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TECHNOLOGY REQUIREMENTS FOR ADVANCED EARTH-ORBITAL TRANSPORTATION SYSTEMS

Summary Report

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16. Abstract

Areas of advanced technology that are either critical or offer significant benefits to the development of future Earth-orbit transportation systems were identified. Technology assessment was based on the application of these technologies to fully reusable, single-stage-to-orbit (SSTO) vehicle concepts with horizontal landing capability. Study guidelines included mission requirements similar to Space Shuttle, an operational capability beginning in 1995, and main propulsion to be advanced hydrogen-fueled rocket engines. Also evaluated was the technical and economic feasibility of this class of SSTO concepts and the comparative features of three operational take-off modes, which were vertical boost, horizontal sled launch, and horizontal take-off with subsequent inflight fueling.

Projections of both normal and accelerated technology growth were made. Figures of merit were derived to provide relative rankings of technology areas. The influence of selected accelerated areas on vehicle design and program costs was analyzed by developing near-optimum point designs.

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PREFACE

This study was performed by Martin Marietta Corporation, Denver Division, under NASA Contract NAS1-13916. Three reports describe the study and results, as follows:

"Technology Requirements for Advanced Earth-Orbital Transportation Systems"

- Summary Report
- Final Report
- Dual-Mode Propulsion

The authors wish to acknowledge the substantial contributions of engineering personnel at NASA Langley Research Center and Lewis Research Center as well as many persons in the Martin Marietta Corporation, Denver Division.

Certain commercial materials are identified in this paper in order to specify adequately which materials were investigated in the research effort. In no case does such identification imply recommendation or endorsement of the product by NASA, nor does it imply that the materials are necessarily the only ones or the best ones available for the purpose. In many cases equivalent materials are available and would probably produce equivalent results.

TECHNOLOGY REQUIREMENTS FOR
ADVANCED EARTH-ORBITAL TRANSPORTATION SYSTEMS

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SUMMARY

Areas of advanced technology that are either critical or offer significant benefits to the development of future Earth-orbit transportation systems were identified. Technology assessment was based on the application of these technologies to fully reusable, single-stage-to-orbit (SSTO) vehicle concepts with horizontal landing capability. Study guidelines included mission requirements similar to Space Shuttle, an operational capability beginning in 1995, and main propulsion to be advanced hydrogen-fueled rocket engines. Also evaluated was the technical and economic feasibility of this class of SSTO concepts and the comparative features of three operational take-off modes, which were vertical boost, horizontal sled launch, and horizontal take-off with subsequent inflight fueling.

The four basic tasks making up this study were (1) a projection of "normal" technological growth in pertinent vehicle system areas, (2) design of vehicle systems and definition of their performance potential based on these nominal growth projects, (3) a perturbation of selected technology areas to define the impact of R&T funding support for accelerated technology programs, and an assessment of various technology parameters in terms of cost/performance/benefit figure of merit, and (4) sensitivity and trade studies to define the impact of these focused program on vehicle characteristics and mission performance, and an identification of critical and high-yield technology.

INTRODUCTION

Various space vehicle systems that offer the potential for substantial improvements in our future space transportation capabilities relative to the Space Shuttle-based transportation system are being studied by NASA. Improved capabilities emphasize cost reductions but may also include different mission requirements from Shuttle. Although the Space Shuttle provides greatly improved capabilities over current expendable launch vehicles and is a cost-effective solution for the projected missions in the 1980-1990 decade, the evolution of launch vehicles is far from being mature. Traffic growth, new technology, and changing mission requirements will eventually make it cost effective to supplement or to replace the Shuttle. One class of potential future systems is the single-stage-to-orbit (SSTO) with horizontal landing capability. SSTO concepts that have been investigated in recent years at Langley Research Center and are considered in this present study have the potential for low recurring cost also present a considerable challenge to many of the associated technologies.

For the purposes of this study, an SSTO was postulated to be the Space Shuttle replacement system beginning flight operations in 1995. (The Shuttle operational lifetime would be about 15 years.) Allowing for an SSTO vehicle development lead time of about eight years, the required technology readiness date is 1987. The ten years between now and 1987 would be available for development of the required technology base. Many technology areas will advance during that time period without special SSTO funding because of ongoing technology programs and transfer from similar areas such as Space Shuttle and aeronautical technology programs; however, in selected areas, it would be necessary or desirable to accelerate the normal technology growth. The identification and prioritization of such areas has been the central issue of this study.

The primary goal of this study has been to identify areas of technology associated with SSTO systems that are either critical to their development of offer significant cost and performance benefits. This was accomplished by assessing the impact of technology perturbations on the vehicle program life-cycle costs (LCC) relative to the research program costs. Secondary goals had to do with the evaluation of SSTO system characteristics, including (1) the definition of performance potential in terms of vehicle design characteristics and life cycle costs, and (2) a comparison of three operational modes. These study goals were met by performing the four major tasks described below.

Government and industrial publications were reviewed in Task 1 to generate historical and future projections of "normal" technology growth primarily in the structures, materials, and propulsion disciplines with secondary emphasis on flight controls, trajectory optimization, and aerodynamics. Funding projections based on recent NASA and DOD actual expenditures and forecasts were made to be used as an aid to predicting "normal" technology growth.

During Task 2, preliminary design were developed for three hydrogen-fueled SSTO vehicles: VTO (vertical takeoff), HTO (horizontal takeoff sled launched), and IFF (inflight fueled). Each was designed for a payload capability of 29 500 kilograms (65 000 pounds), as easterly launch from KSC, and a horizontal landing. Both conventional bell nozzle rocket engines and linear rocket engines were considered. Various thermostructural and propulsion system concepts were evaluated for the three designs. A primary figure of merit (FOM) for vehicle design was minimum dry weight based on use of "normal" technological growth. An economic comparison was made of the total program costs for each concept.

Selected technology areas were perturbed during Task 3 beyond the "normal" growth level to identify the greatest potential payoffs for an accelerated technology vehicle design during Task 4. Technology parameters were assessed in terms of cost/performance/benefit figures of merit relative to the Task 1 and Task 2 base. The results of normal growth and normal funding from the Task 1 evaluation were considered in developing the costs and gains for an accelerated technology vehicle design. The Task 2 VTO vehicle design was used to derive the sensitivity information used in the figure-of-merit (FOM) assessment in performing the assessment of the figures of merit. Performance sensitivities were derived for those technology programs with a high-yield potential.

All technologies offering a clear payoff on a cost/performance/benefit figure of merit were then included in Task 4 designs of near-optimal vehicle configurations. The cost effectiveness of the total system, which used the accelerated technological forecasts, was then evaluated.

Based on these studies of normal and accelerated technological forecasts, funding, vehicle design requirements, and figures of merit, assessments of high-yield and critical areas of technology were made. These provided a basis for recommendations of areas of technology that should be vigorously pursued to support cost-effective, advanced earth-orbital transportation systems.

This summary report presents highlights of the study results. Future studies are anticipated to consider other vehicle alternatives such as use of dual-mode propulsion and control-configured vehicle concepts.

"NORMAL" TECHNOLOGY AND FUNDING PROJECTIONS

The initial phase of this study forecasts "normal" technology levels to be applied to conceptual designs of single-stage-to-orbit (SSTO) vehicles with a first operational flight in 1995. These technology levels therefore are 10 to 15 years in advance of those available for the Space Shuttle program. They are based on extrapolations of historical data using expert judgements of future technology growth. This growth is assumed to be achieved with technology programs continuing at current expected levels using normal research funding.

Sources of historical data for technology and funding included industrial reports, Government technology and budgetary documents, and congressional records. Expert judgements and analysis were applied to interpret, summarize, and project these data into the future. For these "normal" projections, nominal values and also maximum and minimum values (representing estimated 95% probability limits) were specified.

Primary Technology Areas

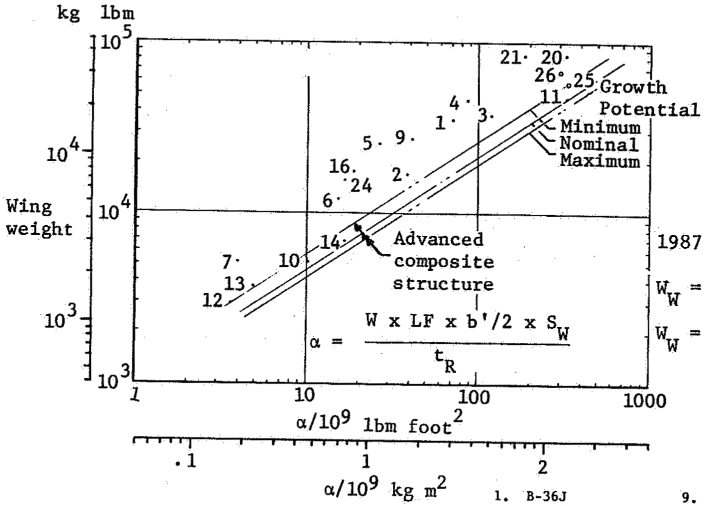
Primary emphasis on technology projections has been placed on those areas that have a strong impact on vehicle weight and center-of-gravity locations because a key goal is to minimize the dry weight of the SSTO vehicles. These primary technology areas encompass materials, structures, and propulsion that when applied to SSTO vehicle concepts reflect vehicle design components having large percentages of total vehicle dry weights. Within these primary technology areas, historical data were analyzed and growth was projected for each of the parameters indicated in Table 1.

Illustrations of the projection techniques are represented by Figures 1 and 2 for wing structure weight and main engine specific impulse, respectively. Structures weight projections are based on use of composites. Engine performance projections are based on improvements that can result by propulsion research focused on the future requirements of SSTO vehicle systems.

Projections and relative merits of wing and body thermostructural concepts were also analyzed. These concepts, with their relative weights, are shown on Figures 3 and 4. Relative weights of the body thermostructures were derived from aerospace vehicle tankage and thermal protection system unit weights and trade studies. Relative weights of the aerosurface thermostructures were derived from Space Shuttle orbiter and aircraft

TABLE 1.- PRIMARY TECHNOLOGY PARAMETERS FOR WHICH PROJECTIONS WERE FORECAST

Surface insulation density
Surface insulation upper limit temperature
Advanced composite fibers, ultimate strength
Advanced composite fibers, modulus
Wing structure weight
Elevon structure weight
Vertical tail structure weight
Integral propellant tank weight
Thrust structure weight
Landing gear weight
Main engine specific impulse
Main engine chamber pressure
Main engine weight
Triple point/slush propellant density
RCS/OMS engine specific impulse
Auxiliary propulsion system weight



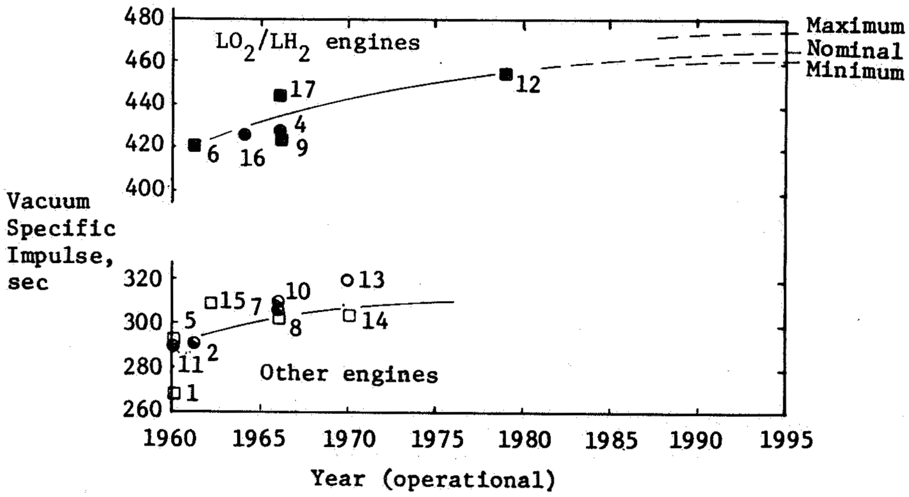
1987 projection (nominal):

W_W = 996 $(\alpha/10^9)$ 0.67 (lbm)

W_W = 3657 $(\alpha/10^9)$ 0.67 (kg)

1. B-36J
2. B-47B
3. B-52A
4. YB-60
5. C-135A
6. B-58A
7. F-105A
8. F-104F
9. C-133B
10. A3J-1
11. XB-70A
12. F-102A
13. F-106B
14. F-108
15. F-101B
16. 880
17. 990
18. C-141A
19. F-111B
20. C-5A
21. 747
22. F-4D
23. F-15
24. Space Shuttle

Figure 1.- Wing structure weight history and projection



Historical data

1. Delta, AJ10-118
2. Saturn, H-1
3. Thor, LR-79
4. M-1
5. Agena, LR-81
6. Centaur, RL-10
7. Saturn, F-1
8. Transtage, AJ10-138
9. Saturn, J-2S
10. Atlas, LR-105
11. Atlas, LR-89
12. Shuttle, SSME
13. Titan III, LR-91-11
14. Titan III, LR-87-11
15. Titan II, LR-91-5
16. Saturn, J-2
17. Centaur, RL-10

Figure 2.- Specific impulse history and projection

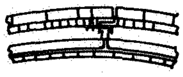
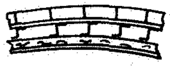
			Comment
Concept I RSI bonded to advanced/composite subpanels integral aluminum tankage insulation		1.0	Recommended for SSTO baseline
Concept II RSI and strain isolator bonded to aluminum structure nonintegral tank with external insulation		1.09	
Concept III Standoff metallic radiative heat shield aluminum tankage with internal insulation		1.25	

Figure 3.- Body thermostructural concepts

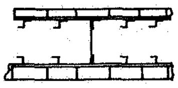
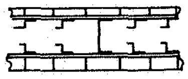
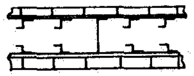
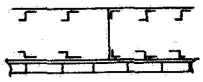
Comment		Relative Weight	Comments
RSI and strain isolator bonded to aluminum structure		1.0	
RSI and strain isolator bonded to advanced/composite structure		0.85	Recommended for SSTO baseline
RSI and strain isolator bonded to titanium structure		0.88	
Partial shielded (RSI) titanium structure		1.25	Problem areas: differential thermal strains
Hot structure		2.9 to 6.5 (Function of material used)	Problem areas: Oxidation coatings differential thermal strains

Figure 4.- Aerosurfaces thermostructural concepts

aerosurface weight data and trade studies. A result of the thermostructural technology analysis was the selection of three candidate thermostructural concepts (Figure 5) to be included in the subsequent parametric comparisons of the performance potential of vehicle systems.

Projections and relative merits of main engine performance, using both bell nozzles and linear nozzles, were also evaluated. Both single-position and dual-position bell nozzles were analyzed with variations in expansion ratios, chamber pressures and oxidizer/fuel (O/F) ratios. Initial vehicle concepts and ascent performance calculations, using bell nozzles and linear nozzles, led to the selection of main engine concepts.

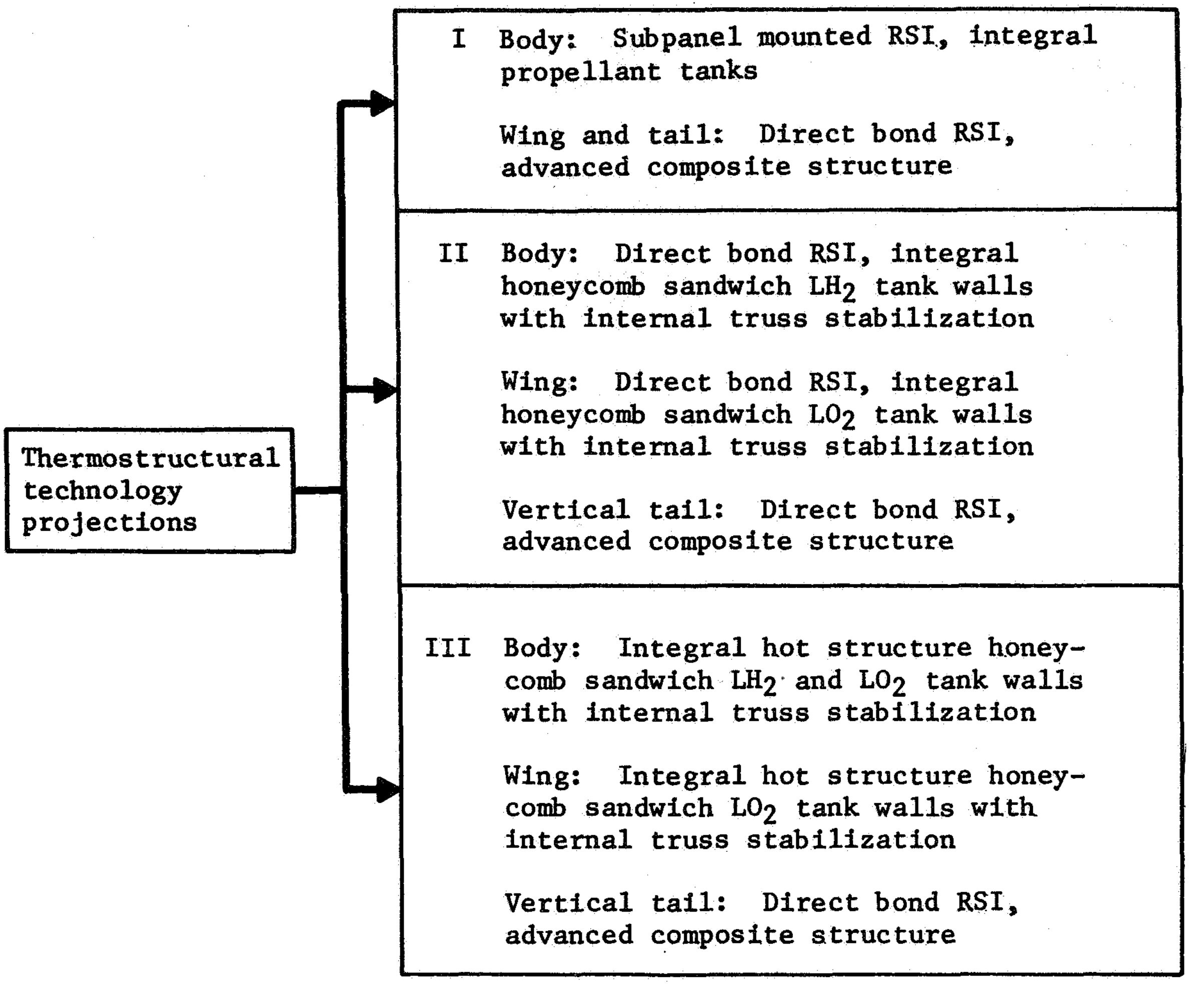


Figure 5.- Thermostructural concepts selection

Using bell nozzles, combinations of both single- and dual-position nozzles were evaluated using parametric values of thrust-to-weight and specific impulse as functions of chamber pressure, thrust, and expansion ratios. Vehicle sizing was found to be optimized using a set of single position and a set of dual-position nozzles together on the same vehicle.

Using linear nozzles, a very limited amount of data characterizing engine weights and performance was available. Parametric data representing variations of linear engine weight with engine performance did not exist for SSTO applications. The data used for this study, believed to be optimistic, nevertheless led to indications that the data was not suitable for the present vehicle configuration concepts. The main part of the study therefore was confined to concepts with bell nozzle engines.

Secondary Technology Areas

Technology projections were examined in technology areas other than materials, structures, and propulsion. These secondary technology areas have less influence on vehicle dry weight and center-of-gravity location than the primary areas, yet overall, they represent technologies important to SSTO vehicle concept designs. These secondary areas include subsystem, environmental, and analysis technologies. They are represented by examples such as flight controls, avionics, life support, auxiliary power, computers, aerodynamics, and aerothermodynamics. Weight and performance improvements were projected for secondary technologies for application to the subsequent vehicle concept comparisons.

Summary of Technology Projection Improvements

Table 2 summarizes and highlights the major areas of technology improvements forecast for "normal" growth with research focused on applications to SSTO vehicle concepts. The technology growth represents overall improvements over current technology capabilities of 2% in main engine specific impulse (leading to reductions of about 20% in vehicle dry weight) and 16% in thermostructural and subsystem weights.

TABLE 2.- SUMMARY OF TECHNOLOGY PROJECTION IMPROVEMENTS

PRIMARY TECHNOLOGY AREAS
Materials and structures
Reusable surface insulation (RSI) density and temperature limits
Advanced composites weights for wing, elevon, fin, thrust structure, and landing gear
Integral propellant tanks weights
Propulsion
Specific impulse and chamber pressure
Engine thrust/weight ratio
Bell nozzles; dual position
Linear nozzles (more parametric analysis needed)
Slush/triple-point propellants (more "large scale" analysis needed)
RCS/OMS and auxiliary propulsion specific impulse and weight
SECONDARY TECHNOLOGY AREAS
Performance and weight improvements
OVERALL
Main engine I_{SP}: improved 2% ($\approx$ 20% dry weight)
Overall dry weights: improved 16%
More efficient design, production, and operations techniques

NASA and DOD funding of research and technology programs support many activities that are related to technologies applicable to SSTO. These activites and funding levels have been identified and form a basis for estimates of "normal" technology growth. These funding levels have been examined from both "top-down" and "bottom-up" approaches.

The "top-down" approach identified NASA budgets and projected budgets for the various NASA offices, and further identified funding in major technology areas related to SSTO (Figure 6). Not all of this funding, however, is applied to activities that would directly apply to an SSTO program.

The "bottom-up" approach was therefore pursued to better identify funding and R&T programs more directly applicable to SSTO. In this approach, funding related to selected NASA RTOPs

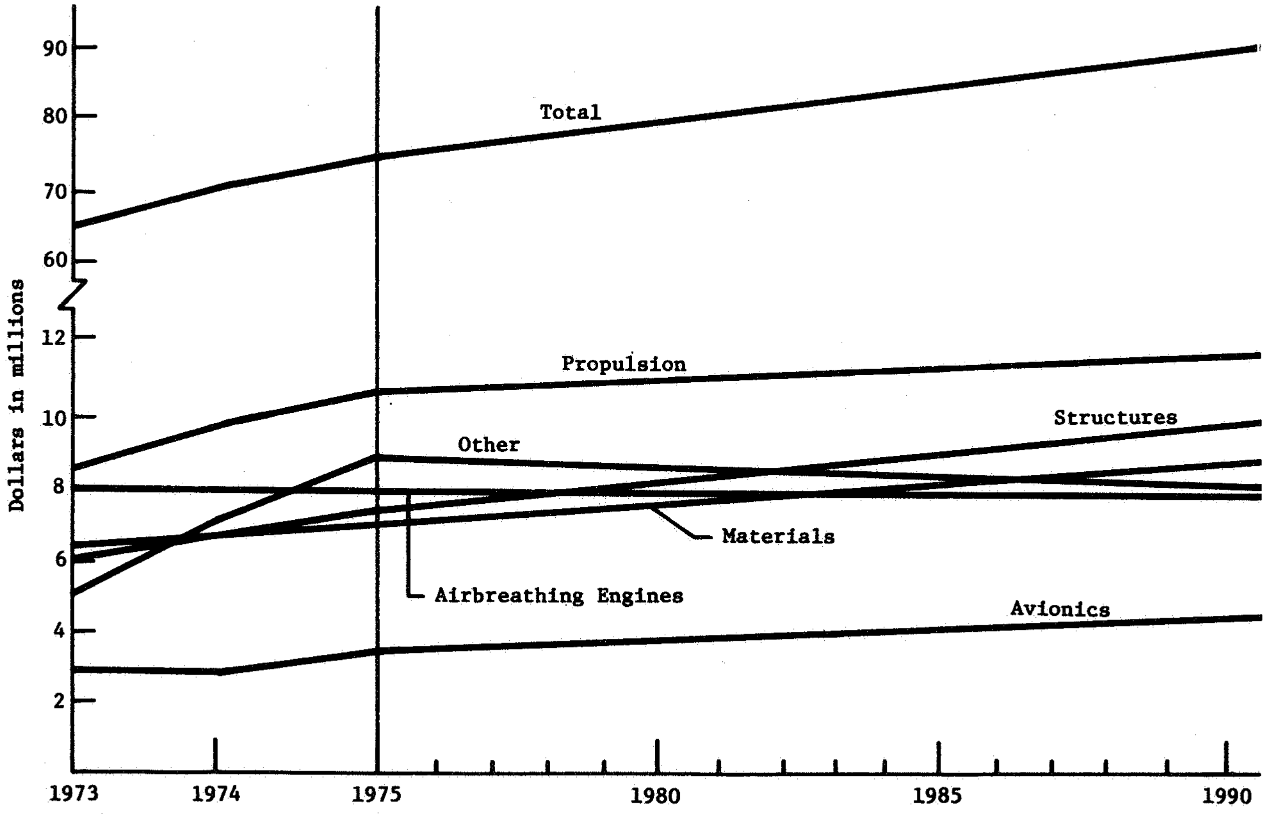


Figure 6.- Related SSTO NASA funding

and DOD research was identified. The RTOPs were selected from the RTOPs Summary reports of 1973 through 1975 with the judgement that the selected programs involved SSTO-related research. The funding for each of these programs was assigned to one of five technology areas, i.e., materials, structures, propulsion, hypersonic technology, and airbreathing engines. The last item was included for possible application in the inflight-fueled SSTO concept. This three-year history was projected from 1975 through 1990 using judgements and polynomial regression techniques. The results of these projections are shown in Figure 7. Similar data for DOD (Air Force) derived from 1975 congressional records are shown in Figure 8. The polynomial regression technique provided equations for deriving 95% probability limits shown in these two figures. These data indicate

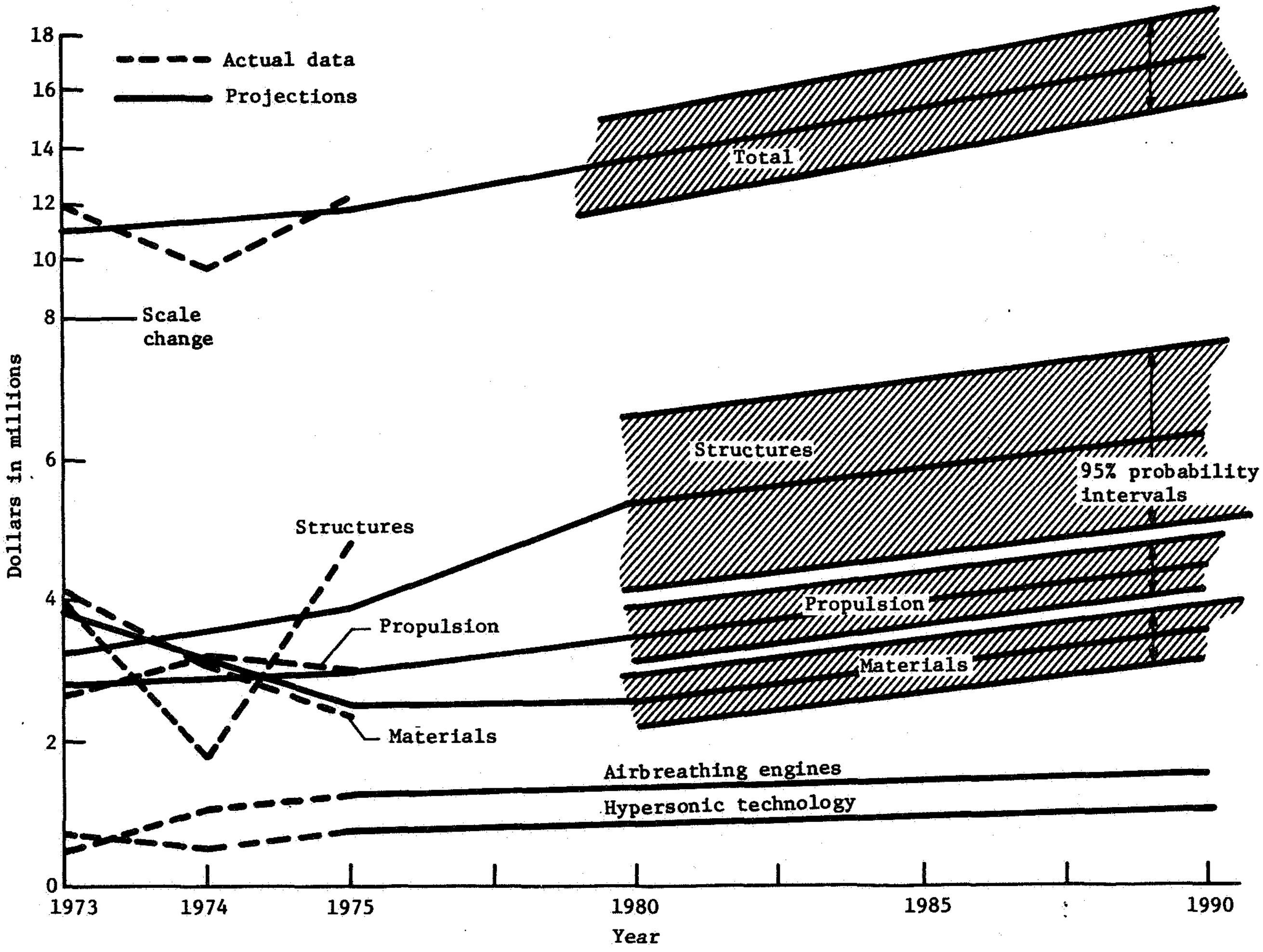


Figure 7.- Selected NASA RTOPs funding

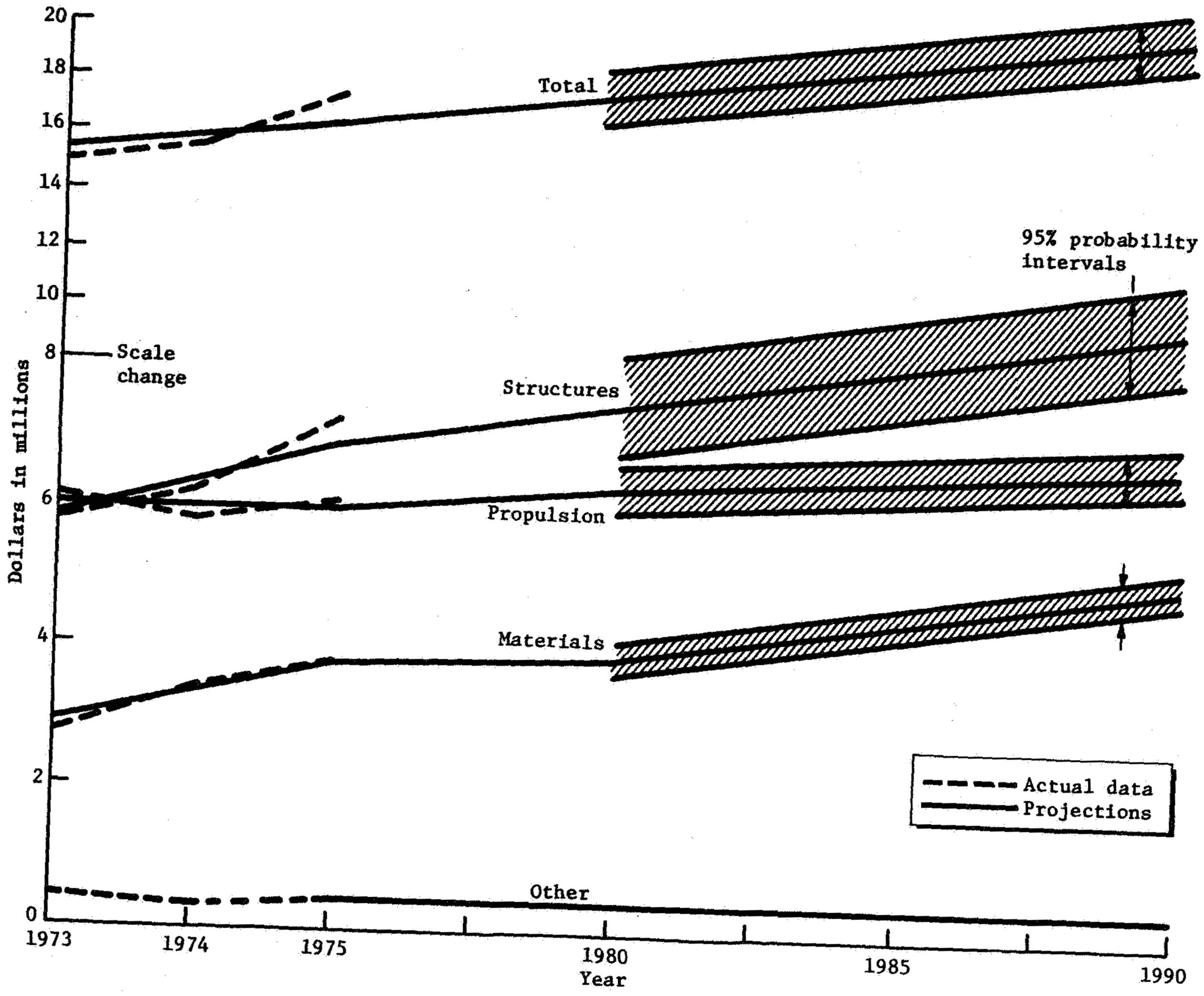


Figure 8.- Selected DOD (Air Force) funding

the levels of "normal" funding applied to research that is specifically related to the SSTO "normal" technology projections. In summary, the projected average "normal" funding for NASA RTOPs in related materials and structures research is $9 million/year, and in related propulsion is $4 million/year.

PERFORMANCE POTENTIAL OF VEHICLE SYSTEMS

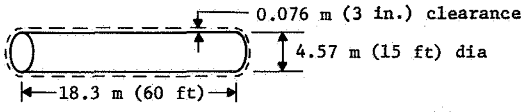
Three single-stage-to-orbit (SSTO) launch modes were applied to vehicle design studies using projections of "normal" technology growth. These modes were vertical takeoff (VTO), horizontal sled-launched takeoff (HTO), and horizontal takeoff with inflight fueling (IFF). All modes included horizontal landing after orbiting payloads of 29 480 kg (65 klb). Vehicle concepts were developed using the design guidelines shown in Table 3, with a goal of minimizing vehicle dry weight.

The approach to arriving objectively at vehicle design concepts for the three launch modes was as follows: The technology projections and assessments described in the preceding chapter were used as a basis for preliminary parametric evaluations of propulsion, thermostructural, and configuration concepts. These preliminary evaluations provided performance and vehicle dry weight data for selecting specific concepts to be applied in more detailed analysis. These selected features were then applied to initial designs and layouts of vehicles, which provided a basis for technical analyses. The results of these analyses then were used to iterate and improve the initial designs. These optimized designs were then technically assessed to ensure that the design guidelines were met, and detailed drawings were developed.

The vehicles to be described in this chapter were designed to carry a payload of 29 480 kg (65 klb). The mass ratio requirements were calculated using ascent performance, employing estimates of lift and drag derived early in the study. Later, aerodynamics for these vehicle configurations were revised and applied to performance calculations of mass ratio requirements for the VTO and HTO vehicles.

The results of using the revised aerodynamics, which exhibited smaller drag coefficients than the initial aerodynamics, showed that the vehicles were capable of lifting payloads heavier than the guideline payload of 29 480 kg (65 klb). Alternatively, the vehicle designs could be modified to a smaller size to meet the guideline payload capability. The HTO vehicle size was found to be considerably improved by drag reductions. Estimates of the VTO and HTO vehicle mass properties based on the revised aerodynamics were made using sensitivity relations. These estimations, as well as the detailed design characteristics of the vehicles, are presented in subsequent sections of this chapter.

TABLE 3.- GUIDELINE DESCRIPTION

Design vertical takeoff, horizontal landing vehicles for minimum dry weight using dual-mode propulsion.
Use dual-mode engine performance and weights from advanced high-pressure engine study (ref. 2).
Use accelerated performance, accelerated technology projections (ref. 1).
n_x = 3-g ascent, n_z = 3-g entry, n_z = 2.5 g subsonic maneuver.
Safety factors: Prelaunch, liftoff, ascent, in-orbit: 1.4 Entry, subsonic maneuver, landing: 1.5
Design to low-cost refurbishment and maintenance. Life: 500 missions.
Payload cylinder 
Mission: Due east from KSC, 28.5-deg inclination, 29 500 kg (65 000 lbm) payload, 198 m/sec (650 ft/sec) OMS ΔV, 30.5 m/sec (100 ft/sec) RCS ΔV, Reference energy orbit, 93 x 186 km (50 x 100 n. mi.)
TPS design mission: Entry from a due east, 28.5-deg inclination, 370 km. (200 n. mi.)-altitude orbit, 29 500 kg (65 000 lbm) payload, and 2 050 km (1100 n. mi.) crossrange capability.
Vehicle loads with and without 29 500 kg (65 000 lbm) payload.
Maximum landed payload = 29 500 kg (65 000 lbm)
Landing requirements: Minimum speed = 306 ± 9 km/hr (165 ± 5 knots) α = 15 deg (sea-level conditions and maximum landed weight)
Aerodynamic requirements: Subsonic - 2% $\bar{c}$ minimum static longitudinal stability margin, 0.0015 minimum static directional stability margin, Hypersonic Trimmable α range (with/without payload) - 25 deg or less to 40 deg or greater, Landing sink speed - 3.05 m/sec (10 ft/sec) maximum Reentry - Trimmable with control surfaces longitudinally and laterally with RCS (non-CCV designs).
4-man crew cabin arrangement.
10% weight margin on all vehicle subsystems except engines.
Provide for stable dynamic properties by using RCS during periods of low dynamic pressure and aerodynamic control surfaces when dynamic pressures are sufficient.
Provide TPS for protecting the primary airframe, the crew, the payload, and vehicle subsystems from aerodynamic heating during ascent and entry and from engine exhaust convective and radiative heating.
Provide a positive docking mechanism (interception, engagement, and release of vehicle with other orbital elements).
OMS requirements: OMS tankage for ΔV capability of 381 m/sec (1250 ft/sec) OMS burn in either single long burn or a series of multiple burns, spread randomly over the mission duration.

Vehicle Concept Comparisons

Main engine concepts.- Both bell-nozzle and linear-nozzle engines were considered candidates for application to SSTO vehicles. Layouts of VTO vehicle concepts using both types of engines were developed and used as a basis for performance and mass properties assessments. Variations of propellant mixture ratios (O/F) were included in these assessments.

The linear-engine configuration, illustrated in Figure 9, used the engine characteristics described previously. (Bell-nozzle configurations are illustrated in following sections). This configuration exhibited a dry weight 22 200 kg (49 000 pounds) heavier than a corresponding bell-nozzle configuration. The lower performance of the linear nozzle was **attributed to** nonoptimized expansion ratios for the initial, low altitude

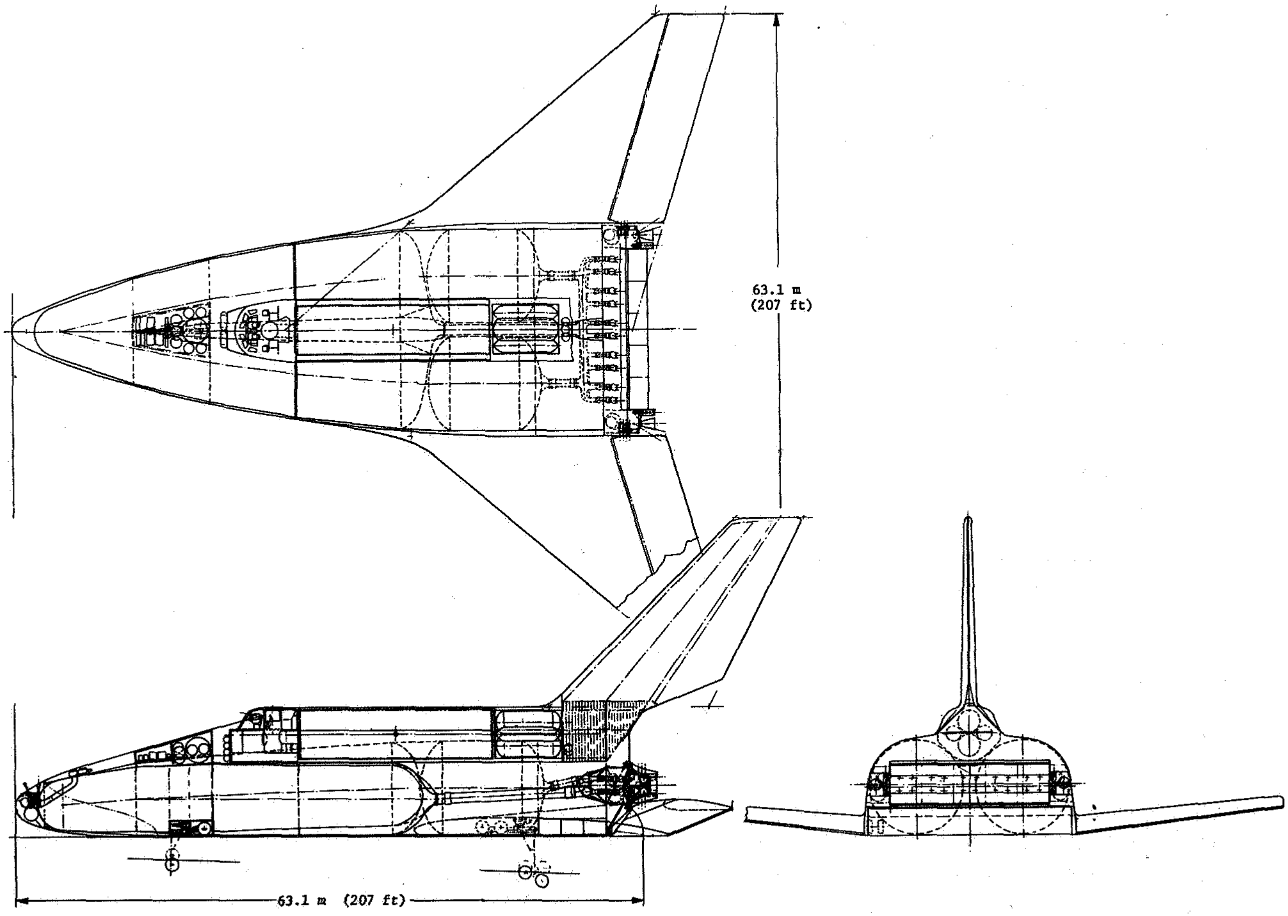


Figure 9.- VTO linear engine inboard profile

flight phase. Parametric engine data have not been available to pursue the optimization. It was concluded that the study would be continued using bell-nozzle engines, with the recommendation that studies should be initiated to develop linear-nozzle engine parametrics.

Assessments of mixture ratio effects for the LO_2/LH_2 bell nozzle engines led to the selection of O/F = 7 on the basis that the VTO bell-nozzle vehicle landing weight was 9,000 kg (20 000 pounds) less than with O/F = 6. Other assessments related to engine performance led to the selection of hydrogen-cooled main engines with single-position nozzles with $\varepsilon = 35$, dual-position nozzles with $\varepsilon = 55/160$. For the VTO concepts, a combination of four dual-position and six single-position engines was selected, using sea-level thrusts in the SSME range of 2,224 kN to 2,446 kN (500 000 to 550 000 lb).

Thermostructural concepts.- Three thermostructural concepts were identified in the technology assessment as candidates for SSTO application (Figure 5). The first candidate (Figure 10) uses membrane aluminum tankage in the fuselage with advanced composite, subpanel-mounted, reusable surface insulation (RSI). The aerodynamic surfaces are advanced composite structure with borsic-aluminum skins. The surfaces are protected from the entry environment by direct-bond RSI (with strain isolators). The second candidate (Figure 11) utilizes an internal truss structure. The titanium honeycomb sandwich skins are protected with direct-bond RSI. The vertical tail and aero control surfaces are advanced composite structure, with direct-bond RSI. The third candidate is the same as the second, except it is constructed of high-temperature alloys (Rene 41), and does not have an external RSI. All tanks are designed for a limit pressure of 1.4 kg/cm^2 (20 psig).

Weight comparisons of these candidates are summarized as follows:

Thermostructural Concept	I	II	III
Dry weight (kg) (pounds)	202 888 (447 295)	207 537 (457 545)	243 530 (536 895)

The vehicle concept with candidate 1 not only has the lightest dry weight, but also has simpler technology, design development, manufacturing and operations requirements. The selection of RSI for thermal protection is not only light weight, but permits a wide entry flight corridor. Candidate 1, integral membrane tankage concept, was therefore selected for continued studies.

Note:

See the second page of Figure 13 for legend.

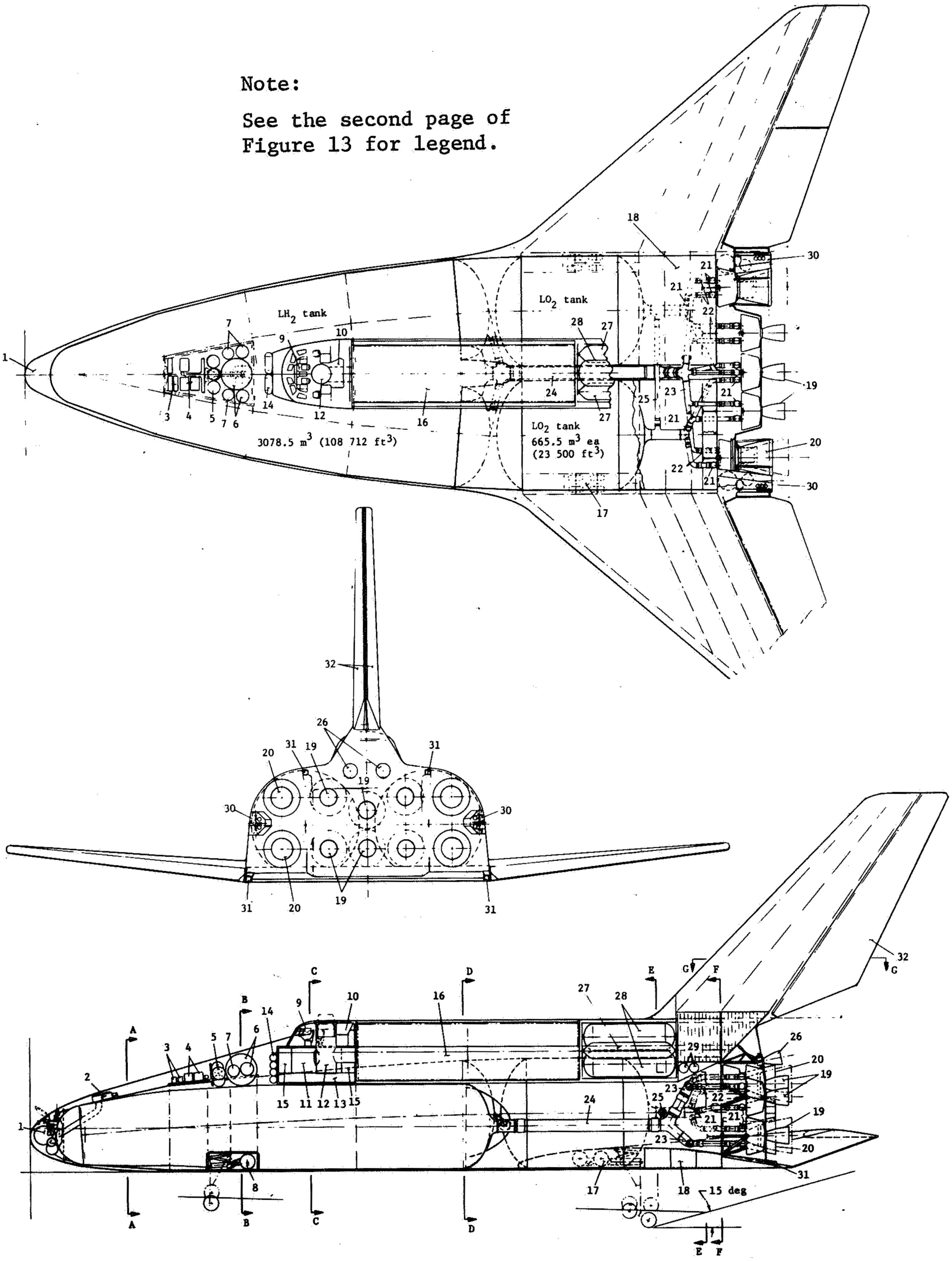


Figure 10.- VTO - integral membrane tankage , Concept I

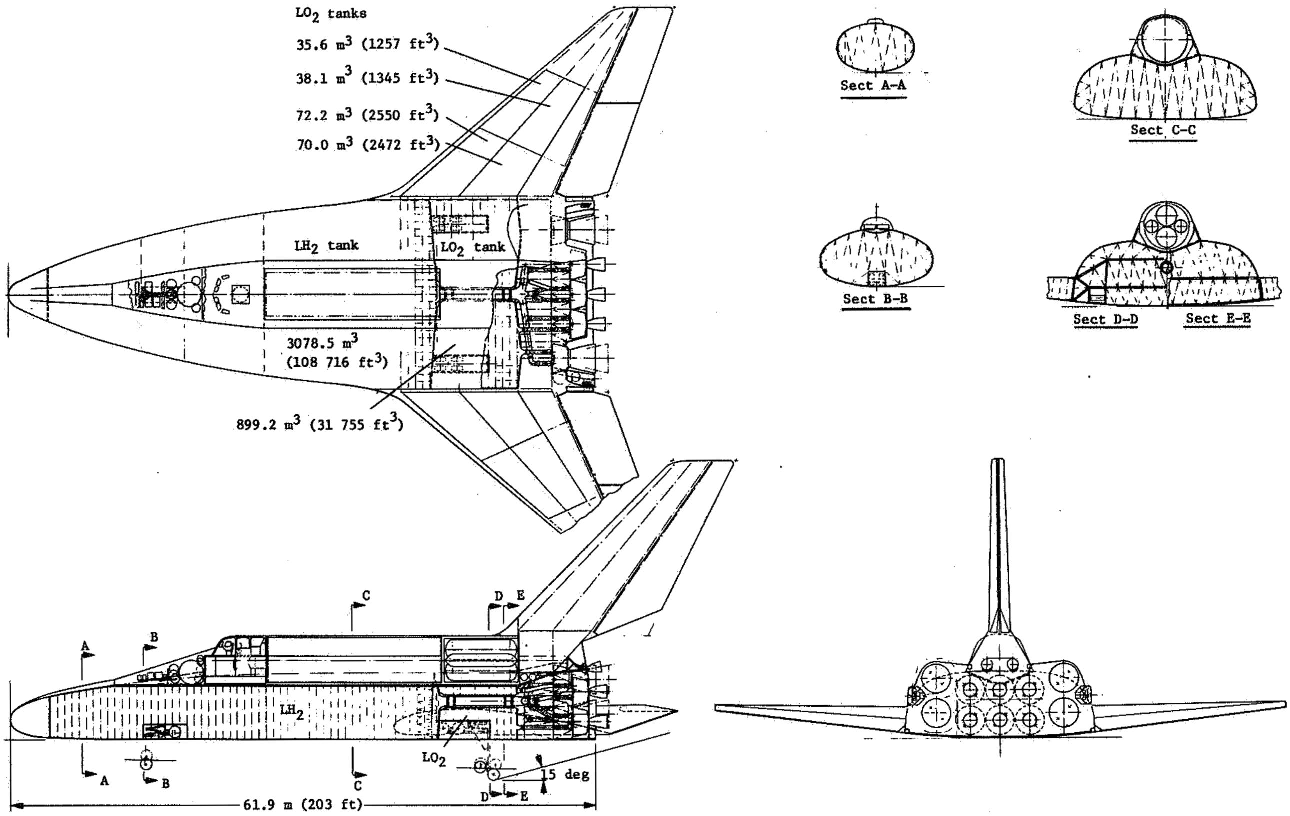


Figure 11.- VTO truss-supported, flattened-tank , Concept II

Vertical Takeoff Vehicle Design

The vertical takeoff (VTO) vehicle design incorporated the propulsion and thermostructural concepts selected in the initial parametric analyses. Activities in design concept development included considerations of the influences on design and weight of specific locations of such components as crew compartment, wing-box, OMS/RCS systems, subsystems, main engines, and propellant feed systems. Effects of variations in wing and vertical tail geometries and locations were also analyzed. An objective leading to minimum dry weight was to arrange the vehicle design for a center-of-gravity as forward as possible, as this leads to smaller wing and fin areas and significant reductions in vehicle size.

VTO design.- General arrangement, inboard profile, and structural arrangement drawings of the VTO concept are shown in Figures 12, 13, and 14. The vehicle structure consists of four major subassemblies, the fuselage-tank module, crew and payload module, wing and vertical tail. Some significant features of the vehicle are detailed in the following paragraphs.

The primary structural arrangement provides an efficient, lightweight design for accommodating propellants and subsystems, and for reacting loads from engine, crew and payload compartments, aerodynamic surfaces, and landing gear. The fuselage structure consists of aluminum tanks and advanced composite nontank shells. The wing, fin, and thrust structures use advanced composites. The wing torque box is located in the lower aft-skirt area to maintain efficient, low-weight thrust-load paths through the tanks and skirt shells.

The thermal protection system (TPS) using RSI is designed to accommodate the heat loads that can be experienced over a large entry corridor, and accommodating as much as a 3-g entry deceleration. Typical isotherms and TPS thicknesses are shown in Figure 15. Maximum heat rates and total heating at the nose stagnation point are 6.4×10^5 watts/m^2 (56 Btu/ft^2 sec) and 2.6×10^8 J/m^2 (23,100 Btu/ft^2), respectively, for a 1.52 m (5 ft) radius nose.

The crew compartment is contiguous with the payload compartment so the crew can easily enter the payload area. The four-man crew area is the same as that of the Space Shuttle, except it is expanded to accommodate a centrally located docking and crew transfer capability. This area is uniquely designed to allow for mobility of the crew among neighboring compartments and for extravehicular activities.

For improved vehicle balance, much equipment is located forward, including electrical and hydraulic power generators, and an RCS module. The OMS module is conveniently packaged just aft of the payload module.

The main engine array consists of ten engines, with six fixed-position and four dual-position gimballed nozzles. These are advanced technology SSME engines providing a liftoff acceleration of 1.3 g. During ascent, the engines are programmed to be shut down in pairs whenever the longitudinal g limit (3 g) is reached. The final two engines are throttled to avoid exceeding this limit. This engine operating sequence, together with the flexibility provided by multiple single-position and dual-position nozzles, helps significantly in ascent with optimal trajectories. The fixed-nozzle engines are somewhat aft of the dual-position engines to minimize plume interference after the four dual nozzles are extended.

Weight			C.G. % Ref Length
Payload	29 483 kg	(65 000 lb)	58.9
Dry weight	202 753 kg	(446 993 lb)	
Landing without payload	207 643 kg	(457 774 lb)	72.7
Landing with payload	237 126 kg	(522 774 lb)	71.0
Ascent propellant	1 660 998 kg	(3 661 873 lb)	
Gross liftoff weight	1 924 654 kg	(4 243 136 lb)	70.1

Volume		
LH_2 tank	3078.5 m^3	(108 712 ft^3)
LO_2 tank	1331.0 m^3	(47 000 ft^3)
Payload		
Diameter	4.572 m	(15 ft)
Length	18.288 m	(60 ft)
Payload Bay Clear Opening		
Diameter	4.725 m	(15.5 ft)
Length	18.517 m	(60.75 ft)

Area		
Body plan area	984.2 m^2	(10 594 ft^2)
Wing, theoretical	1126.0 m^2	(12 120 ft^2)
Wing, exposed	573.0 m^2	(6 168 ft^2)
elevon	181.1 m^2	(1 950 ft^2)
Vertical tail	205.3 m^2	(2 210 ft^2)
rudder	74.3 m^2	(800 ft^2)
Body wetted area	2635.6 m^2	(28 370 ft^2)

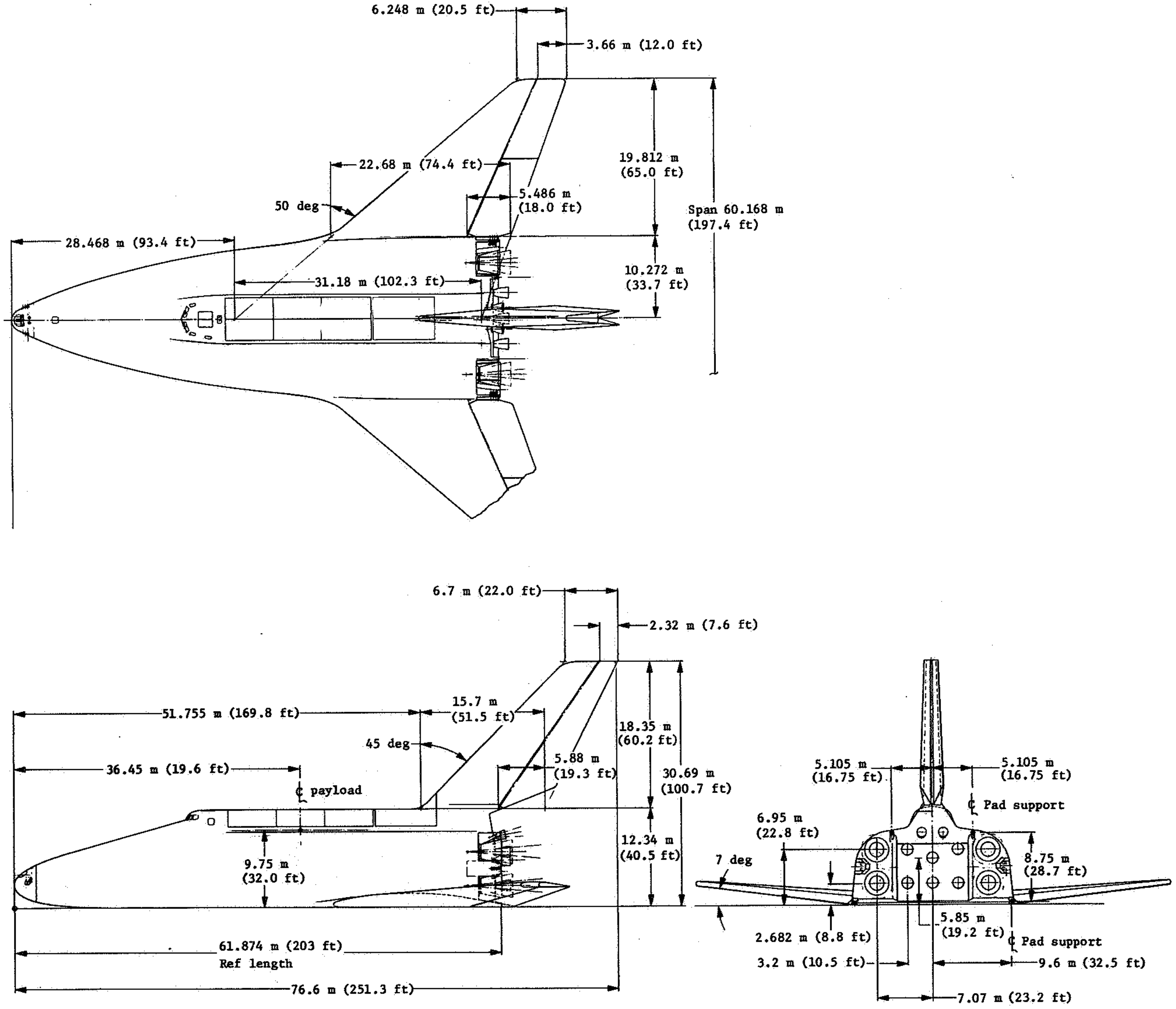


Figure 12.- VTO general arrangement

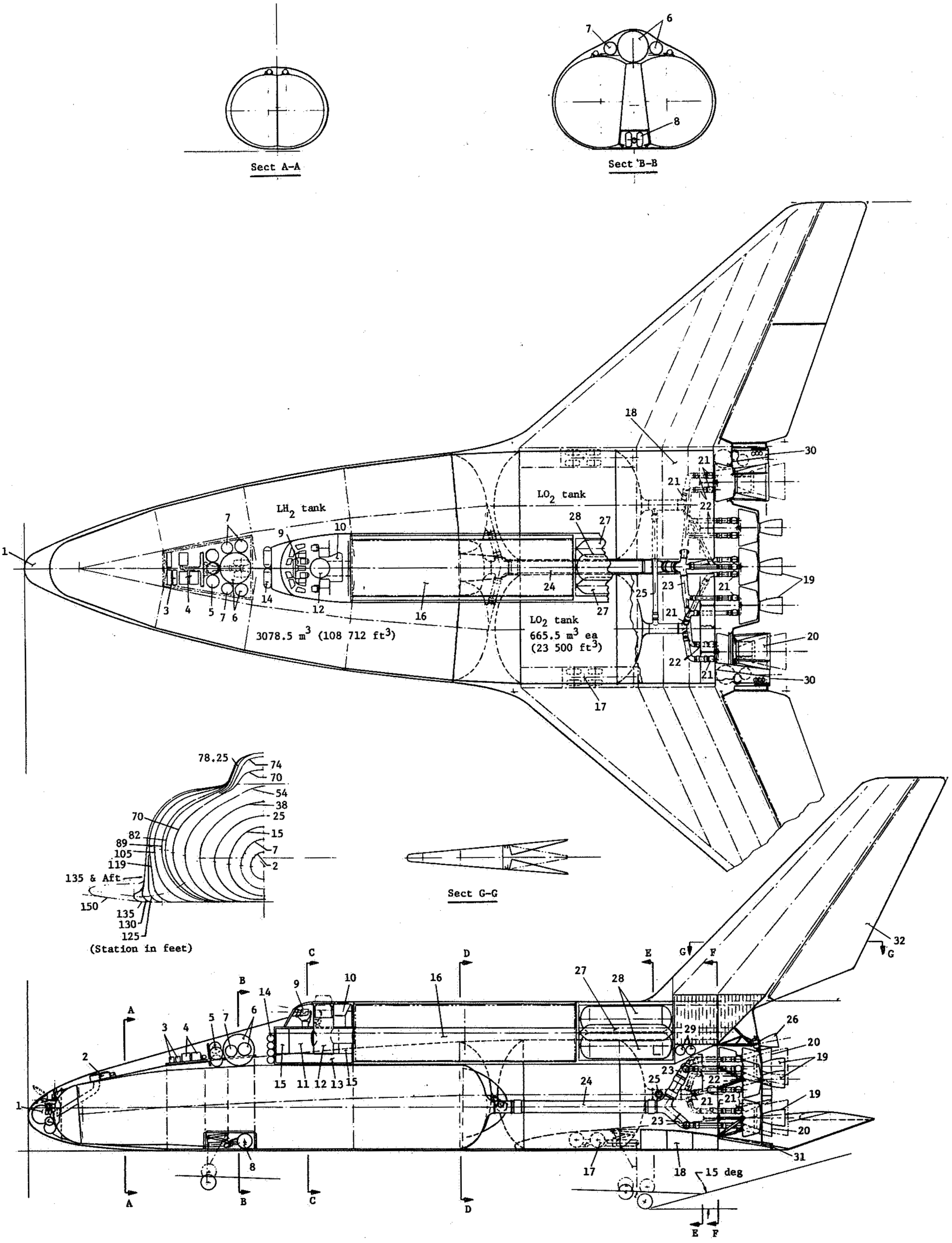
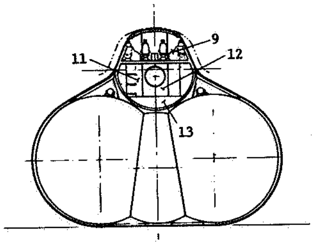


Figure 13.- VTO inboard profile



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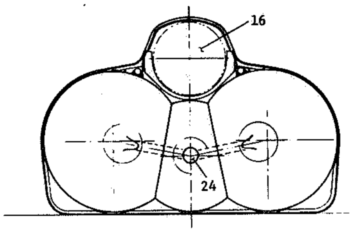

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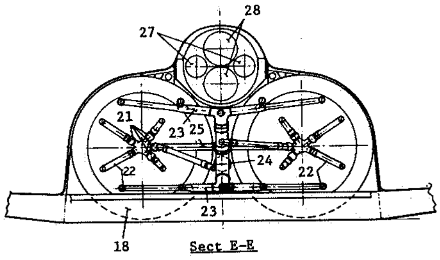
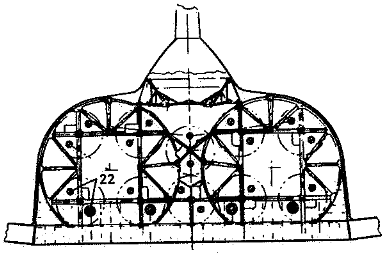


Sect E-E



Sect F-F

Legend:

1. Forward RCS module
2. LH_2 tank vent and pressurization valves
3. Electrical power system, fuel cells
4. Power system, APUs
5. Fuel cell propellants (LO_2-LH_2)
6. APU propellant (LO_2-LH_2)
7. Pressurants (He)
8. Nose landing gear
9. Flight deck
10. Operations deck
11. Rest and passenger area
12. Airlock and docking module
13. ECLSS - system
14. ECLSS supply and purge gas tanks
15. Avionics
16. Payload bay
17. Main landing gear
18. Wing carrythrough structure
19. Main propulsion engine, $\varepsilon = 35$, fixed nozzle, not gimballed
20. Main propulsion engine, $\varepsilon = 55/160$, extendable nozzle, gimballed
21. Propellant prevalve
22. Propellant feedlines
23. LH_2, upper and lower feedline manifolds
24. LH_2 main feedline
25. LO_2 tank interconnect line
26. OMS engine, LO_2-LH_2
27. OMS propellant tank, LO_2
28. OMS propellant tank, LH_2
29. OMS pressurant tanks (He)
30. Aft RCS modules
31. Pad support hard points
32. Split rudder

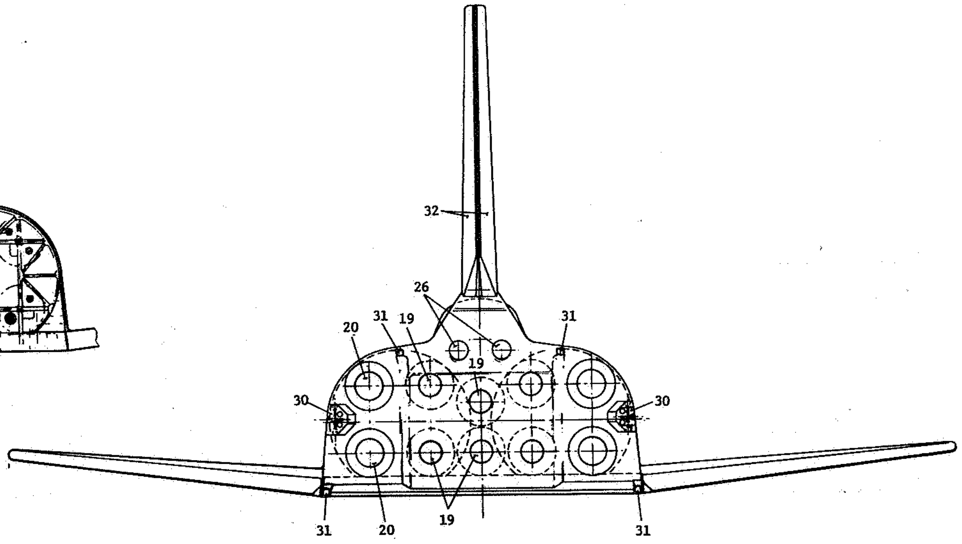
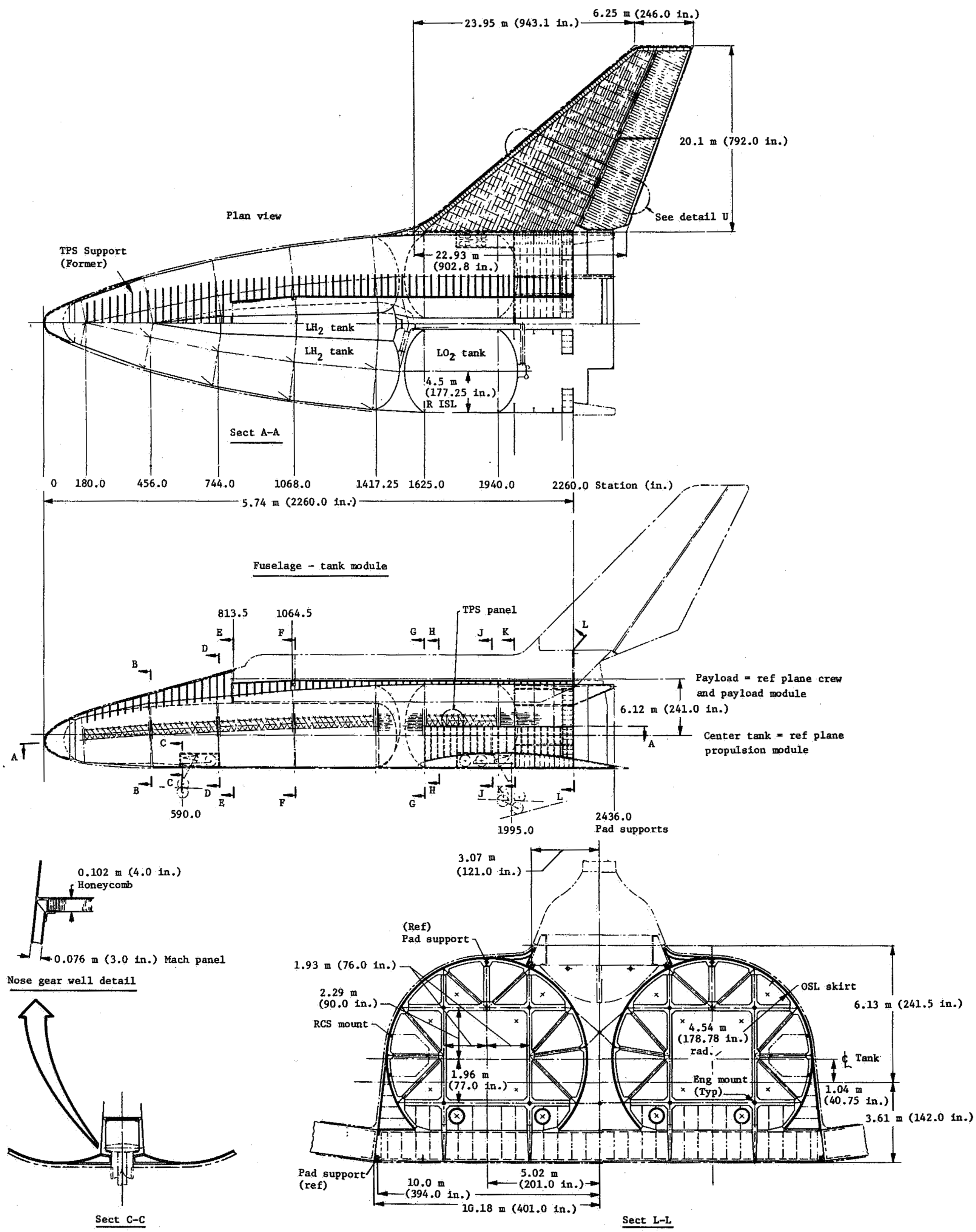


Figure 13.- Concluded



VTO STRUCTURAL ARRANGEMENT AND DETAILS

Figure 14.- VTO structural arrangement and details

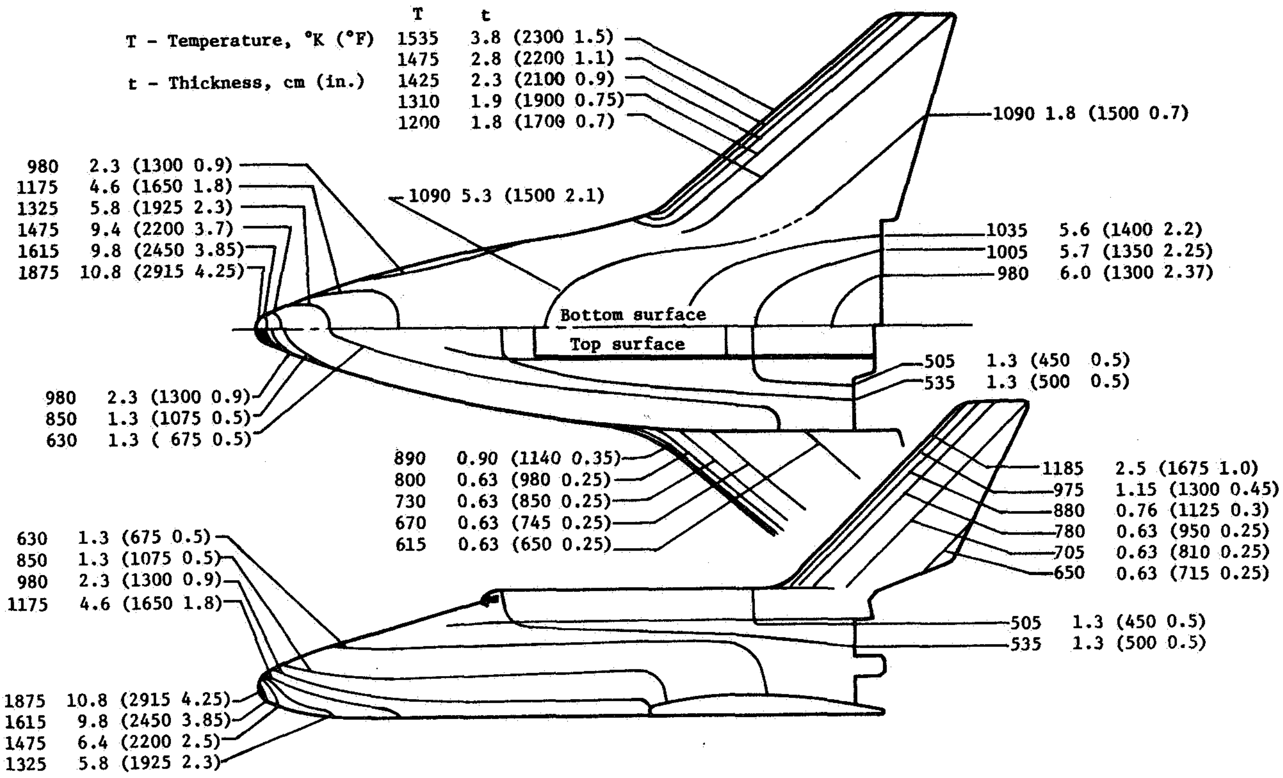


Figure 15.- SSTO-VTO entry surface isotherms and TPS thicknesses

Horizontal Takeoff (Sled Launched) Vehicle Design

The same propulsion and thermostructural concepts as for the VTO were applied to the horizontal takeoff (HTO) vehicle design. Initial parametric analyses were performed and judgements made to select sled characteristics and vehicle characteristics. Vehicle designs were examined with and without LO_2 tanks in wings. An approach for the wet-wing vehicles was to size them to meet the hypersonic aerodynamic trim requirement (trim at 20 deg), then to use these wings as LO_2 propellant tanks auxiliary to an internal LO_2 tank.

Sled concept.- The launch sled, shown in Figure 16, is a flat low-drag configuration that rides on two rails with lubricated slide shoes. The sled contains RP-1 and LO_2 propellant tanks and two F-1 rocket engines. The SSTO support structure consists of two collapsible tripods in the rear, which transmit the thrust load, and a single inverted V-strut in the forward end providing a positive incidence to the SSTO vehicle.

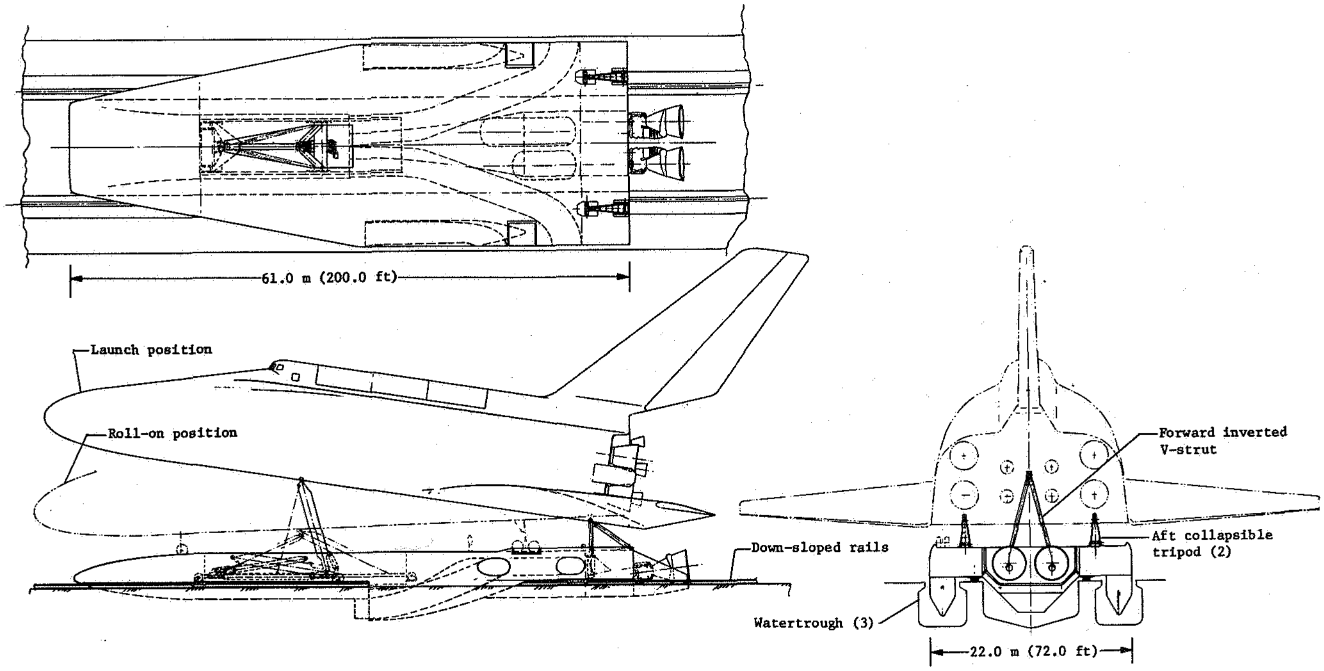


Figure 16.- HTO sled concept

Sled braking after liftoff or in an abort is provided by three water scoops (with appropriate water ducting) that, due to a gradually down-sloping rail, are immersed gradually in the water-filled troughs to give constant deceleration.

The empty SSTO is towed on its landing gear onto the sled platform. The main gear assemblies rest on platforms that move laterally to align the aft support points with the aft tripods, which are now erected. By lowering the platforms, the vehicle is locked in the aft supports. With an auxiliary strut, the forward inverted V-strut engages the forward support point in the vehicle. The scissors struts are erected to the proper incidence with a cable winch mechanism. The support strut is then locked in place and the auxiliary strut is retracted. The SSTO is now in launch position and ready for fueling.

The F-1 and HTO vehicle engines are ignited at the start of the sled run for confirmation of vehicle thrust before release of the sled. Maximum acceleration on the sled is 1.32 g, with a liftoff at Mach 0.6.

Considerations of LO_2 tanks in wings.- Advantages of using the wing volume for LO_2 propellant are in wing bending load relief and overall vehicle packaging efficiency. The wing bending load relief is efficient on the horizontal takeoff vehicles and reduces the overall wing weight by approximately 18%, resulting in a vehicle dry weight decrease of approximately 13.5%.

Tank leak inspection and repair is complicated by the bond-on insulation TPS, but the use of a subpanel mounted RSI TPS system would add approximately 2,700 kg (6,000 lb) to the TPS weight. Also, the requirements of strain isolators to meet the cryogenic temperature environment appear to be severe.

Although our design activities have focused on dry-wing concepts, significant improvements in dry weight have been shown using a wet wing for horizontal takeoff vehicles. Cryogenic wet wings, however, require special attention to design areas such as high-pressure wing designs integrated with appropriate TPS, propellant utilization systems, and prelaunch support of fueled wings. These have been considered to be beyond "normal" technology, but are considered later in horizontal takeoff concepts with accelerated technology.

HTO design.- An inboard profile of a dry-wing HTO vehicle is shown in Figure 17. This configuration is essentially a scaled version of the VTO design with wing and fin areas appropriate for the trim and stability guidelines. Structural interfaces with the sled support struts are included.

The two aft sled support points are located on the rear of the main engine mount bulkhead/wing carrythrough rear spar, and directly below the outboard engine thrust beam. The forward sled support point is on a main tank frame that also carries the forward support fitting for the crew/payload module. The engines are four fixed-position ($\epsilon = 35$) expansion ratio engines, offset by truss structure to the rear of the engine mount beams, and four gimballed engines with dual-position nozzles ($\epsilon = 55/160$) mounted on the beam structure.

Inflight-Fueled Vehicle Design

The inflight-fueled (IFF) vehicle design was patterned after the VTO and HTO designs. Initial emphasis was given to evaluating airbreathing and rocket engine propulsion systems for climbout and propellant-transfer flight phases with the goal of minimizing the dry weight of the IFF vehicle. Rendezvous and fuel transfer were selected to occur at 4.57 km (15 000 ft) and Mach 0.75, based on evaluations of turbofan

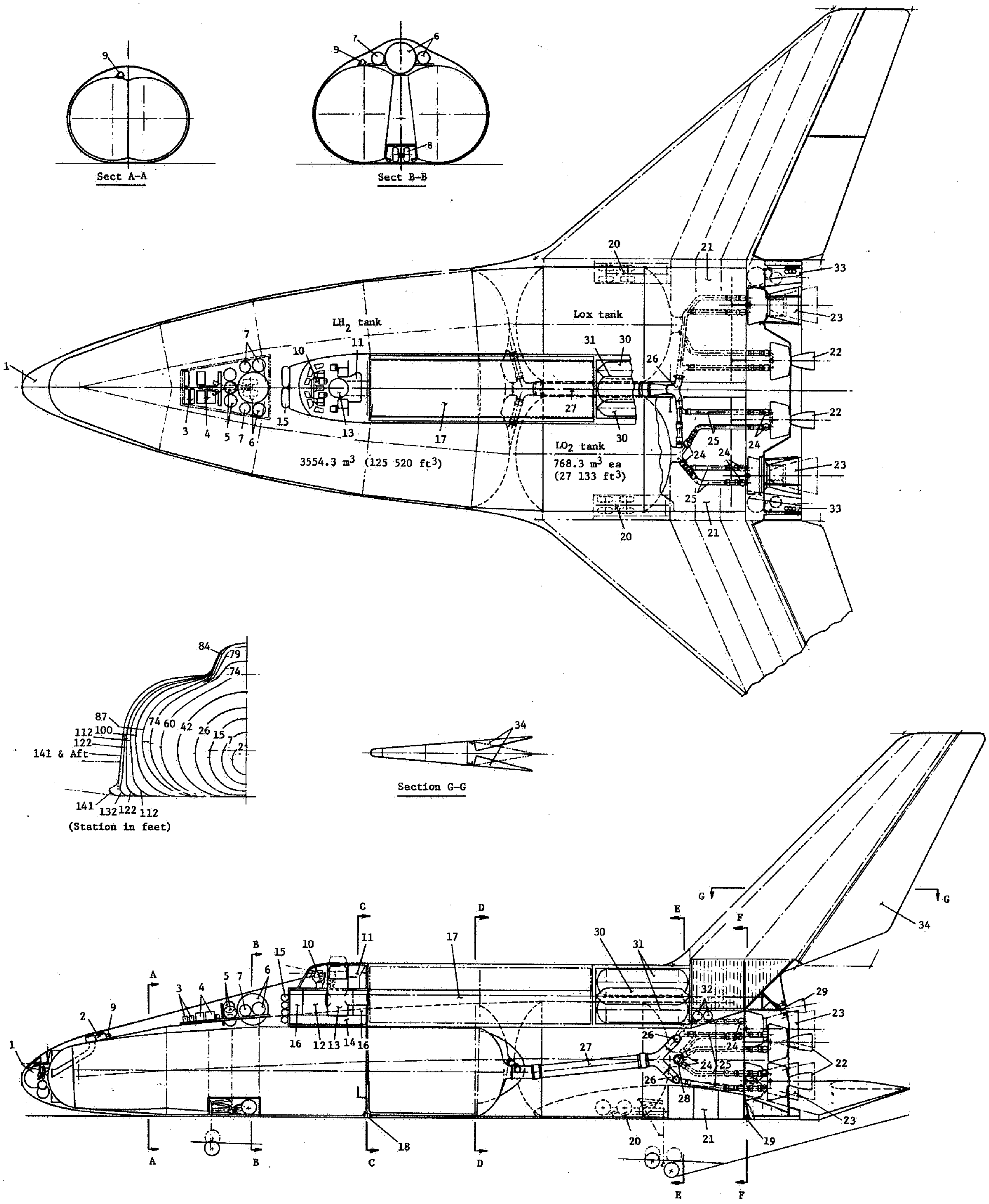
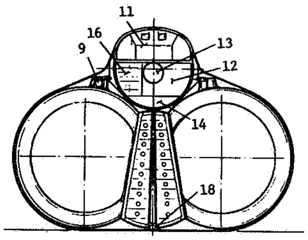
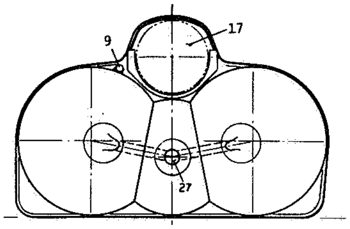


Figure 17.- HTO inboard profile



Sect C-C



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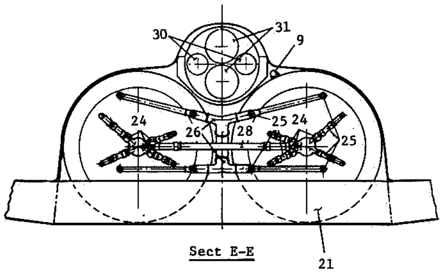

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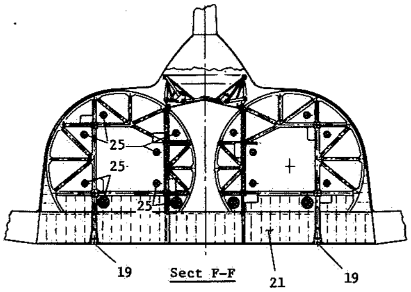


Sect F-F

Legend:

1. Forward RCS module
2. LH$_2$ tank vent and pressurization valves
3. Electrical power system, fuel cells
4. Power system, APUs
5. Fuel cell propellants (LO$_2$ - LH$_2$)
6. APU propellant (LO$_2$ - LH$_2$)
7. Pressurants (He)
8. Nose landing gear
9. LH$_2$ tank pressurization line
10. Flight deck
11. Operations deck
12. Rest and passenger area
13. Airlock and docking module
14. ECLSS - system
15. ECLSS supply and purge gas tanks
16. Avionics
17. Payload bay
18. Forward sled support point
19. Aft sled support points
20. Main landing gear
21. Wing carrythrough structure
22. Main propulsion engine, $\varepsilon = 35$, fixed nozzle, not gimbaled
23. Main propulsion engine, $\varepsilon = 55/160$, extendable nozzle, gimbaled
24. Propellant prevalve
25. Propellant feedlines
26. LH$_2$, upper and lower feedline manifolds
27. LH$_2$ main feed line
28. LO$_2$ tank interconnect line
29. OMS engine, LO$_2$-LH$_2$
30. OMS propellant tank, LO$_2$
31. OMS propellant tank, LH$_2$
32. OMS pressurant tanks (He)
33. Aft RCS modules
34. Split rudder

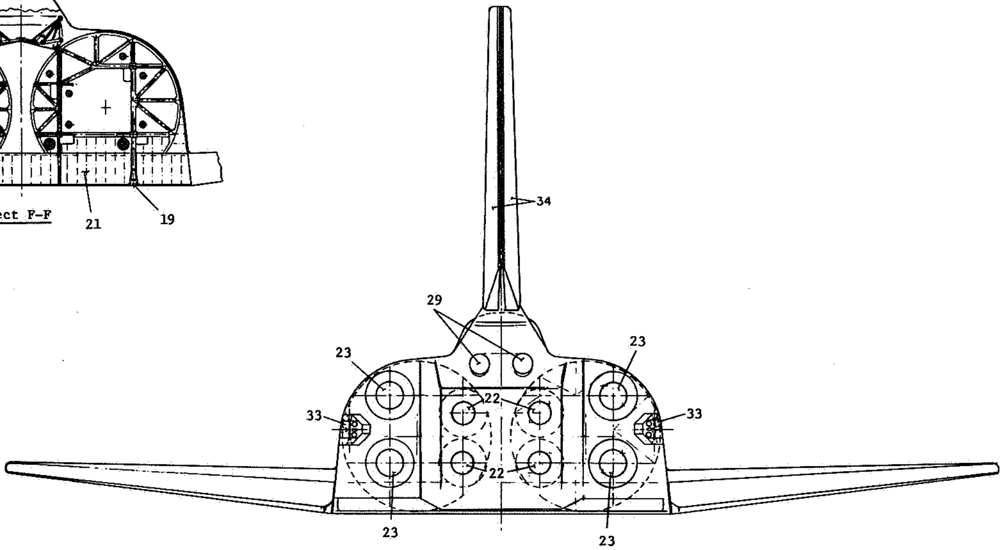


Figure 17.- Concluded

engine performance and IFF aerodynamics. Preliminary size estimates of a tanker aircraft were also made.

Rocket and airbreathing engine comparisons.- Various propulsion concepts were evaluated to establish the best means of accomplishing the takeoff, climb, and propellant transfer phases. The concepts included throttable main rockets, turbojets, turbofans, and a combination of turbofans supplemented by a throttled rocket. Various fuel combinations were also evaluated.

Because of possible hazards associated with inflight transfer of liquid hydrogen, initial comparisons considered LO_2 transfer only. A minimum dry weight vehicle design resulted using a turbofan system supplemented with thrust from one of the main rocket engines during final LO_2 loading. However, due to the necessity of carrying all LH_2 from the ground up, even the minimum vehicle proved unreasonably large. Consequently, subsequent investigations considered transferring both LO_2 and LH_2.

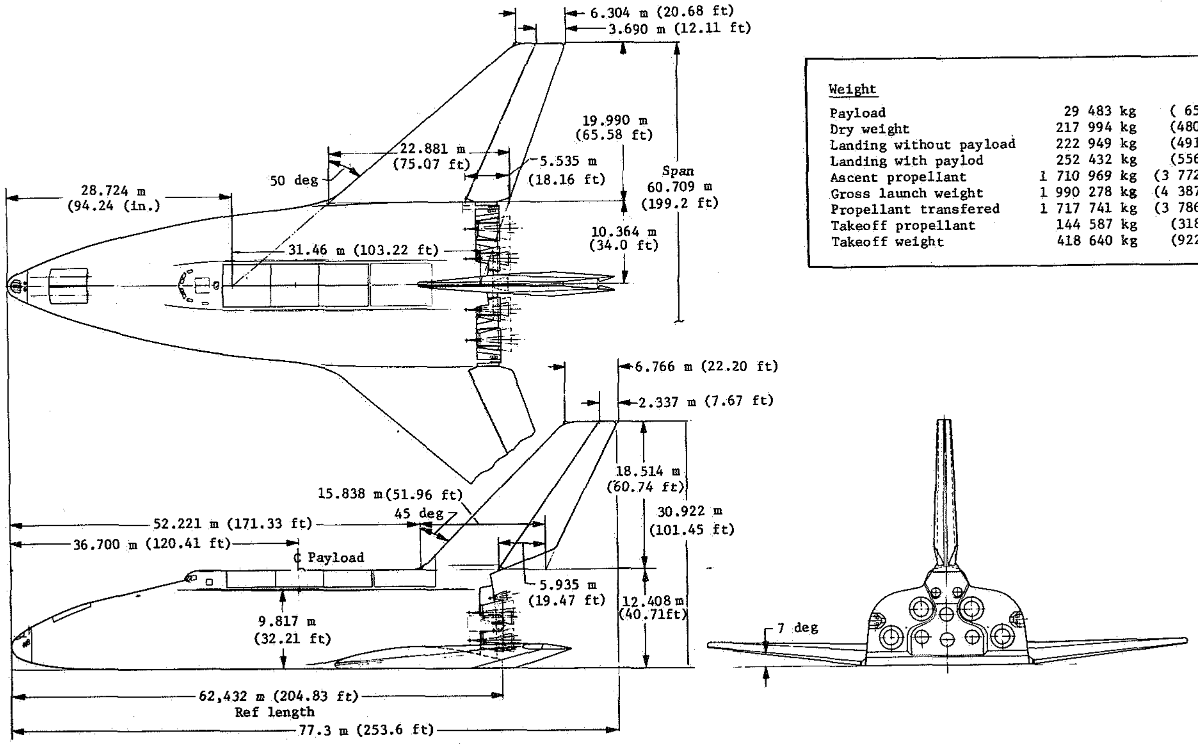
When both propellants are transferred to the SSTO from a tanker aircraft, the all-rocket approach proved to be almost 8% lighter in dry weight than the rocket-supplemented turbofan concept. However, the takeoff weight of the all-rocket version was 24% greater due to the greater amount of propellants required.

IFF design.- A general arrangement of the IFF vehicle with rocket-engine takeoff is shown in Figure 18. This configuration is similar to the VTO configuration in most aspects, but with some unique features. An additional four-wheel bogie is provided on the center of the vehicle to accommodate the large takeoff weight. The rocket engines are four fixed-position $\epsilon = 50$ ratio engines, offset by truss structure to the rear of the engine mount beams, and four gimballed engines with dual-position nozzles ($\epsilon = 55/160$) mounted on the beam structure. Takeoff, climb, and cruise occur using one rocket engine, which is throttled appropriately to meet climb and cruise thrust schedules. The LO_2 feedline of this one rocket engine feeds from the low point of one of the LO_2 tanks. As the LO_2 and LH_2 tanks are refueled while pressurized, a vent relief valve, set at about nominal tank pressure, is provided in the tanks. The refueling ports are located side by side on top of the forward end of the LH_2 tank. The LO_2 refueling boom is connected first and, when hooked up, is capable of maintaining a certain amount of tension on the boom. The LH_2 boom, attached to the LO_2 boom, is engaged subsequently and is not stressed. The propellant coupling is self-closing; redundant shutoff valves are provided. The LO_2 refueling line (68 cm) diameter runs on top of the LH_2 tank sideways of the payload bay to the forward end of the LO_2 tank. The LH_2 line enters the LH_2 tank behind the fitting and shutoff valve.

This IFF vehicle requires over 1.7 Gg (3.7 Mlb) of cryogenic propellants to be transferred in flight from tanker to SSTO. The size of tanker aircraft required to carry this amount of propellants is larger than any now designed, and would therefore itself require extensive development and operational efforts. Furthermore, navigation and flight control for the rendezvous, as well as very high rates of fuel-flow transfer with accompanying safety concerns, would also require new technology.

Volume		
LH_2 tank	3171 m^3	(111 982 ft^3)
LO_2 tank	1370.9 m^3	(48 414 ft^3)
Payload		
Diameter	4.572 m	(15 ft)
Length	18.288 m	(60 ft)
Payload Bay clear opening		
Diameter	4.725 m	(15.5 ft)
Length	18.517 m	(60.75 ft)

Area		
Body plan area	1002.0 m^2	(10 785 ft^2)
Wing, theoretical	1146.4 m^2	(12 339 ft^2)
Wing, exposed	583.4 m^2	(6 280 ft^2)
elevon	184.4 m^2	(1 985 ft^2)
Vertical tail	209.0 m^2	(2 250 ft^2)
rudder	75.6 m^2	(814 ft^2)
Body wetted area	2685.3 m^2	(28 904 ft^2)



Weight		
Payload	29 483 kg	(65 000 lb)
Dry weight	217 994 kg	(480 595 lb)
Landing without payload	222 949 kg	(491 519 lb)
Landing with paylod	252 432 kg	(556 519 lb)
Ascent propellant	1 710 969 kg	(3 772 042 lb)
Gross launch weight	1 990 278 kg	(4 387 811 lb)
Propellant transfered	1 717 741 kg	(3 786 971 lb)
Takeoff propellant	144 587 kg	(318 761 lb)
Takeoff weight	418 640 kg	(922 943 lb)

Figure 18.- IFF general arrangement, rocket engine takeoff

Vehicle Comparison Summary

Table 4 presents a summary of vehicle weights. The lightest vehicle is the HTO vehicle with a wet wing, whereas the heaviest is the IFF vehicle. The IFF vehicle concept introduces many concerns related to requirements for technology developments and flight operations. It also requires development of a new tanker aircraft that not only is larger than any present aircraft, but also requires technology developments for transporting and transferring LO_2 and LH_2 propellants rapidly. The HTO concept also introduces unique technology development requirements that are beyond "normal" growth potential. These are related to design requirements of cryogenic wet-wing thermostructures and TPS integration, as well as to development of a large, high-speed, rocket-powered sled. The VTO concept offers no technology development concerns beyond "normal" growth expectations, and therefore has been selected for focusing studies of the merits of accelerated technology requirements. The HTO wet-wing concept, however, is included with the VTO concept in the subsequent analyses of vehicles using accelerated technology.

TABLE 4.- VEHICLE CONCEPT COMPARISON SUMMARY

	VTO		HTO (dry wing)		HTO (wet wing)		IFF
	Initial aero	Revised aero	Initial aero	Revised aero	Initial aero	Revised aero	Initial aero
Vehicle dry							
kg	202 753	196 923	225 121	217 493	194 190	190 002	217 994
(lb)	(466 993)	(434 142)	(496 307)	(479 491)	(428 112)	(418 882)	(480 595)
Ascent propellant							
kg	1 660 998	1 626 277	1 817 463	1 681 808	1 642 748	1 502 256	1 710 969
(lb)	(3 661 873)	(3 585 326)	(4 006 819)	(3 707 751)	(3 621 640)	(3 311 907)	(3 772 042)
GLOW							
kg	1 924 654	1 883 631	2 106 198	1 960 291	1 901 441	1 752 275	1 990 279
(lb)	(4 243 136)	(4 152 695)	(4 643 368)	(4 321 701)	(4 191 956)	(3 863 105)	(4 387 815)
Sled acceleration propellant							
kg			100 326	93 172	90 718	83 415	
(lb)			(221 181)	(205 409)	(200 000)	(183 898)	
Vehicle loaded							
kg			2 206 524	2 053 463	1 992 159	1 835 703	
(lb)			(4 864 549)	(4 527 110)	(4 391 956)	(4 047 033)	

PROGRAM COST ANALYSIS

Total program costs [life-cycle costs (LCC)] were calculated using a Space Shuttle work breakdown structure (WBS) and aerospace industry cost estimating relations (CERs). Inputs to the cost analyses included vehicle mass properties, TPS areas, configuration complexity factors, system development schedules and launch rates. The cost data were expressed in fiscal year 1976 dollars as well as discounted dollars at a 10% rate.

The WBS contained 419 items from level 1, SSTO System, through level 7, Flight Vehicle Subsystems and Tests. Costs in the WBS were classed as engineering, material and subcontract, tooling, and manufacturing. The WBS was established for DDT&E, production and operations. A system development schedule was used for these SSTO phases (Figure 20) derived in part from Space Shuttle schedules. Operational and launch schedules using five SSTO vehicles were also developed, representing 1,710 launch attempts over a 15-year operations period (1995 through 2009). The CERs included equations relating costs as functions of configuration complexity, materials, labor and overhead rates, vehicle weights and densities, access area complexity, and learning curves. A vehicle design life of 500 missions and a main-engine life of 250 cycles was specified as initial criteria, with engines and facilities Government-supplied. The 1710 flight mission model, if evenly applied to five vehicles, results in a requirement for each vehicle of 342 missions and 171 engine cycles (plus test cycles).

DDT&E Costs

The DDT&E costs included factors for program management, systems integration, and engineering. Facility construction costs assumed maximum use of existing base facilities, but with two SSTO pads (modified Space Shuttle pads) and an SSTO maintenance facility at both KSC and WTR. Ground equipment (AGE) and flight test spares were included. The test program costs included one and a half ground test vehicles, one flight test vehicle to be refurbished and transferred to operations, and one mockup. Static-fire, taxi, and vertical tests were also included. The DDT&E cost results are summarized in Table 5.

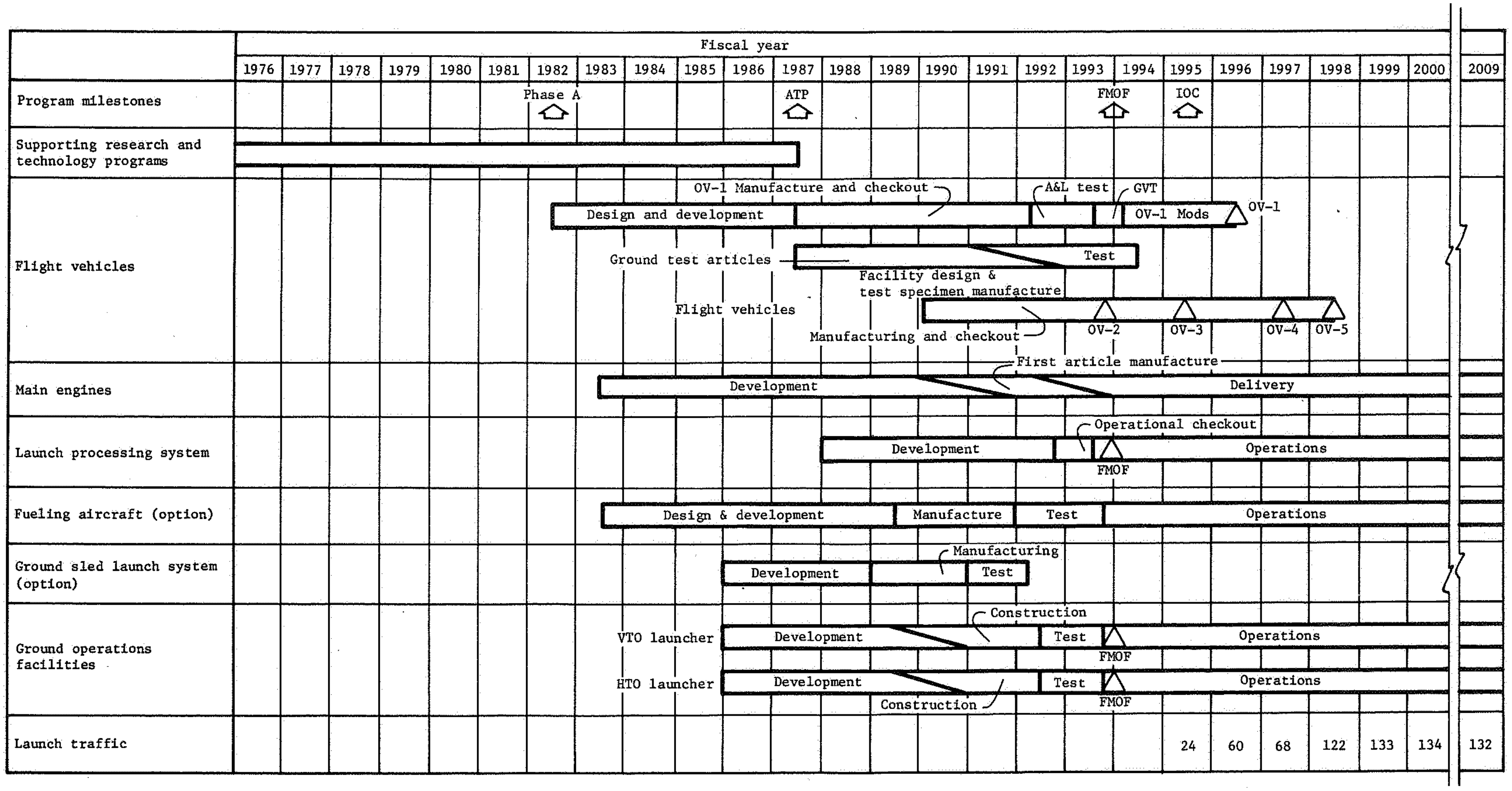


Figure 19.- System development schedule

TABLE 5.- DDT&E COSTS

Cost element	Dollars in millions			
	VTO	HTO		IFF
		Dry	Wet*	
Program management	$ 330	$ 347	$ 335	$ 332
Systems engineering and integration	590	619	599	591
Air vehicle design	2317	2491	2380	2441
Ground support equipment	296	296	296	296
Training	172	172	172	172
Systems test and evaluation				
Test hardware†	904	918	875	928
Test operations	390	390	390	390
HTO vehicle design		122	122	
Logistics	45	45	45	45
Facilities	466	756	756	466
Fee	458	483	466	459
Total	$5968	$6639	$6436	$6120

*LO_2 in wing
†2.5 equivalent air vehicles

Production Costs

Production costs of four flight vehicles (Table 6) for each of the vehicle concepts (VTO, HTO, and IFF) were derived using a 95% learning curve. Factors for sustaining tooling, sustaining engineering and final assembly, installation, and checkout were based on Titan experience.

Operations Costs

Operations costs for SSTO systems were initially estimated using the approach of modifying present Space Shuttle operations

TABLE 6.- PRODUCTION COSTS

Cost element	Dollars in millions			
	VTO	HTO		IFF
		Dry	Wet*	
Structures	$ 307	$ 363	$ 309	$ 346
Thermal protection	40	42	48	39
Landing gear	22	25	22	39
Propulsion	354	292	291	251
Avionics	101	101	101	101
ECLS	28	28	28	28
Power, hydraulics	149	144	153	150
Final assembly and checkout	197	209	198	195
Sustaining engineering	41	45	41	45
Sustaining tooling	52	56	52	57
Fee	108	115	108	108
Total	$1399	$1420	$1351	$1359
First article cost	$ 362	$ 367	$ 350	$ 371

*LO_2 in wing

cost projections for application to a 15-year 55% program. The primary modifications were to delete the Space Shuttle costs related to the external tank (ET) and the solid-rocket boosters (SRB). This approach led to a cost estimate of $6.6 million per launch for SSTO (VTO) compared to $13.9 million per launch for Space Shuttle, based on fiscal year 1976 dollars.

A second more fundamental approach was taken to reflect the potential simplification and combinations of launch and flight operations for an SSTO. This approach involved a functional analysis, anticipating that the next 15 years of Space Shuttle activities provide time for substantial cost reduction improvements. These projected improvements were based on considerations of the automation (computerization) of many functions, as well as the future Space Shuttle operations experience and the less complex SSTO flight vehicle with self-checkout capabilities. Guidelines and results of this approach are presented here.

The SSTO operations costs are based on 1,710 total flight attempts over a 15-year period beginning in 1995. The number of flights each year (Figure 19) are estimated using the 12-year Space Shuttle traffic model extended to a 15-year period. Five flight vehicles are available, three at ETR and two at WTR. Costs are included for new launch pads, or sleds, on existing land. Costs of spares are based on Titan experience and projection for SSTO operations. Flight and launch operations are predominantly repetitive; ground based data systems and flight monitoring are largely automated. Most functions, therefore, can be performed by technicians rather than engineers, significantly minimizing launch and flight operations cost.

A result of the functional analysis was the 60-hour ground operations timeline shown in Figure 20. Manhours and costs to support these functions were estimated and used to develop the costs per flight shown in Table 7. This table shows Space Shuttle data for comparison, indicating significantly smaller costs projected for SSTO operations.

These smaller costs can be achieved with "normal" technology growth focused in improving onboard flight and ground support systems. Examples for operations technology emphasis are as follows:

(1) Onboard flight systems designed with automated self-test and checkout capabilities;

(2) Support systems designed with simplified prelaunch and on-orbit monitoring software and control-center staffing.

Life-Cycle Costs

The life-cycle (total program) costs, summarized in Table 8, in fiscal year 1976 dollars are much the same for the various vehicle concepts. For the VTO vehicle, DDT&E and production costs are 64% and 14% of the total respectively, whereas operations costs are 22% of the total.

The life-cycle costs were discounted at 10% from fiscal year 1976 for comparison with costs in current dollars and as an aid for financial decisions. Discounted costs are shown in Table 8.

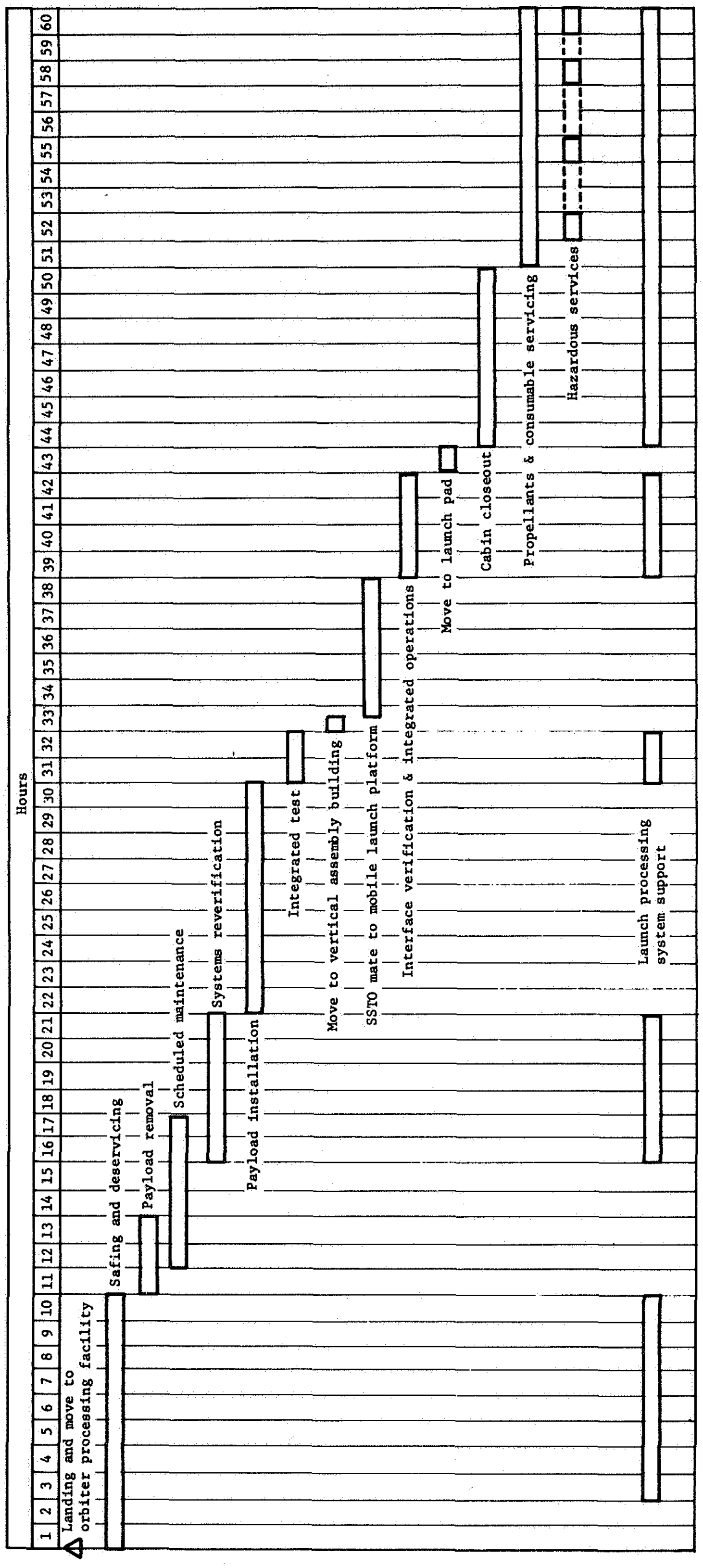


Figure 20.- Typical flow of ground operations

TABLE 7.- OPERATIONS COSTS PER FLIGHT

	Space Shuttle*		VTO	HTO FY '76 $		IFF
	FY '72 $	FY '76 $	FY '76 $	Dry	Wet†	FY '76 $
KSC civil service	0.51	0.67	0.092	0.092	0.092	0.092
Launch operations	2.00	2.75	0.858	0.875	0.815	0.937
Flight operations (JSC)	2.21	2.92	0.703	0.703	0.703	0.703
Refurbishment	0.42	0.55	0.077	0.077	0.077	0.077
Solid rocket booster	3.33	4.40				
External tank	1.75	2.31				
Engines	0.23	0.30	0.210	0.168	0.168	0.168
HTO				0.022	0.022	
Tanker						0.342
Totals	10.45	13.90	1.940	1.937	1.877	2.319

*Control document, JSC 07700, Volume XVI

†LO_2 in wing

TABLE 8.- LIFE CYCLE COSTS

	Space Shuttle		VTO		HTO Dry		HTO Wet*		IFF
	FY '76 $	Discounted	FY '76 $	Discounted	FY '76 $	Discounted	FY '76 $	Discounted	FY '76 $
DDT&E	5 499	3976	5 968	1 777	6 639	1 979	6 436	1 906	6 120
Production	1 000	655	1 399	281	1 420	285	1 351	271	1 359
Operations	14 052	3699	3 317	249	3 312	248	3 210	253	3 965
Totals	20 551	8270	10 684	2 307	11 371	2 512	10 997	2 430	11 444

*LO_2 in wing

SUMMARY COMPARISON OF VEHICLE WEIGHTS AND COSTS

The major results of the vehicle design weight analyses and program cost analyses are shown in Table 9. The weights of the VTO and HTO concepts are for vehicles sized to revised aerodynamics. Dry weight is one figure of merit for comparing concepts and this parameter is least for the HTO vehicle. Other figures of merit are total program costs and the cost per pound of payload in orbit, and these are least for the VTO vehicle. For comparison, the Space Shuttle merit index is \$509/kg (\$231/lb) and \$134/kg (\$60.9/lb) based on fiscal year 1976 and discounted dollars respectively. A mission success factor of 0.925 was used for the HTO and the IFF concepts, and 0.95 was used for the VTO.

Based on the assessments of vehicle cost-performance merits, the VTO and the wet-wing HTO concepts were pursued during the Extended Performance Studies. Advanced Technology Assessments were focused on the VTO concept.

ADVANCED TECHNOLOGY ASSESSMENT

With the preceding background of "normal" technology projections and vehicle design concepts, technology areas were evaluated to determine cost/performance/benefits that can result with additional research funding and emphasis. Vehicle weight and performance parameters were identified that could provide significant cost advantages with advanced research goals and additional funding requirements. Advanced technology programs were then estimated using delphi techniques. Nominal values and upper and lower 95% confidence limits were estimated for both technology goals and funding. Cost/performance/benefit figures of merit were then derived. The VTO vehicle design was selected as a focus for the technology assessments.

Advanced Technology Programs

Twelve advanced technology programs (Table 10) were selected for assessment of their potential benefits in the time frame of interest. The basis for selection was the strong influence of

TABLE 9.- SUMMARY COMPARISON OF VEHICLE CONCEPTS, WEIGHTS, AND COSTS

	VTO	HTO		IFF
		Dry wing	Wet wing	
Dry weight				
kg	196 923	217 493	190 002	217 994
(lb)	(434 142)	(479 491)	(418 882)	(480 595)
GLOW				
kg	1 883 631	1 960 291	1 752 275	1 990 279
(lb)	(4 152 695)	(4 321 701)	(3 863 105)	(4 387 815)
Total program costs dollars in billions				
Fiscal year 1976	10.7	11.4	11.0	11.4
Discounted 10%	2.3	2.5	2.4	2.5
Merit index* dollars/kg (dollars/pound)				
Fiscal year 1976	69.3 (31.4)	71.0 (32.2)	68.8 (31.2)	85.1 (38.6)
Discounted 10%	5.3 (2.4)	5.3 (2.4)	5.2 (2.3)	6.4 (2.9)

*(Operations costs)/(mission success factor) (no. of flights) (payload)

TABLE 10.- ADVANCED TECHNOLOGY PROGRAMS SELECTED FOR ASSESSMENT

Materials, structures, and design optimization	Propulsion
1. Thermal protection systems	6. Main engine injectors/chambers/nozzles
2. Propellant tanks	7. Main engine pumps
3. Wing and vertical tail structures	8. Main engine cooling
4. Thrust structures	9. OMS/RCS systems
5. Miscellaneous structures	10. Triple point propellants
Secondary technologies	Design criteria
11. Subsystems weight reduction	12. Integration engineering

these technology areas on reducing dry weight of the VTO vehicle beyond "normal" technology growth.

The materials, structures, and design optimization programs are selected to support improvements in the major weight parameters. The Miscellaneous Structures R&T program pursues improvements in vehicle areas such as structural interfaces with payload and subsystems, crew compartment including docking, intertank structures and access doors. The propulsion programs are selected to support improvements in engine performance and weight parameters for both main engines and RCS/OMS engines. The Triple-Point/Slush Propellants R&T program is included to pursue improvements that can accrue using higher density LO_2/LH_2 propellants. The Subsystem Weight Reduction program addresses performance and weight reduction potentials in subsystems such as electrical, hydraulics, pneumatics, life support, avionics, and communications. The Integration Engineering program consists of design engineering and costing activities to provide technical focusing and integration of all SSTO-related research programs. These integration engineering activities include continuing efforts toward establishing research goals, guidelines, design criteria and margin requirements, and cost/performance/benefits of SSTO vehicle and program concepts.

Figures of Merit

Results of the cost/performance/benefits analyses are summarized in Table 11. The technology improvement goals (Δ Technology) of each program were used to obtain their effects on reducing VTO vehicle weights. The incremental cost of each research program, discounted at 10% ($\Delta \$R_D$), included considerations of research personnel, facilities, materials, and tests. The improvement goals and research costs were obtained using Delphi techniques. The vehicle weights were used to derive life-cycle cost savings (Δ $LCC) attributed to each program. Discounted values (subscript D) are shown. Each row of data in this table pertains to the given technology program, each taken individually as if it were the only accelerated program that would be given additional funding. In a subsequent section (Merit Analysis and Risk Assessment) example results of implementing meaningful combinations of programs are shown. This table also presents the figure of merit, life-cycle cost saving divided by the added research program cost ($\Delta \$LCC_D / \Delta \$R_D$).

These figures of merit, shown in Figure 21, arranged in order of decreasing merit, include upper and lower limits that represent assessments of negligible risk. Accelerated research activities will yield results within these limits. The statistical expected result based on nominal values of parameters is shown by each circle. Numerical values for integration engineering are not included, but this program is discussed later.

Rankings of the research programs are shown in Table 12 for four figures of merit (FOM), based on expected (nominal) values of parameters. Relative values of each FOM as well as the quartile designation of these values are also tabulated. The programs are listed in the ranking order based on FOM A. A significant result is the definitive groupings of the programs in each quartile, indicating that the quartile ranking would not be different even if there were large changes in the cost or weight estimates. A second significant result is that the rankings are almost the same, observing the quartile designations from left to right across the table, for FOMs A, B, C, and D.

TABLE 11.- FIGURES OF MERIT AND SENSITIVITY DATA

Technology program		ΔTechnology		Δ$		
		ΔI_{sp} - sec, ΔW, kg (lbm)	Δ% ± Tolerance	R_D, <R> $M	max min	ΔW_{dry}, kg (lbm)
1. Thermal protection systems	ΔW	-2970 ± 450 (-6550 ± 1000)	-7.5 ±1.1	10.5 <18.1>	14.2 9.0	-9 510 ± 1 450 (-20 960 ± 3 200)
2. Propellant tanks	ΔW	-2940 ± 1360 (-6480 ± 3000)	-10 ± 4.6	9.0 <15.3>	12.6 7.3	-9 230 ± 4 270 (-20 350 ± 9 420)
3. Wing & vertical tail structures	ΔW	-3750^{+1470}_{-1730} $\left(-8260^{+3250}_{-3820}\right)$	$-13^{+5.1}_{-6.0}$	16.4 <30.8>	22.9 12.6	$-12\ 470^{+4\ 910}_{-5\ 770}$ $\left(-27\ 500^{+10\ 820}_{-12\ 720}\right)$
4. Thrust structures	ΔW	-590^{+360}_{-500} $\left(-1300^{+800}_{-1100}\right)$	$-8.1^{+5.0}_{-6.9}$	4.5 <8.2>	7.2 3.3	$-2\ 990^{+1\ 840}_{-2\ 540}$ $\left(-6\ 600^{+4\ 060}_{-5\ 590}\right)$
5. Miscellaneous structures	ΔW	-1360^{+360}_{-1350} $\left(-3000^{+800}_{-2970}\right)$	$-12.0^{+3.2}_{-11.8}$	4.5 <8.0>	6.8 3.5	$-3\ 910^{+1\ 040}_{-3\ 870}$ $\left(-8\ 630^{+2\ 300}_{-8\ 540}\right)$
6. Main engine (injectors/ chambers/ nozzles)	ΔI_{sp}	$+6^{+2}_{-5}$	$+1.3^{+.4}_{-1.0}$	47.8 <78.8>	66.3 37.8	$-11\ 010^{+8\ 650}_{-3\ 640}$ $\left(-24\ 280^{+19\ 060}_{-8\ 020}\right)$
	ΔW	-45 ± 14/Eng (-100 ± 30/Eng)	-1.1 ± 0.33			
7. Main engine pumps	ΔI_{sp}	+2.5 ± 1	+0.53 ± 0.21	26.3 <40.0>	35.4 18.7	-4 670 ± 1 820 (-10 300 ± 4 010)
	ΔW	-23 ± 7/Eng (-50 ± 15/Eng)	-0.55 ± 0.16			
8. Main engine cooling	ΔI_{sp}	+1.5 ± 1	+0.32 ± 0.21	10.5 <17.2>	13.7 8.3	-3 300 ± 1 830 (-7 280 ± 4 030)
	ΔW	-45 ± 9/Eng (-100 ± 20/Eng)	-1.1 ± 0.22			
9. OMS/ RCS	Propellant ΔW	-830^{+120}_{-140} $\left(-1830^{+260}_{-320}\right)$	$-6.4^{+.92}_{-1.1}$	26.8 <44.4>	36.0 20.0	$-1\ 920^{+270}_{-330}$ $\left(-4\ 240^{+600}_{-720}\right)$
	Dry ΔW	-90 ± 10 (-190 ± 22)	-3.4 ± 0.4			
10. Triple-point propellants	ΔW	-1810^{+420}_{-1150} $\left(-4000^{+930}_{-2530}\right)$	$-6.2^{+1.4}_{-3.9}$	17.5 <27.1>	23.2 12.7	$-15\ 380^{+3\ 570}_{-9\ 770}$ $\left(33\ 910^{+7\ 880}_{-21\ 380}\right)$
11. Subsystem weight reduction	ΔW	-1360 ± 680 (-3000 ± 1500)	-9.7 ± 4.9	4.8 <7.3>	6.5 4.3	-4 140 ± 2 070 (-9 130 ± 4 570)
12. Integration engineering		Refer to text.				

Note: The symbols < > indicate undiscounted nominal values of added R&T funding <R> and resulting LCC savings <LCC>.

TABLE 11.- Concluded

ΔGLOW, kg (lbm)	Δ\$ $DDT\&E_D$, \$M	Δ\$ $Prod_D$, \$M	Δ\$ OPS_D, \$M	Δ\$ LCC_D, max min <LCC> \$M	Δ\$$LCC_D$ − Δ\$$R_D$, \$M	$\frac{\Delta\$LCC}{\Delta\$R}$	$\frac{\Delta\$LCC_D}{\Delta\$R_D}$ max min
−77 950 ± 11 900 (−171 850 ± 26 240)	15.8	4.5	2.8	$23_{19.6}^{26.6}$ <121>	$12.5_{5.4}^{17.6}$	6.67	$2.19_{1.4}^{2.9}$
−75 700 ± 35 050 (−166 890 ± 77 260)	30.0	8.6	4.1	$43_{22.8}^{62.6}$ <203>	$34.0_{10.2}^{55.3}$	13.33	$4.76_{1.8}^{8.5}$
$-102\ 240_{-47\ 310}^{+40\ 250}$ $\left(-225\ 400_{-104\ 290}^{+88\ 730}\right)$	80.7	11.1	6.1	$98_{59.4}^{143.3}$ <405>	$81.6_{36.5}^{130.7}$	13.16	$5.99_{2.6}^{11.4}$
$-27\ 630_{-23\ 380}^{+17\ 230}$ $\left(-60\ 920_{-51\ 550}^{+37\ 990}\right)$	12.9	4.2	2.6	$20_{7.6}^{36.4}$ <403>	$15.5_{0.4}^{33.1}$	12.66	$4.40_{1.0}^{11.0}$
$-32\ 050_{-31\ 710}^{+8\ 550}$ $\left(-70\ 660_{-69\ 900}^{+18\ 840}\right)$	21.1	6.0	4.1	$31_{22.7}^{61.9}$ <161>	$26.5_{15.9}^{58.4}$	20.0	$6.90_{3.3}^{17.7}$
$-137\ 330_{-110\ 210}^{+45\ 510}$ $\left(-302\ 750_{-242\ 960}^{+100\ 330}\right)$	34.9	9.4	6.5	$51_{34.0}^{91.6}$ <276>	$3.2_{-32.3}^{53.8}$	3.51	$1.07_{0.5}^{2.4}$
−58 660 ± 22 580 (−129 320 ± 49,780)	11.2	2.8	2.5	$17_{9.9}^{23.1}$ <87>	$-9.3_{-25.5}^{4.4}$	2.02	$0.65_{0.3}^{1.2}$
−39,460 ± 22 020 (−86,900 ± 48 550)	8.8	2.8	1.4	$13_{5.7}^{20.3}$ <68>	$2.5_{-8.0}^{12.0}$	3.95	$1.24_{0.3}^{2.4}$
$-22\ 000_{-3\ 740}^{+3\ 120}$ $\left(-48\ 510_{-8\ 240}^{+6\ 870}\right)$	6.0	2.0	1.0	$9_{7.7}^{10.5}$ <46>	$-17.8_{-28.3}^{-9.5}$	1.04	$0.34_{0.2}^{0.5}$
$-133\ 330_{-84\ 080}^{+30\ 970}$ $\left(-293\ 940_{-185\ 360}^{+68\ 270}\right)$	44.8	11.0	−7.0	$49_{37.5}^{79.6}$ <117>	$31.5_{14.3}^{66.9}$	4.31	$2.80_{1.6}^{6.3}$
−33 980 ± 16 990 (−74 910 ± 37 450)	12.0	3.4	1.1	$17_{8.0}^{25.0}$ <79>	$12.2_{1.5}^{18.5}$	10.87	$3.55_{1.3}^{5.9}$

These data, then, can be used with acceptable confidence to arrive at general assessments of the merits of the accelerated research programs. The structures, TPS, and triple-point propellant programs, ranked 1 through 7, are primary candidates for focused, accelerated activities. The advanced propulsion programs, ranked 8 through 11, cannot be expected to have acceptable payoffs, although "normal" focused activities in these research areas are required.

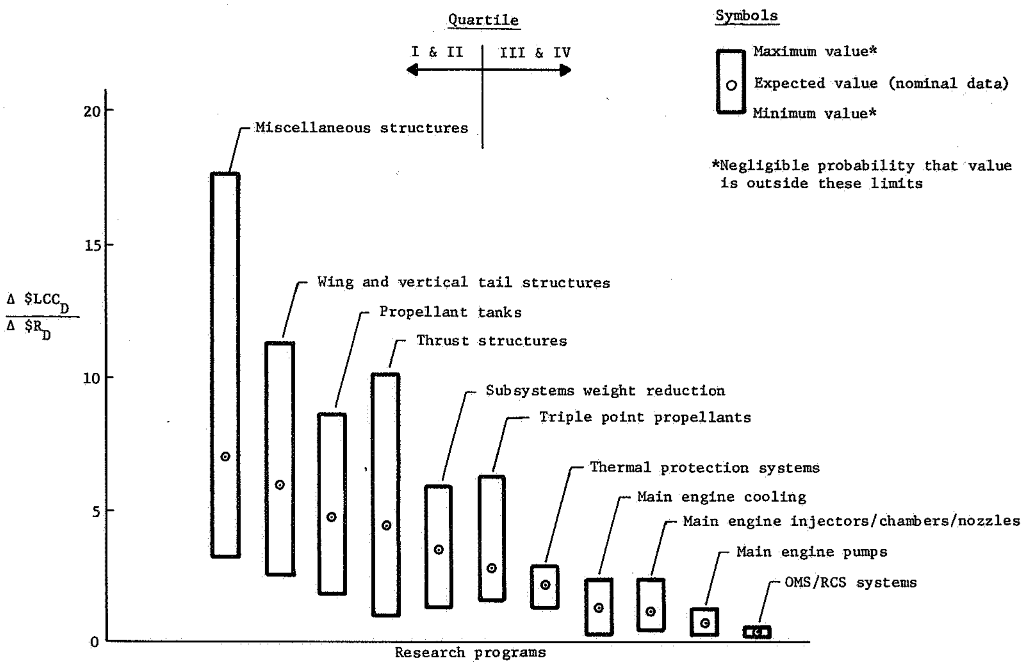


Figure 21.- Figures of merit comparison

The Integration Engineering R&T program is most important, as it provides overall guidance to the R&T programs based on continual evaluations of SSTO design concepts and cost/performance/benefits of related R&T activities. Studies included in the program include continuation in more depth of present study activities, such as research program development and technical management analyses, as well as support technology and configuration analyses. An important goal is to establish specific design criteria, design margin requirements, mission models, and payload definitions as a basis for design engineering. Applications and merits of dual-mode propulsion and controls-configured vehicle (CCV) concepts, for example, have potentially large payoffs and are to be more vigorously pursued in this program. Estimates of the merits of this R&T program were based on assumptions for relaxed stability requirements, reduced design margin requirements, improved aerothermodynamic and design

TABLE 12.- RANKING OF ADVANCED TECHNOLOGY PROGRAMS

Figures of merit		A. $\Delta\$LCC_D/\Delta\$R_D$			B. $\Delta\$LCC/\Delta\$R$			C. $\Delta W_{dry}/\Delta\$R_D$			D. $\Delta\$LCC_D - \Delta\$R_D$		
Research programs													
No.	Title	Rank	Relative Value	Quartile	Rank	Relative Value	Quartile	Rank	Relative Value	Quartile	Rank	Relative Value	Quartile
12.	Integration engineering	0	3.13	I ($\Sigma\$R_D$ = 29.9)	0	2.78	I	0	5.42	I	0	2.27	I
5.	Misc structures	1	1.00		1	1.00		3	0.88		4	0.33	III
3.	Wing & vertical tail structures	2	0.87		3	0.66	II	6	0.75		1	1.00	I
2.	Propellant tanks	3	0.69	II ($\Sigma\$R_D$ = 18.3)	2	0.66		1	1.00		2	0.41	III
4.	Thrust structures	4	0.64		4	0.63		7	0.65	II	5	0.20	IV
11.	Subsystem weight reduction	5	0.51		5	0.54		5	0.85	I	6	0.16	
10.	Triple point propellants	6	0.41	III ($\Sigma\$R_D$ = 28.0)	7	0.22	IV	4	0.86		3	0.39	III
1.	Thermal protection systems (TPS)	7	0.32		6	0.33	III	2	0.89		7	0.15	IV
8.	Main engine cooling	8	0.18	IV ($\Sigma\$R_D$ = 111.4)	8	0.20	IV	8	0.31	III	9	0.04	
6.	Main engine injectors/ chambers/nozzles	9	0.15		9	0.18		9	0.23	IV	8	0.04	
7.	Main engine pumps	10	0.09		10	0.10		10	0.17		10	-0.11	
9.	OMS/RCS systems	11	0.05		11	0.05		11	0.07		11	-0.21	

analysis techniques, and further design optimizations. These estimates yielded FOMs with relative values more than twice as great as any other advanced research program (Table 12), and therefore show that these activities should be vigorously pursued.

EXTENDED PERFORMANCE STUDIES

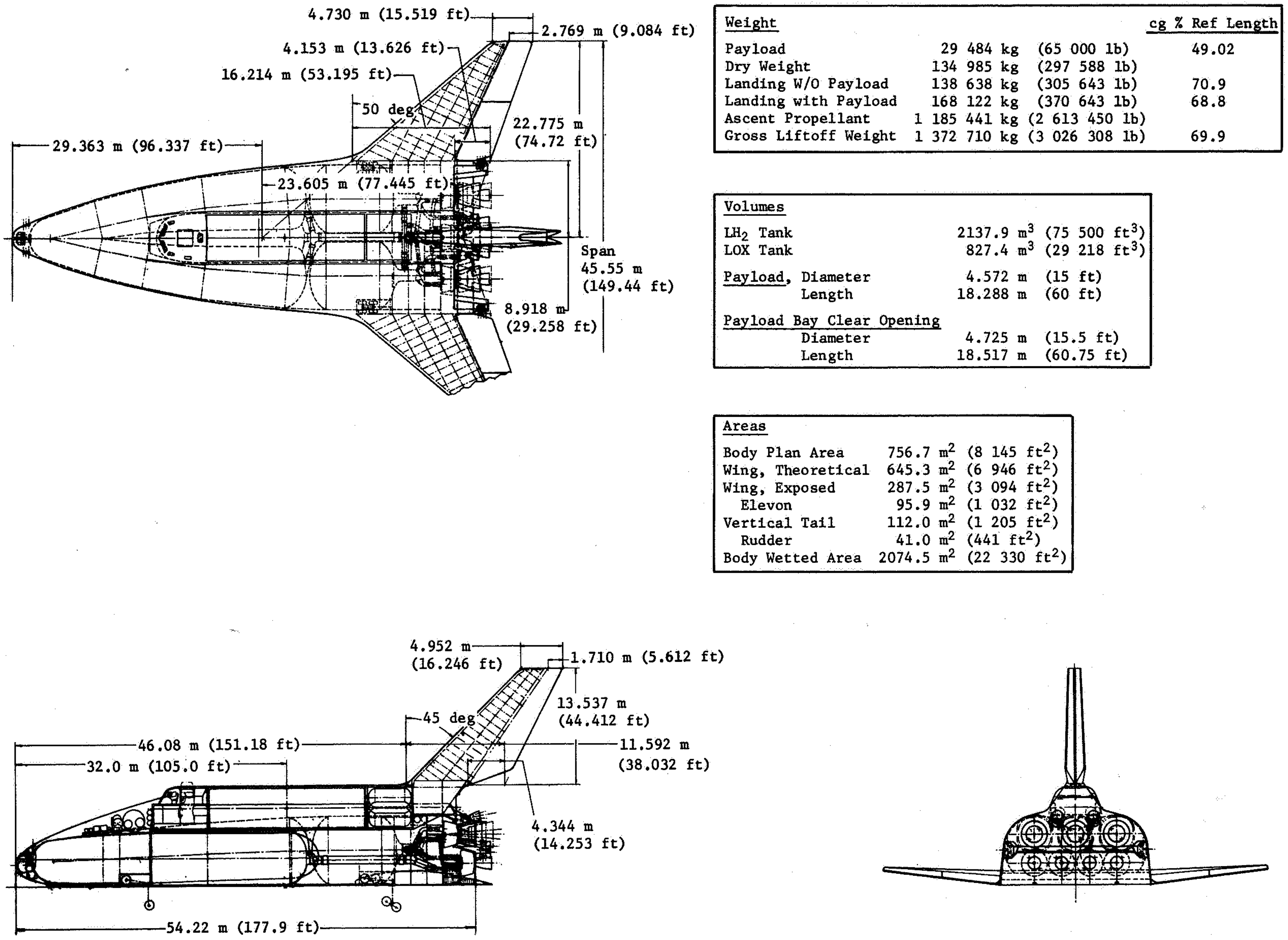
The impact of focused advanced technology programs on vehicle characteristics was developed using both VTO and HTO vehicle concepts. The accelerated technology goals of the Advanced Technology Assessment were applied to these concepts, except that the "normal" technology of the main-engine and OMS/RCS propulsion systems was used. As a representation of program goals of the Integration Engineering R&D program, the static stability guidelines were reduced somewhat; the minimum angle for hypersonic trim was changed from 20 deg to 25 deg, whereas the minimum subsonic lateral directional derivative was changed from 0.002 to 0.0015. These values are representative of current technology and therefore are quite conservative, yet yield significant vehicle dry weight reductions. The advanced vehicle designs, which were developed using the accelerated goals as well as the previous technology assessments, were focus for merit analysis leading to identification of high-yield and critical technology areas.

Vehicle Designs

Based on the previous figure-of-merit analysis, the following advanced technology programs were selected for application to the accelerated performance vehicles: (1) thermal protection systems, (2) propellant tank structure, (3) wing and vertical tail structures, (4) thrust structures, (5) miscellaneous structures, (10) triple-point propellants, (11) subsystems, and (12) integration engineering (represented by reduced subsonic stability margins and reduced hypersonic trim limits). The combined weight advantages from these programs were combined with the projections of "normal" technology in other areas to size new VTO and HTO vehicles. The aerodynamic characteristics were calculated for each vehicle for ascent performance optimization. The mass ratio requirements were then used to obtain near-optimum vehicle weights and sizes.

The inboard profile of the advanced VTO vehicle is shown in Figure 22. The vehicle is similar in concept to the previous VTO vehicle except that the wing and vertical tail areas are smaller relative to the body. The thickness-to-chord ratio of the wing has been increased to 10% at the exposed root. The vehicle has three dual-position nozzle engines and four fixed-position nozzle engines.

The sled-launched HTO vehicle shown in Figure 23 is a wet-wing design concept. Approximately 62% of the oxidizer propellant is in the wing and wing carrythrough box. The oxidizer propellant is transferred to the body tanks by pumps and transfer lines from the aft end of the wing carrythrough box. The wing is configured with a 47 deg leading edge sweep. The main landing gear is housed in the wing structure adjacent to the fuselage oxidizer tank. The aft fuselage is boat-tailed on the sides to minimize drag and meet rocket engine packaging requirements. The main engines are three dual-position nozzle and two fixed-position nozzle configurations. The mass properties are summarized in Table 13 for the VTO and HTO vehicles. The dry weights of the VTO and HTO vehicles are 61 940 kg (136 554 lb) and 42 949 kg (94 686 lb) less than the vehicles designed with "normal" technology gorwth.

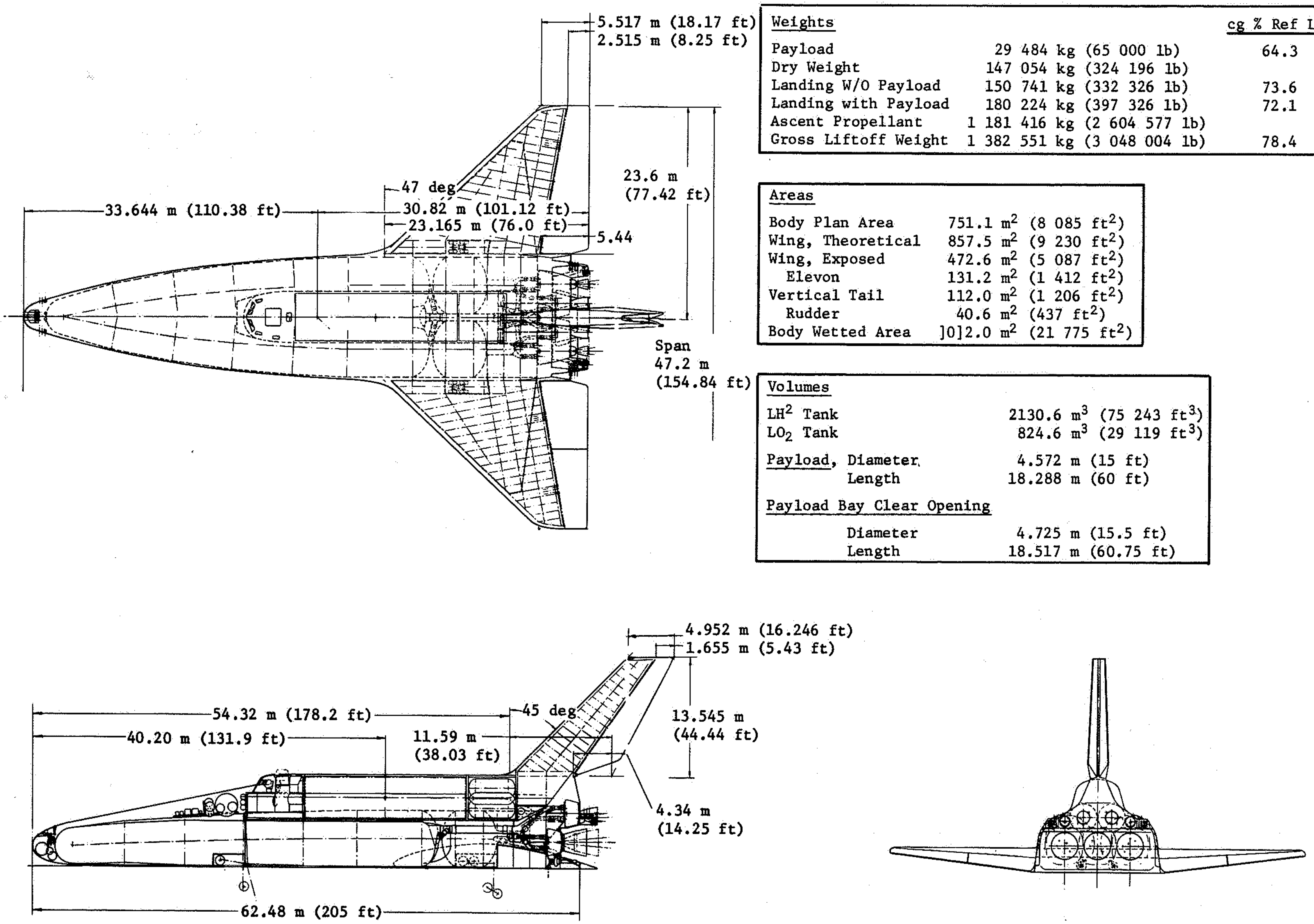


Weight			cg % Ref Length
Payload	29 484 kg	(65 000 lb)	49.02
Dry Weight	134 985 kg	(297 588 lb)	
Landing W/O Payload	138 638 kg	(305 643 lb)	70.9
Landing with Payload	168 122 kg	(370 643 lb)	68.8
Ascent Propellant	1 185 441 kg	(2 613 450 lb)	
Gross Liftoff Weight	1 372 710 kg	(3 026 308 lb)	69.9

Volumes		
LH_2 Tank	2137.9 m^3	(75 500 ft^3)
LOX Tank	827.4 m^3	(29 218 ft^3)
Payload, Diameter	4.572 m	(15 ft)
Length	18.288 m	(60 ft)
Payload Bay Clear Opening		
Diameter	4.725 m	(15.5 ft)
Length	18.517 m	(60.75 ft)

Areas		
Body Plan Area	756.7 m^2	(8 145 ft^2)
Wing, Theoretical	645.3 m^2	(6 946 ft^2)
Wing, Exposed	287.5 m^2	(3 094 ft^2)
Elevon	95.9 m^2	(1 032 ft^2)
Vertical Tail	112.0 m^2	(1 205 ft^2)
Rudder	41.0 m^2	(441 ft^2)
Body Wetted Area	2074.5 m^2	(22 330 ft^2)

Figure 22.- Accelerated performance, VTO inboard profile



Weights		cg % Ref Length
Payload	29 484 kg (65 000 lb)	64.3
Dry Weight	147 054 kg (324 196 lb)	
Landing W/O Payload	150 741 kg (332 326 lb)	73.6
Landing with Payload	180 224 kg (397 326 lb)	72.1
Ascent Propellant	1 181 416 kg (2 604 577 lb)	
Gross Liftoff Weight	1 382 551 kg (3 048 004 lb)	78.4

Areas	
Body Plan Area	751.1 m^2 (8 085 ft^2)
Wing, Theoretical	857.5 m^2 (9 230 ft^2)
Wing, Exposed	472.6 m^2 (5 087 ft^2)
Elevon	131.2 m^2 (1 412 ft^2)
Vertical Tail	112.0 m^2 (1 206 ft^2)
Rudder	40.6 m^2 (437 ft^2)
Body Wetted Area	]0]2.0 m^2 (21 775 ft^2)

Volumes	
LH^2 Tank	2130.6 m^3 (75 243 ft^3)
LO_2 Tank	824.6 m^3 (29 119 ft^3)
Payload, Diameter	4.572 m (15 ft)
Length	18.288 m (60 ft)
Payload Bay Clear Opening	
Diameter	4.725 m (15.5 ft)
Length	18.517 m (60.75 ft)

Figure 23.- Accelerated performance, HTO inboard profile

TABLE 13.- ADVANCED VTO AND HTO MASS PROPERTIES

Item	VTO		HTO	
	kg	(lbm)	kg	(lbm)
Dry weight	134 985	297 588	147 054	324 196
Landing weight without payload	138 638	305 643	150 741	332 326
Payload	29 484	65 000	29 484	65 000
Landing weight with payload	168 122	370 643	180 224	397 326
GLOW	1 372 710	3 026 308	1 382 551	3 048 004
Sled run propellant			19 751	43 543
Gross weight	1 372 710	3 026 308	1 402 302	3 091 547

These designs of extended performance vehicles are based on the nominal research goals projected for selected, focused, advanced technology programs. The advanced HTO sled-launched vehicle uses cryogenic wet-wing technology, which is required to be addressed with advanced R&T. Also, the main engines are ignited while the sled is accelerating near the end of the sled run. Advanced technology is required to develop this technique and to confirm the reliability of ignition in this acceleration environment.

Merit Analysis and Risk Assessment

Research program assessments.- Application of goals of accelerated technology in the combined areas of structures, TPS, triple-point propellants, and integration engineering have resulted in VTO and HTO designs that are much lighter and cost less (Table 14) than the designs based on "normal" technology growth. These results support the previous assessments of the potential beneficial payoffs in these technology areas. Further estimates of vehicle weights and program costs have been made applying other combinations of the goals of accelerated programs to vehicle design.

TABLE 14.- FIGURES OF MERIT FOR ADVANCED PROGRAM COMBINATIONS

Combined technology programs	ΔW_{dry} kg (pounds)	Δ GLOW kg (pounds)	$\Delta\$R_D$ <Δ$R> $M	Δ$LCC <Δ$LCC> $M	$\frac{\Delta\$LCC_D}{\Delta\$R_D}$	Savings, $\Delta\$LCC_D-\Delta\$R_D$	Total Cost $LCC_D+\Delta\$R_D$
1, 2, 3, 4, 5, 10, 11 and 12 applied to VTO	-63 451 (-139 885)	-542 272 (-1 195 506)	76.2 <131.0>	257 <1206>	3.37	180.8	2126.2
1, 2, 3, 4, 5, 10, 11 and 12 applied to wet-wing HTO	-42 949 (-94 686)	-369 724 (-815 101)	76.2 <131.0>	293 <1376>	3.85	216.8	2213.2
1, 2, 3, 5, 10, and 12 applied to VTO	-60 584 (-133 565)	-526 434 (-1 160 589)	66.9 <115.5>	255 <1197>	3.81	188.1	2073.9
All applied to VTO	-73 228 (-161 440	-681 430 (-1 502 296)	187.6 <314.4>	300 <1408>	1.60	112.4	2239.6

Note: The symbols < > indicate undiscounted nominal values of added R&T funding <R> and resulting LCC savings <LCC>.

One result of interest (Table 14) is obtained by combining nominal goals of all programs as this indicates an optimistic limit if additional research fundings were available for all. A second combination is obtained by selecting those research programs that exhibit a minimum, no risk, life-cycle cost savings of at least 1% of the VTO baseline cost. The advanced main-engine program 6 is excluded because its minimum LCC savings are less than the research costs. This combination includes programs 1, 2, 3, 5, 10, and 12.

Assessment of these results together with the individual program results of Tables 11 and 12 concludes that the high-yield advanced technology areas are materials and structures, TPS, triple-point propellants, and engineering integration programs 1, 2, 3, 4, 5, 10, 11, and 12. Meaningful combinations such as this show that total R&T funding would be increased about $12M/year (undiscounted) over normal funding (cf. Figure 7).

An analysis to assist in identifying time-critical technology areas was to estimate the maximum acceptable delays in starting accelerated research without incurring high risks. The time spans of high activity in the R&T programs and related DDT&E were estimated based on the previous schedules. The guideline data of 1987 for ATP and the same total research funding as estimated previously were assumed. The results were as follows:

Technology areas	Maximum delay, years
Wing and fin structures	1
Triple-point propellants, integration engineering	2
TPS, propellant tanks, propulsion systems	3
Thrust and miscellaneous structures, subsystem weight reduction	4

Assessments of high-yield and critical areas are presented in Table 15 for both "normal" and advanced technology growth. High-yield areas are those which have shown acceptable figures-of-merit. Critical areas are those that reflect technology concerns that must be addressed for successful development of an advanced earth-orbital transportation system. These concerns are indicated in the table.

System development schedule assessments.- Possibilities for accelerating the SSTO system development schedule have been assessed. The perturbed schedule which represents results of this assessment is shown in Figure 24. This accelerated schedule is based on the schedules for advanced research programs, as well as considerations of development, test, and production without incurring high risks of schedule delays. This assessment concluded that relative to the guideline schedule (Figure 20) the start of DDT&E could be advanced by approximately three years, whereas the FMOF and IOC could be advanced by one year, without incurring any significant increase in schedule risks.

TECHNOLOGY RECOMMENDATIONS

Recommendations of "normal" technology and advanced technology areas that should be vigorously pursued are discussed in this section.

Thermostructures

Development of lightweight composite materials and structures are important for application to aerosurfaces, thrust structures, miscellaneous structures, and subsystems. Research

TABLE 15.- HIGH YIELD AND CRITICAL TECHNOLOGY ASSESSMENTS

	"Normal" growth (focused)		Accelerated growth	
Technology area	High yield	Critical	High yield	Critical
1 Thermal protection systems				
Reusable surface insulation	X	X Reusability for more than 100 missions must be demonstrated	X	
2 Propellant tanks				
Dry wings	X		X	
Wet wings (applied to HTO)	X	X Large wet wing cryogenic tank technology must be developed Lightweight pressurized structures Propellant utilization	X	
3 Wing and vertical tail structures				
Composite materials	X		X	
4 Thrust Structures				
Composite materials	X		X	
5 Miscellaneous structures				
Composite materials	X		X	
6,7,8 Main engine propulsion				
Multiposition nozzles	X	X 2-position nozzle development is required Extension/retraction Nozzle cooling Seals Dynamic loads		
9 RCS/OMS	Research not high yield nor critical			
10 Triple-point propellants	Not being vigorously pursued at present time		X	X (Based on timeliness) Technology for large scale applications must be developed Manufacture and storage
11 Subsystems weight reduction	X		X	
12 Integration engineering Design integration Design criteria	X	X Continued focusing of technology and evaluations of SSTO concepts are needed	X	

High yield: 1) Attractive cost/performance/benefits and/or dry weight improvements.
2) Technology not highly developed at present (1975-1976).

Critical: 1) Technology development is necessary for SSTO cost and performance success.
2) Timely, near future, focus on SSTO-related research is recommended.

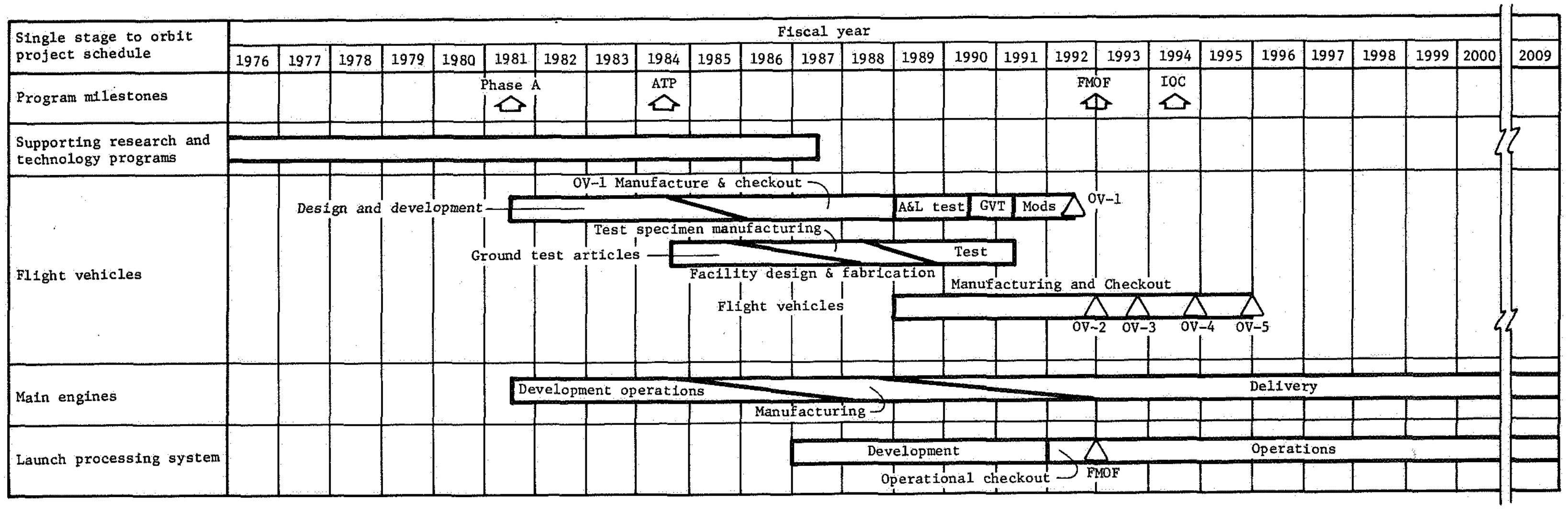


Figure 24.- Accelerated total system development plan

activities should address material improvements, material characterization, design analysis, and fabrication technology. Near-term accelerated research should be applied to technology related to composites for use in primary structures, in particular, aerosurfaces, intertank and thrust structures, and subsystem interfaces.

Integral, load-carrying membrane propellant tanks can be developed using normal aluminum alloys applied to multilobe and isogrid structural designs. Research related to tank design should focus on improving loads and failure prediction analysis and testing techniques applied to multilobe designs with the goals of minimizing weight by reducing design margin requirements and nonoptimum factors. Environmental criteria for research and concept analysis should include triple-point propellant requirements.

Thermal Protection Systems

Thermal protection systems (TPS) will require materials such as reusable surface insulation (RSI), reinforced carbon-carbon (RCC), flexible RSI, ceramics, and metallics. Related research should focus on improved materials, characterization of physical properties, fabrication techniques, testing techniques, structural design (including interfaces with primary structures), performance analysis methods, maintenance, and refurbishment. A critical requirement is to demonstrate reusability of TPS for 100 to 500 reentry cycles.

Accelerated research in TPS technologies should focus on reducing weight and costs of reusable RSIs, and on efficient interfaces among various sections of the vehicle that have different TPS materials or TPS thicknesses. Inasmuch as RSI technology is relatively young, there may be large, unforeseen payoffs from accelerated research. This potential should be considered in evaluating allocations of advanced funding.

Propulsion Systems

Normal propulsion research in the near future should provide sufficient engine parametrics applied to SSTO vehicle concepts to establish the merits of concepts other than LO_2/LH_2

bell-nozzle engines and should also focus on technology related to multiposition bell nozzles, which are critical to SSTO performance. Specific areas of concern are fast-acting extension-retraction mechanisms operable without engine shutdown, means for cooling the extended nozzles, sealing the interface between nozzle segments, and dynamic loads during extension.

Research has been applied to use of triple-point/slush propellants, but this activity is small. Normal growth in this area, therefore, is considered to be inadequate for SSTO applications.

Auxiliary propulsion systems, such as for OMS and RCS, should be continued to be improved by research focused toward LO_2/LH_2 systems for SSTO applications. Normal technology growth is projected to be adequate.

Integration Engineering

The conceptual design and analysis activities are being pursued to identify SSTO program concepts and technology requirements and assessments, as exemplified by the current study. Other supporting research activities were projected to continue, including integrated-computer-aided-design synthesis, wind tunnel testing of configuration concepts, aerothermodynamic analysis, and performance optimization. Additional near-term, normal activities should focus on further assessments of dual-mode engines, controls-configured vehicles (CCV), and payload effects on vehicle design. Future activities should focus on establishing in more depth mission and payload requirements, design criteria and design margins, research requirements, and cost/performance/benefit assessments.

Normal Space Shuttle program developments during the next 14 years will provide an efficient operations system base for SSTO operations. The R&T activities should focus on improved computerization and software techniques for automating repetitive and redundant functions, and on improved data-link systems. Inasmuch as liquid hydrogen costs have inflated greatly (more than doubled in 1975), research should focus toward achieving low-cost hydrogen production.

Advanced R&T should also focus on parametric design, research requirements, and cost analyses for SSTO systems using guidelines other than those anticipated with "normal" technology funding to support detailed recommendations for allocating relevant R&T resources.

CONCLUSIONS

A fundamental goal of this study was to identify important areas of technology associated with future earth-orbit transportation systems. These systems were represented by reuseable, single-state-to-orbit vehicle concepts with vertical and horizontal (sled-launched and inflight-fueled) takeoff capabilities. Payload and mission requirements were similar to Space Shuttle, which the SSTO system could replace in 1995.

The study goal was pursued by a sequence of analyses that included projecting "normal" technology growth over the next ten to fifteen years, applying the technology to vehicle designs, and calculating total program (life cycle) costs. Assessments of advanced technology were then made, projecting goals that could be achieved in accelerated research programs. Assessments were aided by developing figures of merit that reflected cost-performance benefits. The advanced goals were then applied to vehicle designs and program costs, providing a basis for assessments of high-yield and critical areas of technology.

The major results of the study are as follows:

(1) Single-stage-to-orbit concepts have exceptionally worthwhile cost-performance merits as advanced earth-orbital transportation systems using "normal" technology growth.

(2) Guidelines of this study led to the specific design concepts of this report. Changes to the guidelines such as reduced dry-weight margins, relaxed stability criteria, and other main-engine and propellant combinations can lead to smaller and lighter vehicles for the same payload requirement. Such guideline changes, however, would not affect the major conclusions that identify technology requirements, except for propulsion.

(3) Assessments of the potential benefits of advanced technology indicate the high-yield areas that should be vigorously pursued are thermal protection systems, propellant tanks, wing and vertical tail structures, thrust structures, miscellaneous structures, triple-point propellants, subsystem weight reduction, and integration engineering.

(4) Critical areas of technology are the reusability demonstration of RSI materials for more than 100 missions, the development of main engines with multiposition nozzles, and the continuing evaluations of vehicle concepts and supporting technology. Also, wet-wing technology is critical for HTO concepts. Advanced growth technology requires timely emphasis on large-scale applications of triple-point propellants, in particular, their manufacturing and storage requirements.

(5) Projections of "normal" technology growth over the next ten years indicated that overall improvements over today's technology will result in a vehicle dry-weight saving of 16% or more. Advanced growth in selected technologies would increase this saving to 27% or greater.

(6) Evaluations of thermostructural concepts indicated weight and technology advantages for using primary fuselage structures composed of integral, multilobe, load-carrying aluminum propellant tanks, protected from entry heating by RSI materials. Advanced composities were selected for primary structures in the wings and vertical tail, as well as for other structural elements. This concept is applicable to both VTO and HTO vehicles.

(7) Comparison of linear and bell-nozzle main engines for the SSTO resulted in selection of high-pressure staged combustion bell-nozzle engines, similar to the SSME. The selected configurations include both fixed nozzle and dual-position nozzles. Unless future studies by engine manufacturers show significant potential improvements in linear engine performance and weight, they do not appear to be competitive with bell-nozzle engines in SSTO applications.

(8) The VTO vehicle is optimized better with dry wings, whereas the HTO vehicle is better with wet wings.

(9) The inflight-fueled vehicle concept is not feasible because it requires unique technology for rendezvous and for large-scale propellant transfer, and it requires development of tanker aircraft that would be considerably larger than heavy aircraft now in use.

(10) Additional studies are required to establish the cost-performance benefits of linear and dual-mode engines. Other advanced main engine concepts, such as vehicle-integrated nozzles (e.g., body flaps) and air-augmented (composite) engines, appear to be beyond the time span of Space Shuttle follow-on vehicles.

(11) Future low-recurring costs can be achieved by continued and expanded emphasis on use of new operations technology that includes automation, computerization and combinations of functions of flight and mission operations.

(12) Further studies of SSTO concepts applied to other payload and mission models, and with control-configured vehicle concepts, are recommended to demonstrate their payoffs as advanced transportation systems.

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