guidelines. - The following ground rules and guidelines were provided by NASA:

1. Launch rate = 114/yr baseline. This rate will be perturbed (± 30%) - for rates on both sides of the baseline to determine launch rate sensitivity.

2. Program length = 15 years
   1710 flight total for baseline.

3. Two operational sites (KSC and Vandenberg).

4. Costs in 1976 dollars and present value analysis (Discounted at 10% year).

5. LO_2/LH_2 propellant costs = \$.352/kg (\$.16/lb) for O/F mixture ratio of 6:1 (LH_2 = \$2.20/kg (\$1.00/lb), LO_2 = .044/kg (\$.02/lb).

The following ground rules and guidelines were developed by Boeing. Vehicle and facility numbers were developed from turnaround and service life requirements.

1. The working units of the cost model which was used to determine DDT&E and Production costs are manhours; resulting costs are provided in 19[illegible] dollars. The Boeing cost model predicts the cost of aerospace programs from a set of preliminary physical or performance inputs.

2. Manhours are converted to dollars using current Boeing direct and indirect labor and material rates and factors.

3. Model is based upon a detailed breakout of all functional organization effort contributing to space and airplane programs in which Boeing has participated plus Space Shuttle.

4. Program Management and SE and I are factors.

5. Facilities requirements:

   a. Assumes minimum use of existing KSC and WTR facilities;

   b. Requires a two-launch position at each launch site; and

   c. Discrete manufacturing, test and launch facilities identified.

6. Vehicle quantities:

   a. Ground test SSTO's (PTA and STA);

   b. One flight test SSTO and 1/2 unit flight spares;

   c. Four production SSTO's; and

   d. Four production sleds.

7. Propulsion system costs furnished by Rocketdyne Division of Rockwell International

8. Program management includes the contractors effort only. NASA program management is not included.

9. Spares are valued as percentage of production hardware.

10. No fee is included.

DDT&E and Production Costs. - DDT&E costs are based on buildups from constituent functional categories. These functional relationships are based upon strong statistical correlations occurring in all Boeing space programs and aircraft programs. The manufacturing technology organization provided inputs to the finance organization based on vehicle structural drawings and experience gained on the SST program with aluminum brazed titanium honeycomb. In addition the producibility of the Rene'41 was compared to that of aluminum and titanium for milling, drilling, tapping, and turning operations. The average ratio was used as a complexity factor in the cost model.

Hardware development costs were based on inputs from the designers as to which complexity/availability classification the subsystems were categorized. These inputs were a result of the Task I technology study and range from catalogue order to new development. By using the adjustment factor, the benefit of using off-the-shelf designs, or modifications of existing designs, can be accounted for as a reduction in necessary design effort. Unit cost build-up is basically a function of Manufacturing, Quality Control and assembly and checkout effort. The inputs for DDT&E are selectively distributed to the first unit cost category by subsystem element and related with support elements.

Operations Costs. - It is felt that the ultimate successor to the Space Shuttle must operate in a transportation mode approaching commercial aircraft. Operational costs must be driven down to where fuel costs dominate the cost per flight element. A national goal of achieving a manned lunar landing within a tight time schedule required that research and development be accomplished concurrently with hardware production and operations on earlier manned space programs. As a result, governing criteria for space vehicle (booster stages and spacecraft) design emphasized maximum vehicle performance and mission and crew safety.

To minimize turn-around/launch operations costs of future programs, it is necessary that the SSTO vehicle should be designed for processing from recovery through the next succeeding launch with a minimum of vehicle-to-ground interfaces, ground operations and ground processing time.

The basic assumptions for this approach are: a standardized vehicle design will allow turn-around/launch operations for each vehicle to be essentially the same as for the previous vehicle and will allow maximum learning benefits to be realized. Designing the vehicle independent of the cargo with the cargo pre-packaged and self-sustaining will minimize the effect of cargo loading and unloading operations on grund operations. Prelaunch payload integration procedures similar to commercial air cargo carriers must be developed and employed.

Each flight within the program requirements envelopes will be repetitive in type. The vehicle will serve only as the carrier of the cargo and will deliver the cargo to or recover the cargo from some destination in earth orbit.

The vehicle must be designed so that airplane techniques of turn-around operations can be applied. The vehicle and facility must be designed to be mutually compatible and with a minimum number of interfaces and cost generating functions (operations) involved.

In order to determine the system, vehicle and facility requirements, a launch operations processing schedule was prepared for each vehicle. The schedule covers the operations from vehicle approach and landing after the mission through launch of the next vehicle and launch facility refurbishment. The schedule was developed by reviewing operations analysis of the Space Shuttle and commercial aircraft. A typical flow for the HTO/SSTO vehicle concept is shown in Figure 10 and resulted in a direct "hands on" vehicle contractor or estimate of 4340 manhours per flight.

The Main Propulsion Engine cost data are summarized in Table 5 with the SSME data shown for reference. The total cost/flight column reflects two separate costs. The total engine costs per flight are shown above the line and include everything associated with the main engine. The value below the line are the costs associated with the main engine cost per flight element. The differences are labor costs associated with replacement and are included in the ground operations cost per flight element discussed previously.

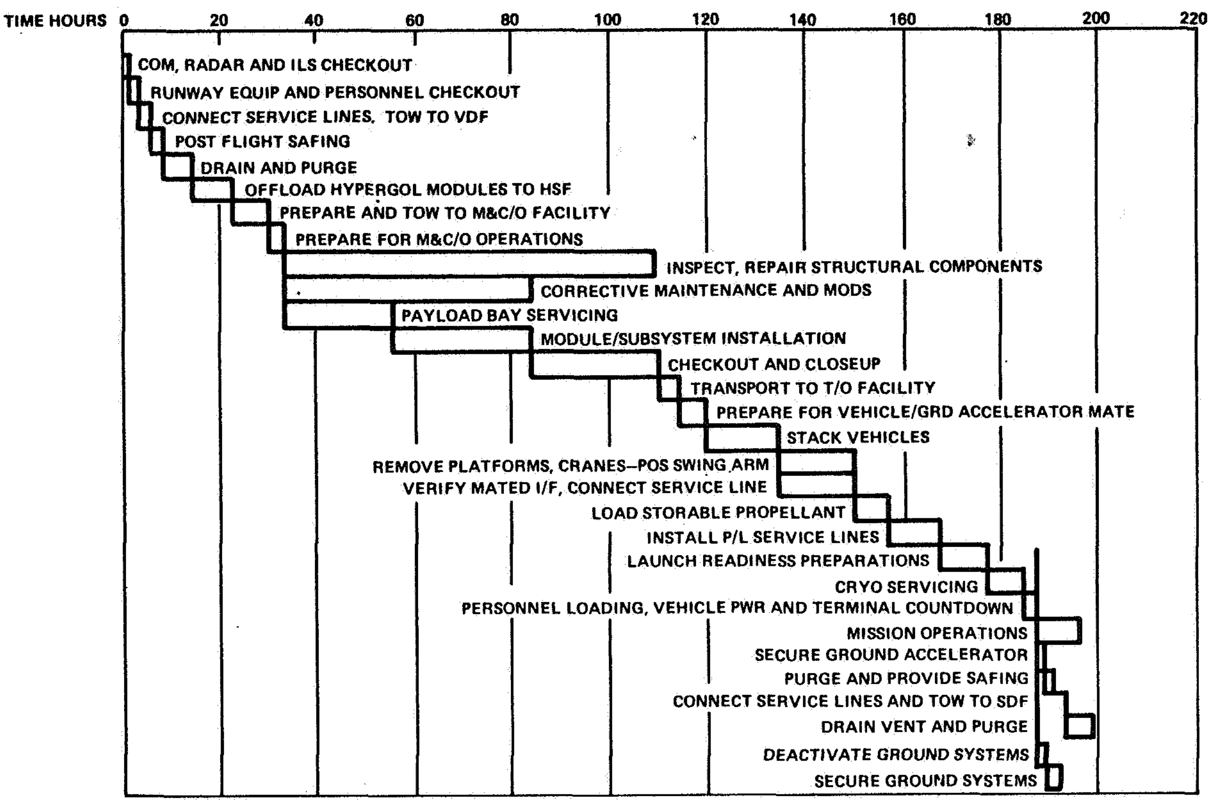


FIGURE 10. HTO-SSTO BASELINE OPERATIONS FLOW

TABLE 5. SSTO MAIN ENGINE COST SUMMARY

Engine \ Cost element	Develop cost ($M)	First unit cost ($M)	Overhaul cost/flt ($K) [1]	Flight servicing cost/flt ($K) [2]	Replacement rotation cost/flt ($K) [3]	Flight support cost/flt ($K)	Propellant and trans. cost/flight ($K)	Total cost/flight ($K)
Space shuttle SSME (ref.)	520	11.3	106.6	52.5	158.6	136.5	52.3	506.5
2.09 MN (470K lb) THRUST		11.3	118.9	33.5				
2 POSITION NOZZLE	50	1.0	10.5	4.0	122.8			292.0
3 ENGINE CLUSTER	50	12.3	129.4	37.5	57.8	2.3		227.0
3.02 MN (680K lb) THRUST	350	13.8	145.2	33.5				
2 POSITION NOZZLE	50	1.2	12.7	4.0	149.6			347.3
3 ENGINE CLUSTER	400	15.0	157.9	37.5	70.4	2.3		268.3
4.89 MN (1100K lb) THRUST	550	17.0	357.9	54.5				
2 POSITION NOZZLE	50	1.5	15.9	4.0	349.0			859.7
3 FIXED/3-2 POS. CLUSTER		18.5	373.8	58.5	162.5	56.7	21.7	673.2
GROUND ACCELERATOR BOILER PLATE SSME	–				82.9			176.2
5 ENGINE CLUSTER $\epsilon = 35:1$		11.3	79.3	14.0	33.1	–	–	126.4
GROUND ACCELERATOR BOILER PLATE SSME					66.3			159.6
4 ENGINE CLUSTER $\epsilon = 35:1$	–	11.3	79.3	14.0	26.5	–	–	119.8

[1] SCHEDULED MAINTENANCE
30% of new engine cost/70 flights

[2] 1/2 shuttle cost

[3] UNSCHEDULED MAINTENANCE
Same factor as shuttle 2.5/5.0 equivalent engines for 710 flights for hardware which is 40% of total cost (i.e., 60% labor) + x unit spares for turnaround

Cost Summary

Operations costs are presented in Table 6 for the three study concepts by major cost element. Ground operations costs include vehicle contractor launch personnel, propulsion, labor for the vehicle and sled (if applicable), and vehicle spare labor. Main engine support includes flight servicing, overhaul (parts and labor, spares material, flight support and propellants and transportation for all engines (sled and vehicle). Spares include replenishment items other than the main engine. Fuel and propellants include the main ascent propellant, subsystems fluids, as well as facility fluids and gases. Program support includes the flight and mission operation costs as well as the facility operations personnel (i.e., GSE contractor, facilities, maintenance, fire, security, etc.). All tanker operations are included in the one cost element.

Life cycle costs are presented in Table 7 for the three different configurations. The major cost brackets are design, development, test and engineering (DDT&E), production, and operations.

$1976 millions	HTO/sled	IFF	VTO
Expendable hardware	0	0	0
Ground operations	513	360	775
Main engine support	675	388	1,151
Spares	195	145	309
Fuels and propellants	670	496	1,330
Program support	249	233	367
Subtotal	2,302	1,622	3,932
Tanker operations	—	741	—
Total	2,302	1,622	3,932
CPF	1.35	1.38	2.29
Transportation cost $/kg ($/lb)	45.64 (20.7)	46.96 (21.3)	78.04 (35.4)

SSTO OPERATIONS

COST PER FLIGHT ELEMENTS

TABLE 6.

$1976 millions Cost element	HTO	IFF	VTO
DDT&E*	3,395	4,142	4,887
Production**	2,327	2,731	3,568
Operations***	2,440	2,505	4,168
Total	8,162	9,378	12,623

*2.9 test units
**4 vehicles
***1,710 flights

SSTO LIFE CYCLE COST COMPARISONS

TABLE 7.

The total program costs are presented in Figure 11 for the three study concepts. The shaded area represents the costs discounted at 10% per year. The costs are nearly proportional to the size of the SSTO vehicles. In addition, the operations analysis accounts for the differences between a horizontal type aircraft launch and servicing and the conventional vertical booster type servicing. In order to provide discounted costs, schedules were developed For each program. Based on an IOC of 1995, a program start was required in 1987 for an eight year design and test activity. This provided approximately ten years of R&D funding (1977-1987) prior to ATP. Flight operations occurred between 1995 and 2010 at the rate of 114 flights per year with a total mission model of 1710 flights.

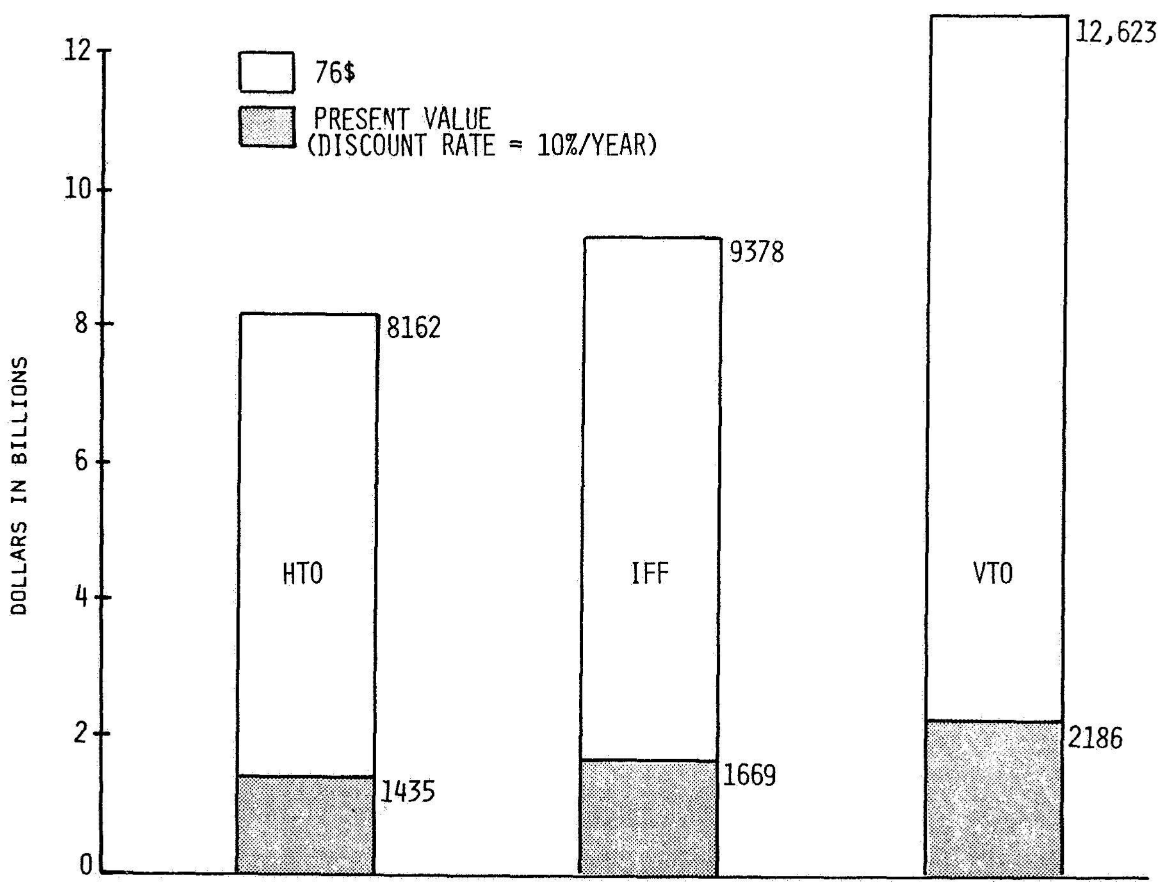


FIGURE 11. SSTO COST SUMMARY

As a result of the size and cost differences and the technical difficulties (cryogenic refueling, balance and stability and large tanker development) associated with the inflight fueled concept, the sled assisted horizontal takeoff vehicle was selected with Government concurrence for the advanced technology assessment in Task III.

The tanker airplane operations costs are very similar to the HTO/Sled (2363 vs 2302 million) even though the flight vehicle is smaller. The 741 million dollars for tanker operations over the 1710 flights reflects aircraft operational philosophy except for the cryogens and size. However, the tanker requires a completely different logistics program as it has no real commonality with the flight orbiter.

The breakdown of these dollars is as follows:

Three hundred thirty-five million dollars for ground operations. This value is based on an estimate of the "hands on" and "hands off" manhours required for post and preflight serving of the tanker airplane as well as routine support operations between flights.

One hundred twenty-two million dollars for engine support. This includes refurbishment at 6% per 100 flights and replenishment at 0.5%/100 flights. Estimated value of the airbreathing engines is 65 million dollars.

Two hundred twenty-nine million dollars for aircraft spares (less engines). This includes refurbishment at 6% per 100 flights and replenishment at .18%/100 flights. Estimated value of the tanker aircraft is 335 million dollars.

Seventeen million dollars for fuel and propellants. This estimate is based on the 747 airplane requirement of $425/flight hour for fuel. A factor of 7.2 was used to account for the additional engines at higher thrust levels.

Thirty-eight million dollars was estimated for program support. The value is a historical percentage number based on previous program experience.

For the single operational concept selected by NASA in Task II, subsystem weight and performance sensitivities relative to vehicle payload, weight and GLOW were determined. This process defined those subsystems or technology areas where performance advancements had the greatest payoff. For those subsystems selected, for the technology improvements, a dollar estimate to establish the basic technology was made. This estimate was based on in-house experience where applicable, in addition to discussions with outside vendors when appropriate. The Rocketdyne Division of Rockwell International provided the majority of estimates associated with the Main Propulsion System (see Figure 12). The dollar estimate to "produce" is defined at the technology program cost estimate to bring the program to demonstration of feasibility. This does not include the normal DDT&E cost associated with that technology during the regular vehicle program startup. However, in most cases, the DDT&E program is reduced somewhat by the early R&D funding.

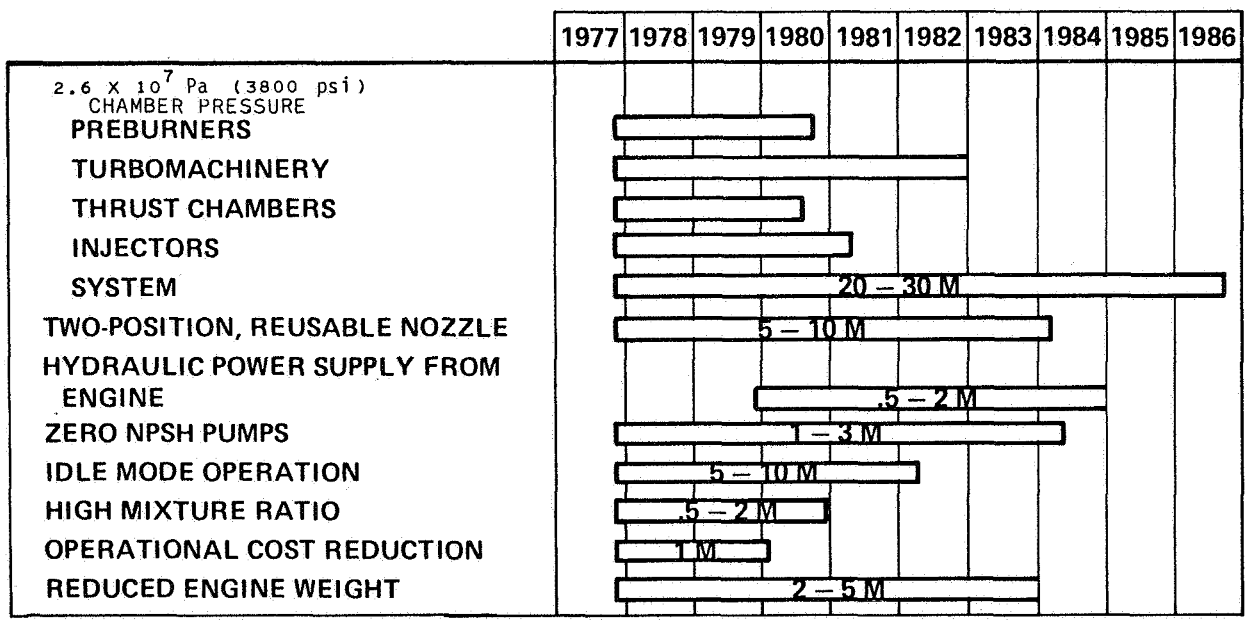


FIGURE 12. PROPULSION TECHNOLOGY DEVELOPMENT PLAN

In reviewing the projections for normal technology, it became apparent that although certain technology items were considered in this category, if for some reason the projection was too optimistic the technology program might not get the consideration it warrants. Examples of this are the Rene' 41 honeycomb development and the SSME two-position nozzle development. In each case these areas were classified as normal technology growth. The rationale was based on the application potential of both technology benefits to other programs such as Space Shuttle growth, hypersonic research vehicle, Space Shuttle booster derivatives, heavy lift, etc.

As a result, some of the normal technology items which were felt critical to development of an all metallic reusable thermal structural concept and some technology developments which could be high yield investments to an advanced shuttle derivative were placed in a category called "focused" technology, and evaluated based on "figure of merit" (see Table 8).

Normal technology (No additional funding)	Focused technology (Redirected funding)	Perturbed technology (Additional funding–new starts)
● 2.8% landing gear	● Titanium honeycomb	● Linear engine
● 3.45×10^7 Pa hydraulics (5000 psi)	● Rene' 41 honeycomb	● Tri-propellant engine
● Flight control actuators	● SSME 2-position nozzle	● Slush/triple point hydrogen
● LSI circuitry	● SSME idle mode operations	● Slush/triple point oxygen
● Laser radars	● LO2/LH2 APU	● Slush/triple point hydrogen/oxygen
● Micro processor	● Zero NPSH pump	● SSME hydraulic power
● Solid state displays	● SSME operations cost reduction	● Increased chamber pressure
● Bubble memories		● Increased mixture ratio
● Solid state power conditioning and switching equipment		● Increased engine thrust
● Boron aluminum composites (non cryogenic application)		● Metallic/atomic hydrogen
		● Integrated subsystems
		● Flight control actuators
		● All movable tail
		● Advanced landing gear
		● Advanced composites
		● 866 K (1100°F) titanium

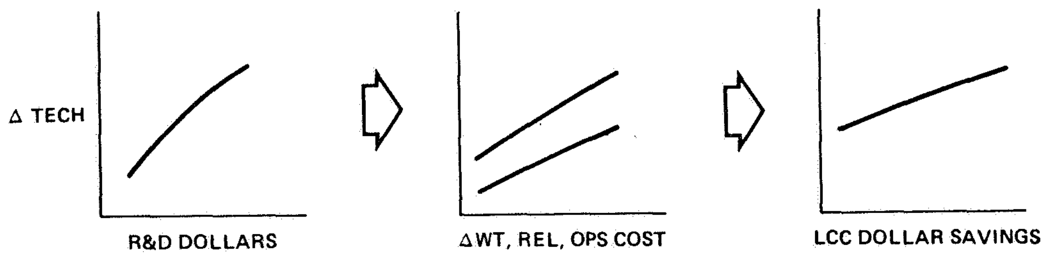
TABLE 8. SSTO TECHNOLOGY CLASSIFICATION

The advanced technology programs which would require additional funding and, in some cases, new starts to support an SSTO type program were categorized separately under perturbed technology.

Figure of Merit Methodology

Once the R&D cost estimates were made, the technology programs were ranked based on the ratio of the change in life cycle costs to the dollar investment. This ranking was made with both 1976 and 10% discounted dollars. The rationale and methodology for the "figure of merit" is shown on Figure 13.

$$\text{FIGURE OF MERIT (FOM)} = \frac{\Delta \text{ LIFE CYCLE COST DOLLARS*}}{\text{R\&D PROGRAM DOLLARS**}}$$



*SAVINGS IN DDT&E, PROD OR OPERATIONS AS A RESULT OF TECHNOLOGY IMPROVEMENT

**ESTIMATED R&D (TECHNOLOGY IMPROVEMENT PROGRAM COST) TO DEMONSTRATE TECHNICAL FEASIBILITY

FIGURE 13. ADVANCED TECHNOLOGY "FIGURE OF MERIT"

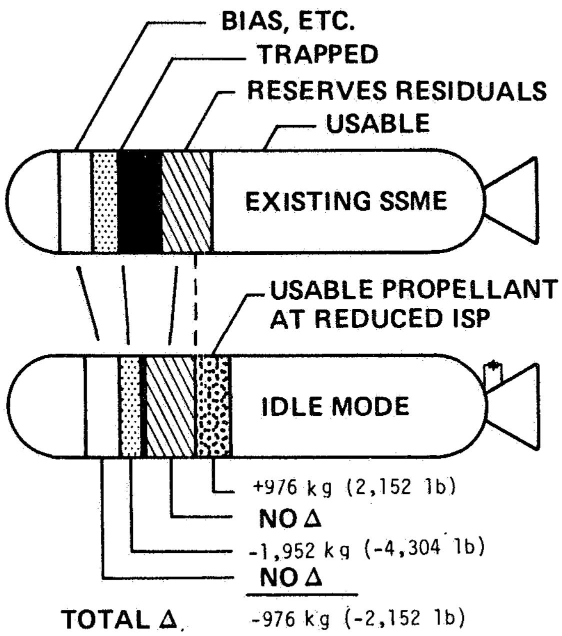
Figure of Merit Analysis

Table 9 is a representative example of one of several pages which illustrates the actual figure of merit analysis for certain development programs. The technology development program column lists the programs which were previously outlined with the associated rationale under their respective categories. The R&D cost in most cases expresses a range of dollars estimated by subcontractors, vendors or qualified personnel in the field who were consulted during the study. The weight columns are self-explanatory and in the majority of cases represent a change in dry weight which can be directly associated with a change in the GLOW. In some instances, performance improvements are combined with dry weight additions to provide an overall payload gain. The cost savings (in most cases) are broken down between DDT&E, production and operations and cumulated in the life cycle cost column. The FOM column shows the LCC change over the R&D cost forecast in the first column. Savings are shown in 1976 dollars (no brackets), and dollars discounted from 1976 at 10% per year (with brackets).

TABLE 9. FIGURE OF MERIT EXAMPLE

TECHNOLOGY DEVELOPMENT PROGRAM	R & D COST $	INERT Δ WEIGHT kg (lb)	PERF. Δ WEIGHT kg (lb)	P/L Δ WEIGHT kg (lb)	DRY Δ WEIGHT kg (lb)	DDT&E COST Δ $	PROD COST Δ $	OPS COST Δ $	L.C.C Δ $	FIGURE OF MERIT LCCΔ$/R&D	RNK
RENE'41 H/C DEVELOP. PROGRAM + ALUM. BRAZED TI H/C DEVELOP. PROG.	14-18M (7.09)	-16,329 (-36,000)	- -	+16,329 (+36,000)	-16,329 (-36,000)	1746M	632M	742M	3120M	3120M / 16 = 195 (66)	

In all cases, a detailed examination was made of the technology program to define the weight savings and life cycle cost impact. In certain areas (slush/triple point propellants), although the technology improvement resulted in a weight savings which could be related directly to a LCC savings, some additive costs associated with the program reduced the overall savings. A typical figure of merit analysis is detailed in Figure 14 which is provided to illustrate the depth and level of analysis behind each calculation. The example provided outlines the analysis involved with modifying the SSME engine to operate on an idle mode which would enable complete usage of all of the liquid propellant above the main engine valving. A detailed analysis of residuals in the HTO vehicle tankage indicated that approximately 1018 kg (2244 lb) of oxygen and 934 kg (2060 lb) of hydrogen were trapped in lines between the tank sumps and the main engine. This does not include the 819 kg (1806 lb.) of propellant trapped within the engine itself. The estimated cost of this program, provided by Rocketdyne, is 7.5 million dollars. The actual weight derivation is illustrated by the tank illustrations on the left hand side of the figure. The upper tank which utilizes the existing SSME contains usable propellant (derived from the performance analysis) reserve and gaseous residuals, trapped liquid propellants, and propellant gaging errors and bias propellant.



① Present HTO analysis
Trapped propellant = 1,017.9 kg (2,244 lb) of LO_2
= 934.4 kg (2,060 lb) of LH_2
Engine propellant = 819.2 kg (1,806 lb) of LH_2/LO_2
② Add idle mode to engine (R&D = \$7.5 M)
③ Burn propellant at 1.09 mixture ratio
(~1/2 nominal engine performance)
④ Total inert weight savings = 976 kg (2,152 lb)
⑤ Total GLOW reduction = 32,206 kg (71,000 lb)
⑥ Total LCC reduction = 186 M
⑦ Figure of merit

$$\$76 = \frac{186}{7.5} = 24.8$$

$$10\%\ \text{discount} = \frac{41.4}{5.34} = 7.7$$

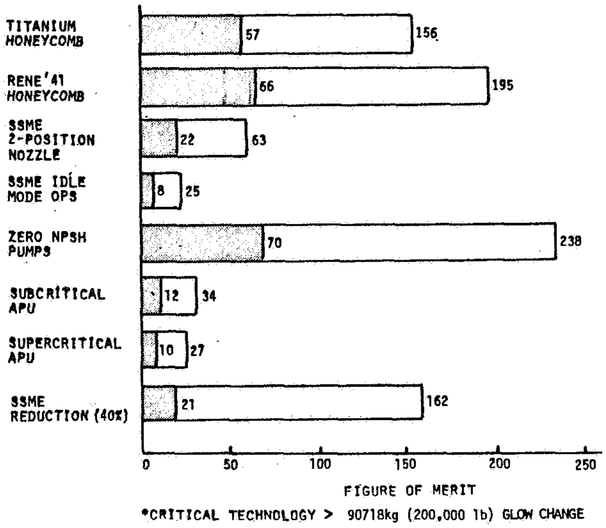
FIGURE 14. SSME IDLE MODE OPERATIONS ANALYSIS

The addition of an idle mode allows burning of the trapped propellant at a much lower flow rate and an off design mixture ratio. The resultant ratio of 1.09 is estimated to achieve a performance of about 1/2 the nominal. As a result, the 1952 kg (4304 lb.) of trapped propellant is burned completely but requires an additional 976 kg (2152 lb.) of loaded propellant due to the performance degradation. Overall inert weight savings is 976 kg (2152 lb). This would be applicable to a case in where the reserves have already been utilized due to dispersions, etc. in the ascent trajectory. Savings of 976 kg (2152 lb.) results in a GLOW reduction of 32206k (71,000 lb.). This reduction in overall vehicle GLOW transcribes to yield a program cost savings of 186 million dollars. The 186 million dollar life cycle cost savings over the estimated 7.5 million dollar research and development program cost gives a figure of merit value of 24.8. Discounted dollars at 10% per year yield a F.O.M. of 7.7.

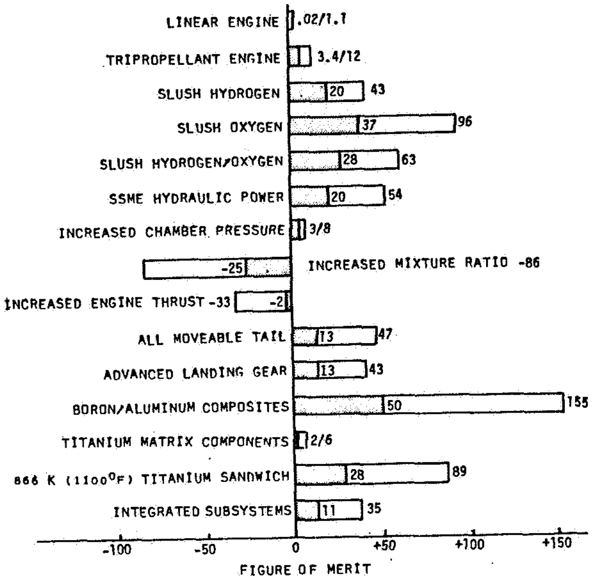
Advanced Technology Ranking

Figure 15 shows the relative ranking of the "focused technology" development programs. The total bar represents FOM in 1976 dollars. The shaded portion represents 10% discounted dollars. The zero NPSH pumps have the highest value for FOM. This results from the weight savings associated with reducing the overall design operating pressure limit due to the reduction in ullage pressure. The Rene'41 and titanium honeycomb programs follow in ranking again due to the significant weight impact they have on inert weight. The Rene'41 honeycomb reflects the combined usage of both Rene'41 and titanium honeycomb on the lower and upper vehicle surfaces respectively. The titanium honeycomb program reflects a complete overall surface utilization of titanium with the addition of insulation system on the lower surface to prohibit temperatures in excess of 700k (800^{o}F). This would require extension of the present adhesive strain isolation system which is limited presently to about 464k (375^{o}F). Reductions in main engine operation costs of up to 40% show a relatively high figure of merit. It is interesting to note that when discounted, the overall rating of the operations cost reduction is reduced. This is attributed to the cost savings occurring in the later stages of the program when the discounted rate tends to drive the savings to a lower value. The SSME 2-position nozzle program, when analyzed with projected improvements in structural technology, has a relatively high ranking. Ranking of the subcritical and supercritical APU's and the SSME idle mode operations follow.

Figure 16 shows the relative ranking of the perturbed technology development programs. Again the difference between 1976 dollars and discounted dollars is indicated by the plain and shaded portions of the bar respectively. The boron aluminum composite work, in addition to the 593.3^{o}C (1100^{o}F) titanium sandwich, show high yields in terms of figure of merit. The slush and triple point propellant programs offer a high potential for reducing the life cycle costs in relationship to the R&D investment. The programs to the left of the vertical centerline (a FOM ranking of zero) indicate that the R&D program investment yielded an increase in life cycle costs.



SSTO FOCUSED TECHNOLOGY
FIGURE OF MERIT
FIGURE 15.



SSTO PERTURBED TECHNOLOGY
"FIGURE OF MERIT"
FIGURE 16.

Extended Performance - Task IV

Sensitivity and trade studies were performed on the HTO vehicle system selected by the Government in Task II to define the impact of the focused programs established in Task III on the vehicle characteristics and mission performance. Using these results, the characteristics and performance of the systems offering the optimum potential for resource investment were identified. Critical and high yield technology items which have been identified and included in this section are the areas of technology which should be vigorously pursued.

Technical Application

Figure 17 summarizes the technology areas which are recommended for application to the Task II vehicle. A combination of normal technology growth with avionics, 3.45×10^7 Pa (5000 psi) hydraulics and 2.8% landing gear as examples, and focused technology growth (zero NPSH pumps, Rene'41 honeycomb, titanium honeycomb, and the SSME 2-position nozzle as examples) yield a vehicle GLOW of 1.0×10^6 kg (2.2 million lb). Engine trades reduce vehicle GLOW over 45400 kg (100,000 lb.). The inert weight decrease associated with technology programs recommended is 4195 kg (9,248 lb.). This provides an additional reduction to GLOW of nearly 90800 kg (200,000 lb.). Shown on the figure as additional technology programs which could provide additional benefits but which are not recommended for incorporation into the final extended performance vehicle design, are triple point cryogens, all moveable tail, increased chamber pressure, linear engine, etc.

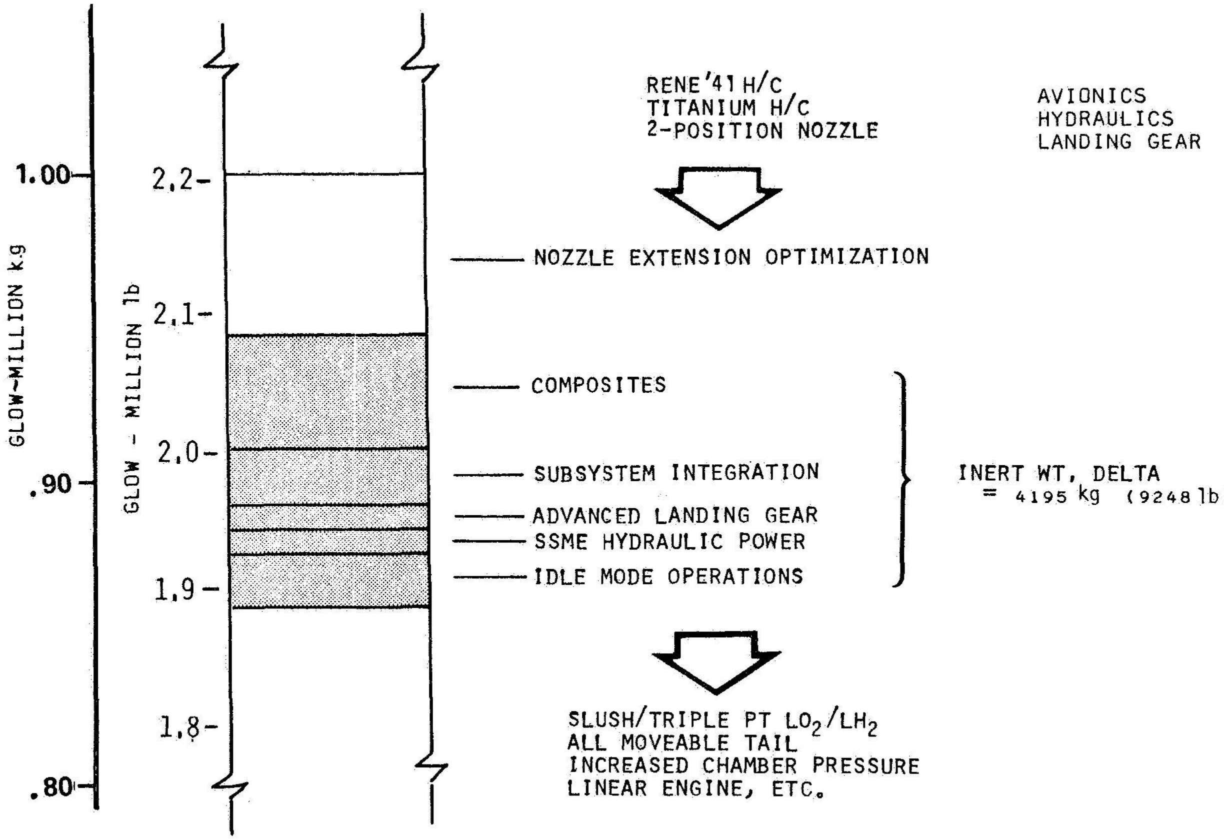
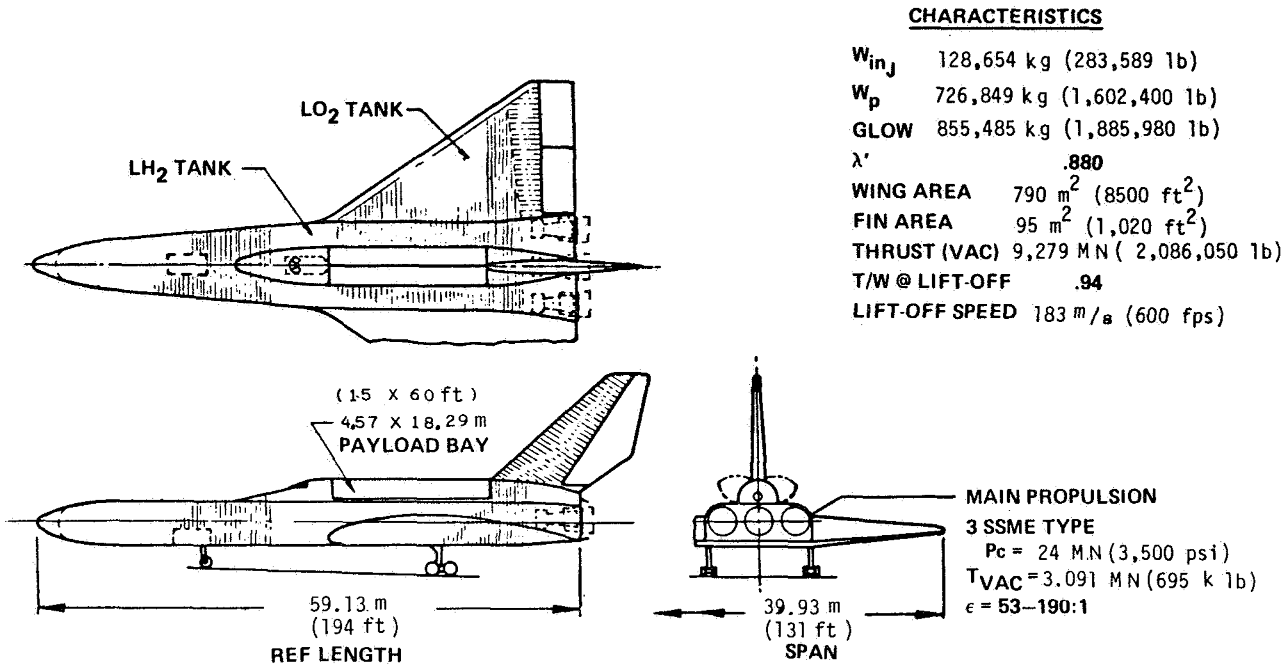


FIGURE 17.

VEHICLE EXTENDED PERFORMANCE SUMMARY

Extended Performance

Vehicle Configuration. Figure 18 lists the characteristics of the extended performance vehicle as a result of incorporating the recommended technology developments discussed in Section III. The overall vehicle GLOW is reduced from 1.0×10^6 kg (2.2 million lb.) to $.855 \times 10^6$ kg (1.9 million lb.). Body length is shortened to 59m (194 ft.) from 63m (206 ft.) and wing span is decreased from 42.7m (140 ft.) to 39.9m (131 ft.). Wing area (reference) is reduced from 883m^2 (9500 ft^2) to 790m^2 (8500 ft^2).



EXTENDED PERFORMANCE CONFIGURATION SUMMARY

FIGURE 18.

Vehicle System Cost. Resultant vehicle system costs were reestimated both for 1976 dollars and 10% discounted dollars. Overall life cycle costs (1976 dollars) are reduced by 652 million dollars to 7510 million. The projected cost per flight is 1.26 million dollars or a transportation cost of slightly under 19.4 dollars per pound based on full payload load factor.

STUDY CONCLUSIONS AND RECOMMENDATIONS

The study effort identified no definite obstructions to the SSTO concept within the development assumptions and depth limitations. The potential advantages of the SSTO system on a cost/performance basis warrant continued investigation and study.

The HTO concept appears to offer the lowest GLOW and life cycle costs of the various candidates studied. The inflight fueled or air launch programs appear unattractive at this time due to the technical problems associated with aerial refuel of cryogenics and separation during flight.

Several technology development programs are universally applicable to several transportation concepts and should be initiated. The all-metallic, completely reusable thermal/structural concept proposed by Boeing has direct application on either a HTO or VTO type launch. The airframe system, although using off-the-shelf materials, does require a major engineering program to develop fabrication and assembly procedures and to demonstrate structural characteristics in the presence of LO_2 and LH_2. In addition, this airframe approach can be applied to selected portions of the Space Shuttle (body flap), hypersonic research aircraft, commercial aircraft engines and other proposed space transportation systems. The same is true for the SSME 2-position nozzle program, advanced composites and key subsystem elements previously discussed.

Within the propulsion constraints of the study, based on figure of merit, little or no gain is evidenced in developing a new LO_2/LH_2 propulsion system. The study excluded hydrocarbon propellants and combinations of hydrocarbon and LO_2/LH_2 propellants (dual mode). The linear engine system analysis indicated a relatively low FOM ranking. This analysis based on preliminary data showed a net loss in performance when compared to the 2-position nozzle on the SSME type engine. A potential for better performance or decreased engine weight in terms of a constant installed thrust is possible with the linear engine. Net savings in thrust structure and installation weights did not have a significant impact. However, the installation was made more or less on a one to one basis with the SSME (i.e. similar to the aerospike design) and did not take advantage of the full capabilities of the linear engine design. It is felt that a more detailed study of the linear engine is warranted in that it is sensitive to the configuration. Integration of the engine with a new HTO design could offer reduced engine weights resulting in a more stable vehicle in addition to providing the potential for added lift during ascent.

The technology programs associated with modifications and/or improvements to the existing SSME show relatively high gains. The 2-position nozzle would not only benefit the SSTO program, but could provide performance gains to shuttle derivative and heavy lift programs as well.

The slush/triple point cryogenic propellant programs indicated a potential for reducing the overall volume requirements. It is felt, however, that a more detailed analysis of this option is required due to the limited depth of the analysis. Of particular concern are the added cryogenic transfer cool down losses, the specific facility requirements including lines, refrigeration equipment, etc., and the propellant gaging tolerances. The later problem is associated with thermal gradients within the vehicle tankage, how they are impacted with delays or hold times, and the variations in density which could negate some of the volumetric reductions.

Several technology programs indicate a rather high yield FOM because of the low R&D funding required to demonstrate feasibility of rather moderate weight savings. Typical of these programs are the LO_2/LH_2APU, the engine driven hydraulic pumps and integration of cryogenic propulsion systems such as the OMS, RCS, and APU. All of these programs have had some effort directed at them in the past, whereas the forecasted R&D program does not reflect a new start.

Several technology programs which are not direct hardware developments, but have a significant impact on hardware systems, require continued support. In most cases the ability to actually attribute a specific weight savings or life cycle cost reduction to these activities would be arbitrary. However, their importance and broad application in terms of advanced space transportation systems analysis cannot be discounted.

The requirement for iterations on various vehicle configurations has revealed the importance of computer aided design as a vital tool in future configuration and system studies. The ability to associate several key technology disciplines and to determine the interactions and constraints of each on vehicle design not only results in massive labor savings, but assures a complete and total analysis of vehicle design changes.

Control configured design offers a potential solution to the age old stability problem associated with rocket powered flight vehicles. Its application is not concept oriented as both the HTO and VTO vehicle configurations could benefit from this design technique. The HTO inherently due to its lower thrust to weight ratio has less of an airframe balance problem. However, it spends more time in the horizontal flight regime where flight control is required.

Mold line tankage and integrated equipment packaging are important factors in minimizing vehicle total internal volume. The lower internal volume will in general result in lower airframe weights. Mold line tankage as applied to the Boeing approach results in a single multifunctional surface panel that maximizes the use of total vehicle internal volume and should contribute to vehicle serviceability.

Additional data are required to understand boundary layer transition and interference heating. Additional trajectory analysis and flight data also required to reduce performance margins and conservatism.

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16. Abstract • – The fundamental objective of this study was to identify those areas of technology associated with future earth-to-orbit transportation systems which are either critical to the development of such systems or which offer a significant cost and performance advantage as a result of their development. Additional objectives were to determine the most efficient operational mode for such systems and to define performance potential as a function of technology growth. The intent was to utilize vehicle system studies as a means of identifying critical and high yield technology areas upon which to base the planning for and the development of advanced technology programs.

Normal technology requirements applicable to Single Stage to Orbit (SSTO) systems were projected to the 1985 time period in Task 1. These technology projections were then incorporated in a vehicle design analysis of three different operational concepts resulting in four configurations of a Single Stage to Orbit system in Task 2. The resultant performance, weights and costs of each concept were then compared and a system concept selected. A "figure of merit" was developed for advanced technology programs based on a cost/performance basis in Task 3. The selected advanced technology programs were then used to reassess the Task 2 vehicle to determine the impact on performance, weight and cost in Task 4.

Based on study results, recommendations are provided in the two above mentioned categories of technology areas associated with future earth orbit transportation systems. The recommendations address advanced space transportation system design considerations, both hardware and software technology program requirements and suggested areas of future effort. This work is covered in detail in Volume 2: Summary Report. Results of an additional investigation dealing with dual mode propulsion are reflected separately in Volume 3: Summary Report – Dual Mode Propulsion.

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