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TECHNOLOGY REQUIREMENTS FOR ADVANCED EARTH-ORBITAL TRANSPORTATION SYSTEMS, DUAL-MODE PROPULSION

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16. Abstract

The present study addresses the application of dual-mode propulsion concepts to fully reusable single-stage-to-orbit (SSTO) vehicles. Dual-mode propulsion uses main rocket engines that consume hydrocarbon fuels as well as liquid hydrogen fuel. Liquid oxygen is used as the oxidizer. These engine concepts were integrated into transportation vehicle designs capable of vertical takeoff, delivering a payload to earth orbit, and return to earth with a horizontal landing. Benefits of these vehicles were assessed and compared with vehicles using single-mode propulsion (liquid hydrogen and oxygen engines).

Technology requirements for such advanced transportation systems were identified. Figures of merit, including life-cycle cost savings and research costs, were derived for dual-mode technology programs, and were used for assessments of potential benefits of proposed technology activities. The results of this study show that dual-mode propulsion concepts have the potential for significant cost and performance benefits when applied to SSTO vehicles.

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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, Final Report

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.

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SUMMARY

Advanced earth-orbital transportation systems are being studied to identify their potential cost and performance benefits and to determine their future technological requirements. The present study addresses the application of dual-mode propulsion concepts to fully reuseable single-state-to-orbit (SSTO) vehicles. Dual-mode propulsion uses main rocket engines that consume hydrocarbon fuels as well as liquid hydrogen fuel Liquid oxygen is used as the oxidizer.

The performance, weight, and size characteristics of these dual-mode engine concepts have been based on results of recent NASA-sponsored analyses of typical engines. These engine concepts were integrated into transportation vehicle designs capable of vertical takeoff, delivering a 29 484 kg (65 000-pound) payload to earth orbit, and return to earth with a horizontal landing. Benefits of these vehicles were assessed and compared with vehicles using single-mode propulsion (liquid hydrogen and oxygen engines).

Technology requirements for such advanced transportation systems were identified. Figures of merit, including life-cycle cost savings and research costs, were derived for dual-mode technology programs, and were used for assessments of potential benefits of proposed technology activities. The results of this study show that dual-mode propulsion concepts have the potential for significant cost and performance benefits when applied to SSTO vehicles.

INTRODUCTION

The Space Shuttle is being developed to take scientific, commercial, and military payloads into Earth orbit throughout the 1980 to 1995 time period. The Space Shuttle program provides a space transportation capability that is timely and cost effective using the best technology now available.

During the next 20 years, various advancements in technology can be anticipated that have the potential to reduce the costs of such transportation significantly. For example, lighter structures, more efficient rocket motors, improved design and manufacturing techniques, and better launch and flight operations can all lead to reduced size and costs of the future vehicle program.

These advancements can be enhanced by focusing research activities toward meeting technological goals that are related to specific needs of these space transportation systems. A major step toward authorizing and directing this research is to identify the main technology requirements of the future systems that yield the highest potential payoffs in cost and performance benefits.

Historically, as much as 10 or 12 years lead time is required to initiate and carry out research programs that will yield the necessary technology knowledge. A further six or eight years is required for design and development. A system that is to be operational in 1995 requires that its research goals be addressed now.

These factors have led to the present study to identify technology requirements of advanced space transportation systems (ref. 1). As a focal point for these considerations, typical mission and vehicle design guidelines were defined. These systems would provide cost-effective means to place payloads in orbit during the 1995 to 2010 time period, subsequent to successful operations with the Space Shuttle beginning in 1980. A guideline of this study was to carry a Space Shuttle-like payload of 29 484 kg (65 000 pounds) into orbit using a reuseable single-stage-to-orbit (SSTO) vehicle, and return it to earth with a horizontal landing. The study began with analyses of vehicle concepts that used main rocket engines burning liquid hydrogen and liquid oxygen only. Technological projections of the future performance, weight, and size characteristics of such engines were based to a large extent on the Space Shuttle Main Engine (SSME), upgraded to represent an additional 10 years of technology advancements.

While these analyses were under way, characteristics of advanced engines related to dual-mode propulsion were being developed at Aerojet Liquid Rocket Company under NASA sponsorship (ref. 2). Dual-mode propulsion is a means to improve vehicle performance by using a high density hydrocarbon fuel at liftoff and switching later in the flight to a low density liquid hydrogen fuel. This engine study provided parametric data relating engine performance, weight, and size to engine thrust, chamber pressure, and nozzle expansion ratio. The availability of these data made it feasible to extend the SSTO technology requirements study to include dual-mode propulsion. One of the fuels studied, RP-1 (ref. 2), was selected to represent a typical hydrocarbon for this investigation.

Previous reports presented the concepts and discussed potential benefits of dual-mode propulsion (ref. 3, 4, and 5). These, supported by further in-house studies at NASA Langley Research Center, provided technical bases and incentives for more detailed parametric analyses and point designs of SSTO vehicles as represented in the present study.

The dual-mode propulsion study, reported here, has the purpose of evaluating the potential cost/performance benefits of dual-mode compared to single-mode (liquid hydrogen fuel only) propulsion as applied to SSTO vehicles with vertical takeoff (VTO) and horizontal landing characteristics. Conceptual designs of vehicles are described using advanced technology projections to provide a focus for assessing the relative merits of the advanced technology and for identifying critical technology areas. These projections use the results of the preceding single-mode study, which identified high-yield and critical technologies, together with results of the engine study, which provided the characteristics of advanced-technology dual-mode propulsion. Both parallel and series propulsion concepts are applied to VTO vehicle designs. Life-cycle costs and research program costs are calculated and used as a basis for determining figures of merit. These are used to aid in the assessments of the potential benefits of dual-mode propulsion relative to single-mode propulsion. This study activity is a continuation of the study and results of reference 1, and the relative assessments and conclusions are consistent with and augment those of reference 1.

SYMBOLS

C*	characteristic velocity
F_{vac}	engine vacuum thrust
F/W	thrust/weight ratio
FOM	figure of merit
GLOW	gross liftoff weight
g	acceleration of gravity
h	altitude
I_{sp}	specific impulse
LH_2	liquid hydrogen
LO_2	liquid oxygen
M	mach number
MR	mass ratio, GLOW/WBO
NPSH	net positive suction head
n_x	force in x-direction/weight
n_z	force in z-direction/weight
O/F	oxidizer-to-fuel mixture ratio
P_A	atmospheric pressure
P_C	thrust chamber pressure
q	dynamic pressure
RP-1	hydrocarbon fuel, type RP-1
RSI	reuseable surface insulation
SL	sea level

T	temperature
TPS	thermal protection system
t	time
VTO	vertical takeoff
W	weight
WBO	burnout weight
WP	ascent propellant weight
WPL	payload weight
W_L	landing weight
$\dot{W}$	propellant flow rate
x, y, z	vehicle coordinate axes
α	angle of attack
ΔW_{DRY}	dry weight increment
Δ\$LCC	undiscounted life-cycle cost increment
Δ\$$LCC_D$	discounted life-cycle cost increment
Δ\$R	undiscounted research cost increment
Δ\$$R_D$	discounted research cost increment
ΔV_1, ΔV_2	mode 1, 2 velocity increment
ΔV^*	ideal total velocity increment
ε	nozzle expansion ratio

Subscripts:

1	mode 1
2	mode 2
c.g.	center of gravity

SL	sea level
T	Total

TECHNOLOGY BASE

Identification of Technologies

The research study reported in reference 1 identified technology areas that were highly important to development of future single-stage-to-orbit (SSTO) advanced earth-orbital transportation systems. The main technology drivers were materials, structures, and propulsion. Within these categories, specific technology areas were selected for analysis to identify those areas with the greatest potential payoffs. As part of this analysis, research goals were projected, looking forward to an ATP (authority to proceed) for vehicle design in 1987. These goals, described as weight or specific-impulse performance improvements, were projected both for "normal" and for "accelerated" technology growth. The "accelerated" goals would require additional R&T activities and funding during the next ten years above and beyond those projected as results of "normal" activities and funding. The goals were applied to vehicle designs and life-cycle costs to derive figures of merit (FOM) as a basis for defining the relative payoffs of the R&T programs and identifying the high yield and critical technology areas. The main propulsion systems were constrained to use LO_2/LH_2 propellants (single-mode). Design guidelines for these vehicles are summarized in table 1.

Based on the FOMs, eight technology areas were identified (ref. 1) as offering significant potential payoffs for accelerated technology growth. These areas were as follows:

(1) Thermal protection systems (TPS);

(2) Propellant tanks;

(3) Wing and fin structure;

(4) Thrust structure;

(5) Subcooled propellants;

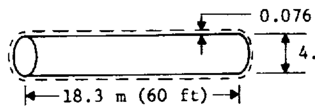
(6) Subsystem weights;

(7) Miscellaneous structures;

(8) Integration engineering (including launch and flight operations).

These programs, as well as propulsion programs, were described, with their decreased weight and increased performance goals, in

TABLE 1.- 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.

reference 1. The goals for these advanced programs, combined with goals for "normal" technology advancement in other areas, were used in the sizing of vertical takeoff (VTO) and horizontal takeoff sled-launched (HTO) vehicles.

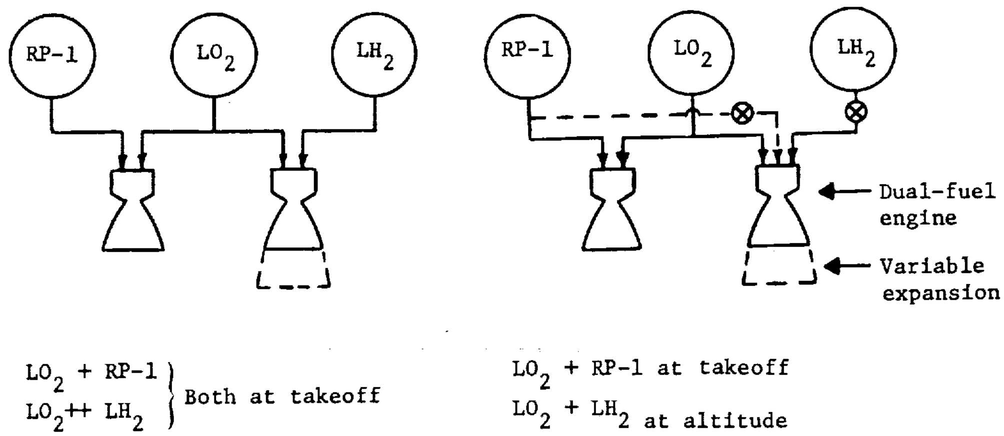
The results of these activities included vehicle designs using thermostructural concepts with insulated structures and LO_2/LH_2 engines. The VTO vehicle design using the eight accelerated technology goals (combined with normal goals in other areas) later was selected to be used in the present study as a reference for comparing the potential merits of dual-mode propulsion concepts applied to SSTO vehicle programs. (This single-mode VTO vehicle is described in the next section. The technology base for the dual-mode propulsion is then presented).

Dual-mode propulsion, figure 1, uses a high-density hydrocarbon (such as RP-1) in the early flight phases, and uses a high performance fuel (liquid hydrogen) in later flight phases. The parallel burn concept shown in figure 1(a) uses two types of engines at launch, one type burning RP-1 with liquid oxygen (LO_2), the second type burning LH_2 with LO_2. As the flight progresses, the RP-1 engines are throttled and then shut down, continuing on the LH_2 engines alone. The LH_2 engines have two-position nozzles. The series burn concept shown figure 1(b) uses a LO_2/RP-1 engine type and a dual-fuel engine type which burns LO_2/RP-1 at launch and later switches fuels from RP-1 to LH_2. The dual-fuel engines also have two-position nozzles.

Reference VTO Vehicle

The accelerated technology VTO vehicle with single-mode (LO_2/LH_2) propulsion is shown in figure 2. This vehicle design, developed in reference 1, is used as the reference single-mode vehicle for developing and for comparing the further benefits of dual-mode propulsion.

Mass properties for this vehicle are summarized in table 2. The vehicle is 52.3 meters (171.6 ft) long and has a liftoff weight of 1 207 219 kg, (2 661 463 lb). It is equipped with three dual-position nozzle engines and four fixed nozzle engines, all using LO_2/LH_2 propellants. The dual position nozzles are gimabled. The liftoff acceleration is 1.3 g. Payload capability to the required 93 km (50 n mi) perigee, 186 km (100 n mi) apogee easterly orbit is 29 484 kg (65 000 lb).



(a) Parallel burn

(b) Series burn

Figure 1.- Dual-mode propulsion terminology

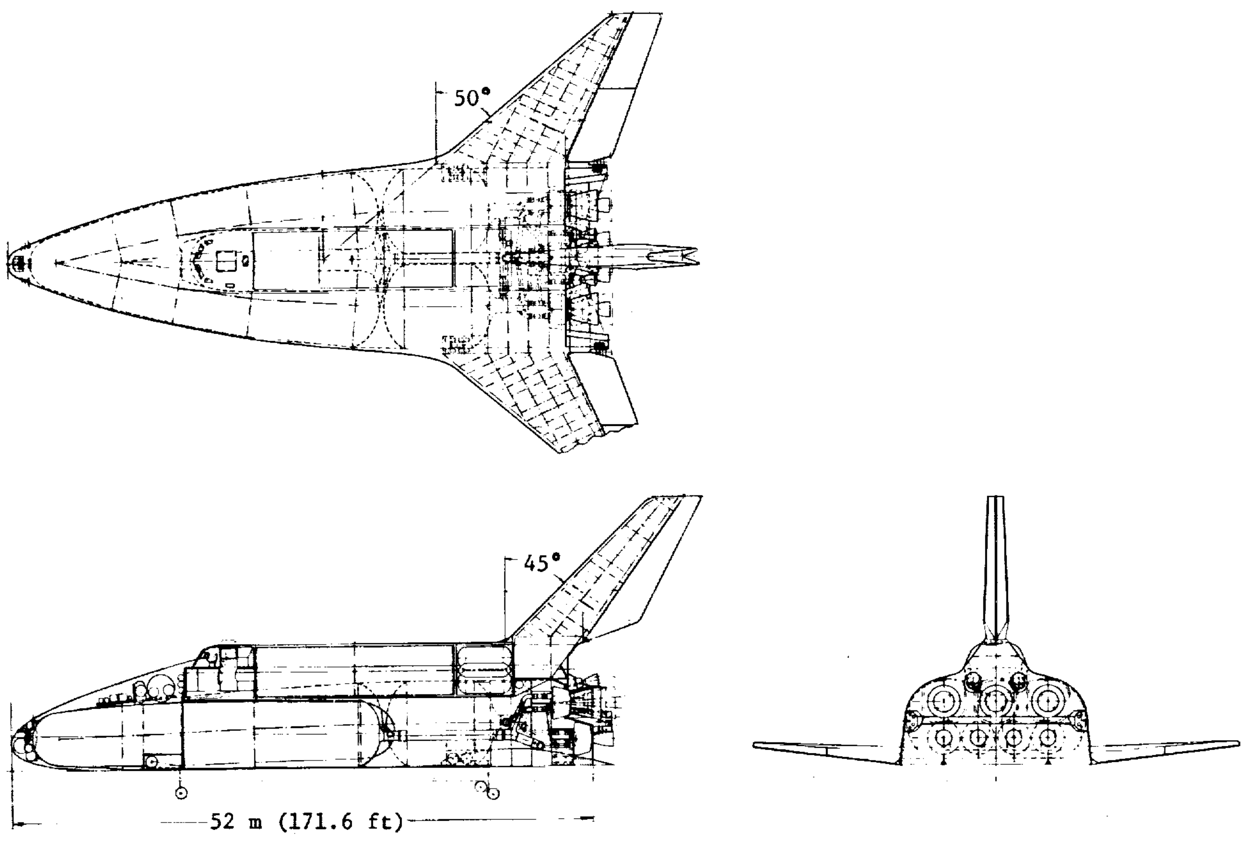


Figure 2.- Accelerated technology VTO vehicle (single-mode propulsion)

TABLE 2.- REFERENCE VTO (ACCELERATED TECHNOLOGY) MASS PROPERTIES SUMMARY

Code	System	Mass, kg		Weight, pounds	
1.0	Wing group	7 049		15 541	
2.0	Tail group	1 857		4 094	
3.0	Body group	33 441		73 725	
4.0	Induced environmental protection	22 366		47 103	
5.0	Landing and auxiliary systems	4 211		9 284	
6.0	Propulsion ascent	24 623		54 285	
	6.1 Engine accessories		1 139		2 510
	6.2 Feedlines		2 487		5 483
	6.3 Engines		20 997		46 292
7.0	Propulsion-RCS	1 444		3 183	
8.0	Propulsion-OMS	1 068		2 355	
9.0-	Prime power				
10.0	Electrical conversion and distribution	3 050		6 724	
11.0	Hydraulic conversion and distribution	1 464		3 228	
12.0	Surface controls	1 542		3 400	
13.0	Avionics	1 965		4 333	
14.0	Environmental control	1 721		3 795	
15.0	Personnel provisions	499		1 100	
18.0	Payload provisions	270		595	
19.0	Margin	8 457		18 645	
	Dry weight	114 029		251 390	
20.0	Personnel	1 199		2 644	
23.0	Residuals and gases	2 202		4 854	
	Landing weight	117 430		258 888	
22.0	Payload	29 484		65 000	
	Landing with payload	146 913		323 888	
23.0	Residuals dumped	5 843		12 882	
25.0	Reserve fluids	3 014		6 644	
26.0	Inflight losses	1 613		3 555	
27.0	Ascent propellant	1 041 766		2 296 700	
28.0	Propellant-RCS	1 220		2 690	
29.0	Propellant-OMS	6 851		15 104	
	GLOW	1 207 219		2 661 463	

Center of gravity: Body length = 52.3 m (171.6 ft)

Condition	$X_{c.g.}$, % of body length
Dry	69.23
Landing	68.90
Landing with payload	66.89
Liftoff	65.18

The thermostructural materials selected for the vehicle concepts of this study are illustrated in figure 3. The propellant tank material is aluminum of the 2219 alloy family. The fuselage nontank skirt structural material is advanced composite construction using the graphite/epoxy family. The engine mount beam structure is also constructed of graphite/epoxy. The aerosurfaces are constructed of borsic/aluminum skins and boron/epoxy substructure. The payload bay doors and the vertical tail support structure are also borsic/aluminum skins and boron/epoxy substructure. The borsic/aluminum skin was used to provide a higher heat sink capacity for external TPS sizing than graphite/epoxy.

The TPS for the wing, vertical tail, and payload-vertical tail support structure is direct bond RSI with strain isolator and direct bond FRSI (flexible reuseable surface insulation) on the areas where heating is 700°F or less. The fuselage-tank module TPS is RSI mounted on graphite/epoxy sandwich subpanels, supported by aluminum rails.

Propulsion Characteristics

LO_2/LH_2 Engines.- For those SSTO vehicles incorporating LO_2/LH_2 engines, the engine performance and weights were continued at the technology levels identified in reference 1 and used for the reference VTO vehicle design. These engines were considered to be growth SSME-type engines operating at 98 percent of theoretical performance. The engine nozzles were two-position extendible. For the reference VTO single-mode vehicle the engines have the following characteristics:

	Single Position	Two Position
Number per vehicle	3	4
Thrust, SL - 10^3 N (10^3 lbf)	2198 (494)	2198 (494)
Thrust, vacuum - 10^3 N (10^3 lbf)	2462 (553)	2554 (574)
I_{sp}, SL - sec	399.0	399.0
I_{sp}, vacuum - sec	445.2	466.3
Engine weight - kg (lbm)	1865 (4112)	3850 (8489)
Chamber pressure - 10^6 N/m^2 (psia)	27.6 (4000)	27.6 (4000)
Expansion ratio	55	55/200

LO_2/RP-1 and dual fuel engines.- Parametric engine performance and weight data supplied by NASA/Lewis Research Center from the Aerojet Liquid Rocket Company Advance high pressure engine study (ref. 2) was used to describe LO_2/RP-1 and dual-fuel engines. Later information updated the initial parametric data to reflect propellant isolation requirements with consequent increased engine weights of approximately 454 kg (1000 lbm) for the dual-fuel engine. Additionally, the gas generator cycle LO_2/RP-1 engine was resized slightly so the resulting performance equaled that of the staged combustion cycle engines. Details of engine characteristics used for the dual-mode vehicles of this study are presented later in this report.

The staged combustion LO_2/RP-1 is LO_2 cooled and is used with the dual-fuel engine because of the commonality with the features of the dual-fuel engine. For the parallel burn concept (separate engines) either the gas generator or staged combustion cycles could be used depending on the overall sizing advantages. The gas generator cycle uses a small amount of LH_2 for cooling and to fuel the gas generator.

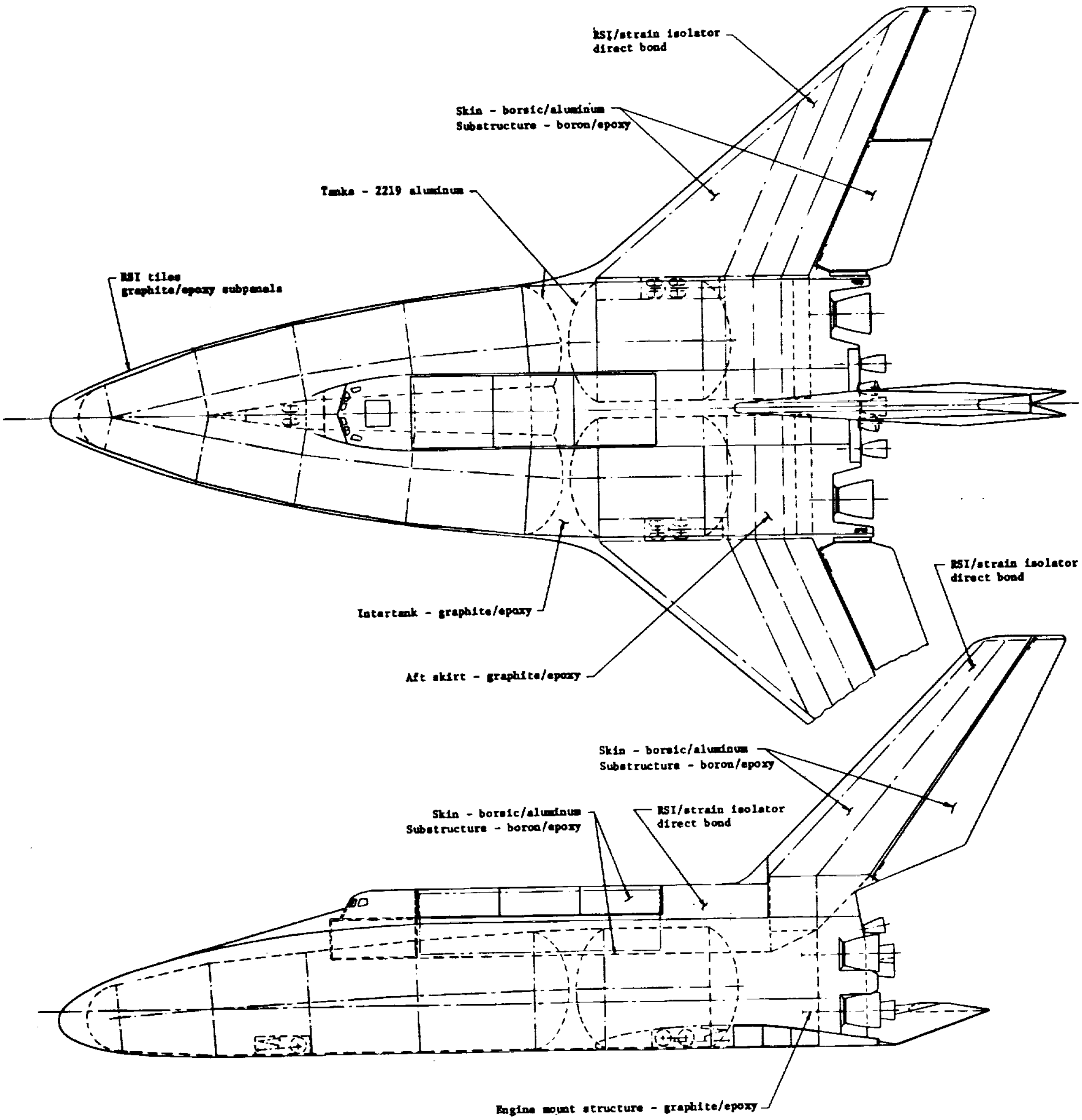


Figure 3.- Thermostructural materials.

VEHICLE ANALYSIS AND DESIGNS

Approach and Guidelines

The potential benefits of dual-mode propulsion in comparison to all LO_2 + LH_2 propulsion were derived by examining variations of vehicle parameters and design concepts leading to optimal, minimum dry-weight vehicles and program costs. Figure 4 indicates various parameter and vehicle options, and indicates the analytic process undertaken to select the most advantageous combinations among these options. The steps illustrated here, as well as the analysis results, are described in the following subsections. They include considerations of the sequences using the main engines during ascent, the computation of optimal trajectories to define the mass ratio (MR) and ideal velocity (ΔV) requirements, the development of vehicle concepts meeting these performance requirements as well as reflecting efficient design integration into a VTO-SSTO meeting all the design guidelines (table 1) and, finally, the comparison of weight parameters resulting from these variations.

Engine Utilization Strategies and Ascent Performance

Vehicle concepts being considered for VTO-SSTO operations include propulsion options (fig. 4) such as the numbers of single-fuel and dual-fuel engines, with an without two-position nozzles and throttling capabilities. Figure 5 illustrates typical sequences of events during ascent that can provide near-optimal engine use. This acceleration-time diagram (g,t diagram) reflects the 3-g limitation used in this study, and shows corresponding nozzle extension, engine throttling and engine shutdown sequences. The g,t diagrams, such as shown here, are useful for developing and describing strategies for best using the performance capabilities and flight sequencing flexibilities offered by dual-mode propulsion concepts. Among these are options for relative thrust levels of engine types, expansion ratios, extendible nozzles, throttling and shutdown, together with the overall sequence of events during ascent. Objectives for optimal performance are to accelerate to the 3-g limit in a short time while maintaining an optimal flight path leading to orbit insertion, and to extend two-position nozzles at altitudes where the larger expansion ratio provides the better specific impulse. These objectives are among those that minimize propellant weights for a given liftoff weight, and lead to the goal of a vehicle with minimum dry weight.

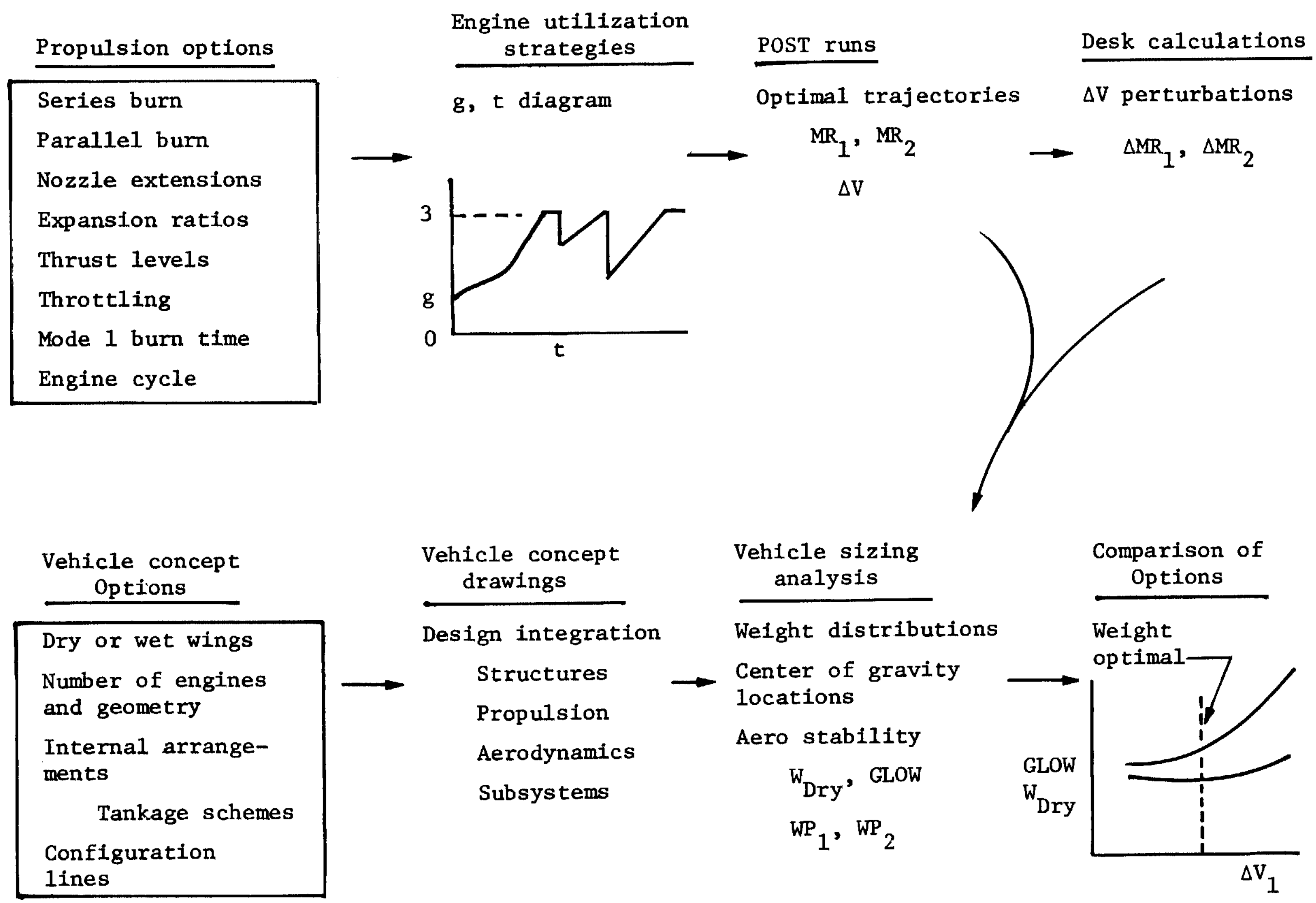


Figure 4.- Logic diagram for parametric studies.

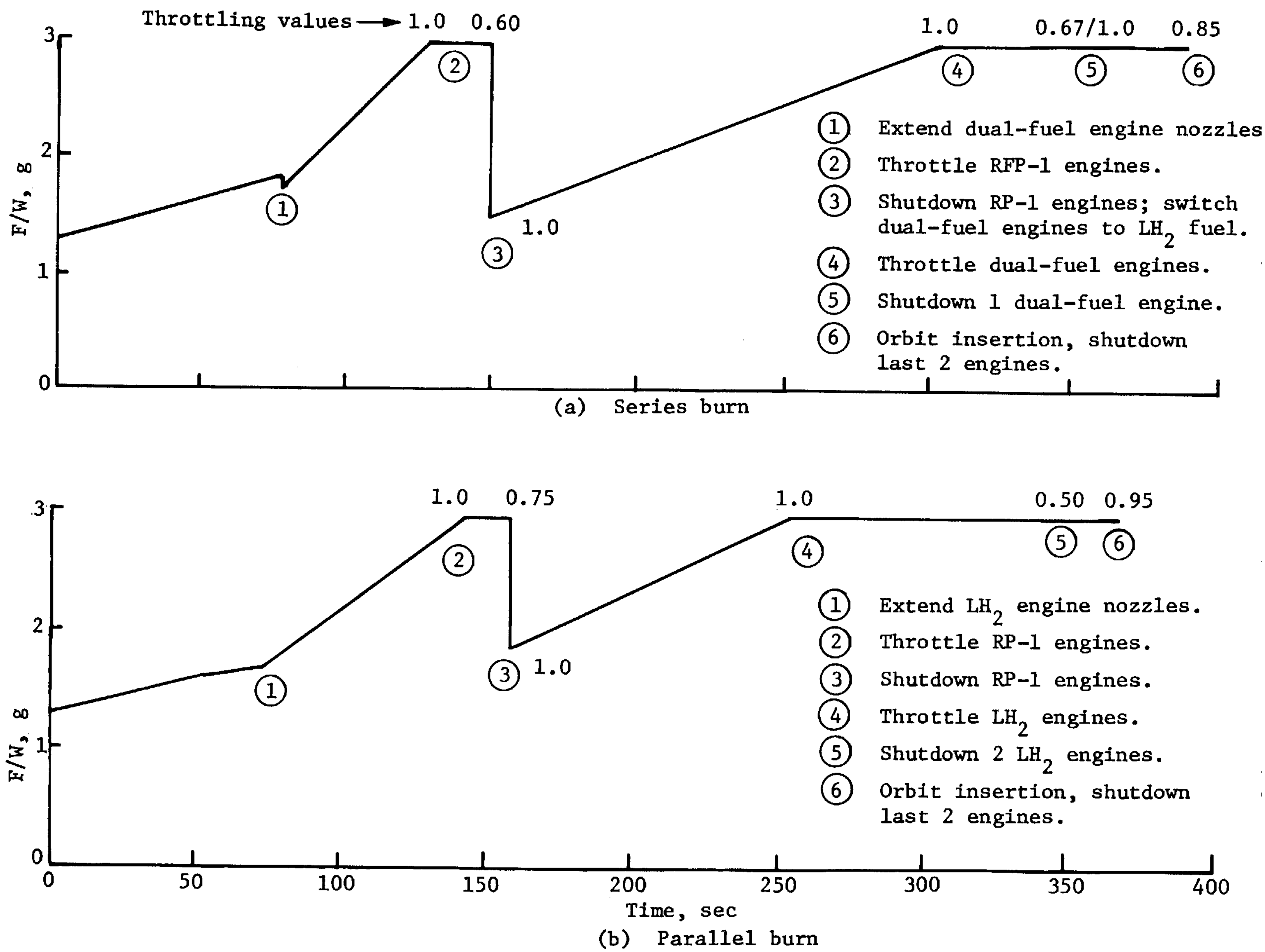


Figure 5.- Ascent engine utilization strategies.

Strategies such as shown in Figure 5 were incorporated in calculations of optimal ascent trajectories for both the parallel and the series burn propulsion modes. Typical altitude and velocity histories are shown in Figure 6. These optimal trajectory calculations yielded mass ratio requirements for vehicle designs using specific engine use strategies and specific proportions of RP-1, LH_2, and LO_2 propellants. With the baseline values for mass ratio requirements, extrapolations of mass ratio requirements for other proportions of propellants were analytically determined.

Mass ratio requirements are given in Figure 7(a) for series-burn and parallel-burn SSTO vehicles. The requirements are given over a range of Mode 1 velocity ratio to total velocities, $\Delta V_1/\Delta V^*$, as obtained from baseline POST trajectory output data, extended by desk calculations.

The vehicle mass ratio and propellant fraction requirements for vehicle sizing are defined as follows:

$$MR_T = \frac{GLOW}{GLOW - (WP)_{Mode\ 1} - (WP)_{Mode\ 2}}$$

$$MR_1 = \frac{GLOW}{GLOW - (WP)_{Mode\ 1}}$$

$$MR_2 = \frac{GLOW - (WP)_{Mode\ 1}}{GLOW - (WP)_{Mode\ 1} - (WP)_{Mode\ 2}}$$

$$MR'_1 = \frac{GLOW}{GLOW - \left(1 + \dot{W}_{LO_2}/\dot{W}_{RP-1}\right)\left(W_{RP-1}\right)_{Mode\ 1}}$$

$$MR'_2 = \frac{GLOW}{GLOW - \left(1 + \dot{W}_{LO_2}/\dot{W}_{LH_2}\right)\left(W_{LH_2}\right)_{Modes\ 1\ and\ 2}}$$

$$\gamma_{REQ} = \frac{\left(1 - \frac{1}{MR'_1}\right) + \left(1 - \frac{1}{MR'_2}\right)}{1 - WPL/GLOW}$$

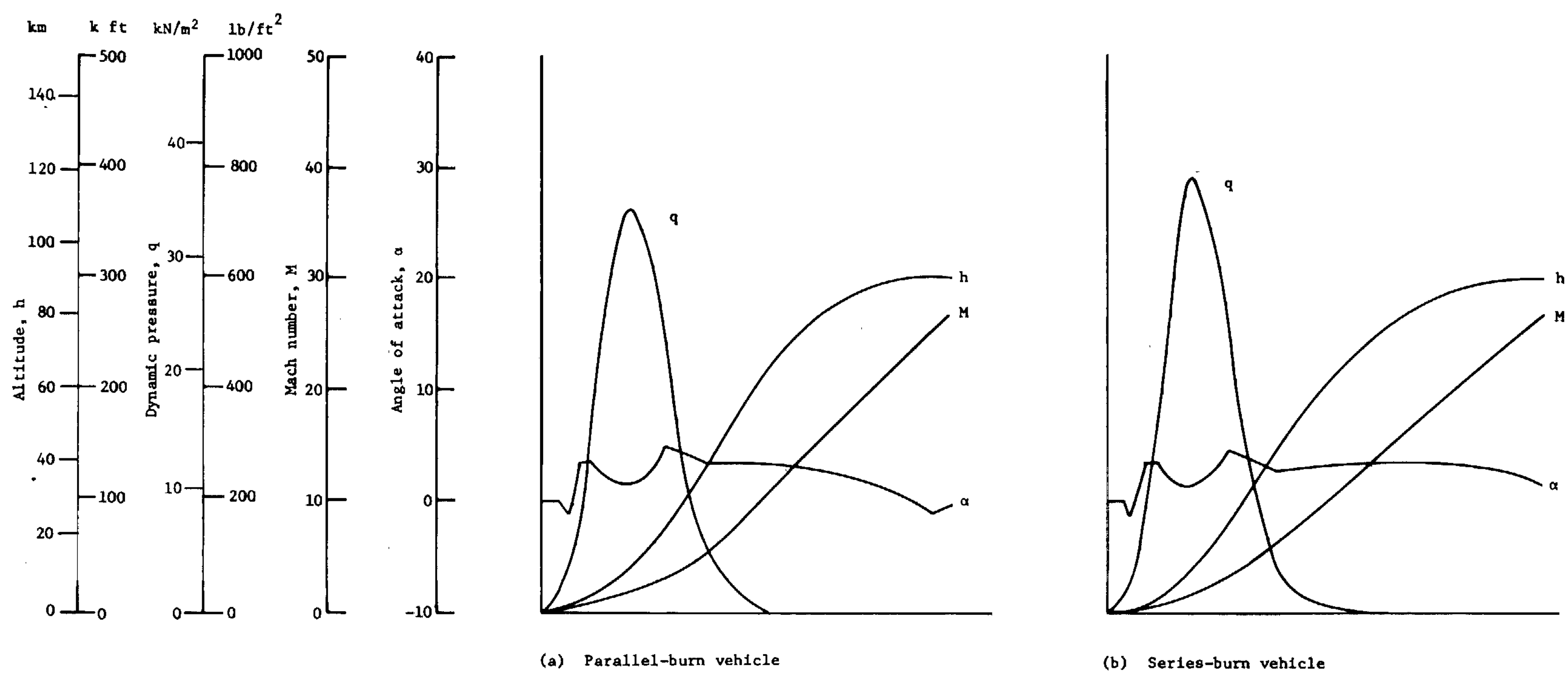
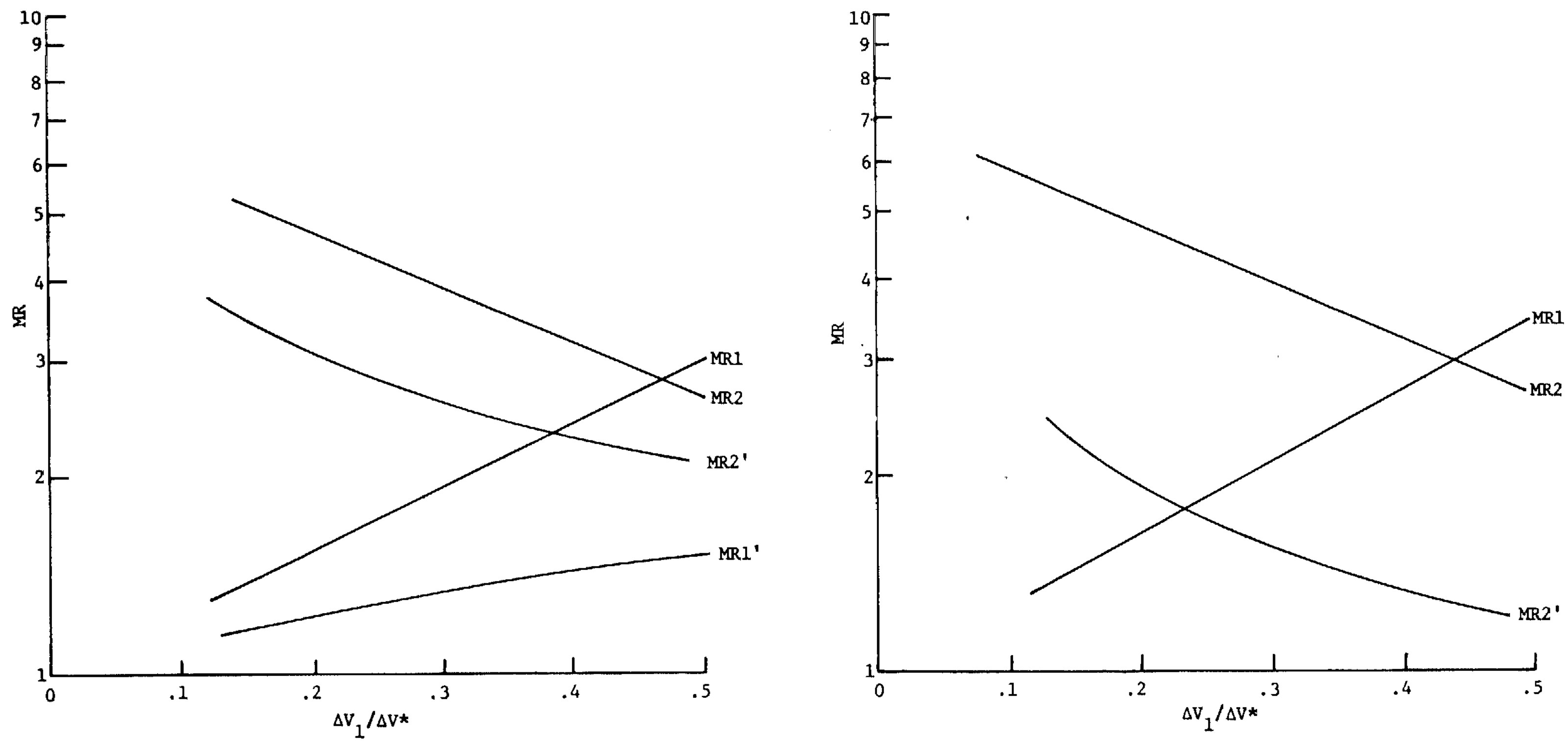


Figure 6.- Ascent trajectory parameters.



(a) Parallel vehicle

(b) Series vehicle

Figure 7.- Mass ratio requirements.

where

$GLOW$ = Gross vehicle liftoff weight

MR_T = Total mass ratio requirement

MR_1 = Mass ratio requirement for Mode 1 operation, engines using both LO_2/RP-1 and LO_2/LH_2

MR_2 = Mass ratio requirement for Mode 2 operation, engines using only LO_2/LH_2

MR'_1 = Mass ratio requirement for LO_2/RP-1 engine operation

MR'_2 = Mass ratio requirement for LO_2/LH_2 engine operation

γ_{REQ} = Propellant fraction requirement

WP = Propellant weight

W = Propellant flow rate

Subscripts

Mode 1 = Engines using both LO_2/RP-1 and LO_2/LH_2

Mode 2 = Engines using LO_2/LH_2 only

The aerodynamic data that were used in these vehicle performance calculations were derived in the study of reference 1. It was found there that the ascent performance and sizing requirements of vertical takeoff SSTO vehicles were not affected noticeably by moderate changes in aerodynamic lift and drag coefficients. The vehicle designs of the present dual-mode propulsion study have nearly the same geometry as those of reference 1, but scaled somewhat smaller, so that the previously derived coefficients are appropriate to use again here.

Propulsion System Parametrics

Study guidelines were established and certain assumptions made regarding the propulsion system to facilitate performance computations and vehicle sizing analysis. All engines were assumed capable of being throttled to as low as 50% thrust to remain within the 3-g acceleration limit. The specific impulses at 50% thrust were reduced 1/2% from their values at full thrust.

The trajectory analyses were also constrained so as to not allow deployment of the large area ratio, two-position, engine nozzles until the vehicle reached an altitude where the nozzle exit flow static pressure was at least one-third of the local ambient air pressure. This constraint was imposed to preclude nozzle flow separation and possible thrust vector distortion and thrust loss. The contours of the nozzles were assumed to be near-optimum at each of the two nozzle positions.

Engine performance used for the dual-mode propulsion studies correspond to chamber pressures ranging between 29.3 MN/m^2 (4250 psia) and 20.7 MN/m^2 (3000 psia) for LO_2/RP-1 and LO_2/LH_2 modes. These chamber pressures compare favorably with those used in reference 1 and with SSME operating conditions, and they are consistent with NASA and engine manufacturers' recommendations for engine characteristics projected to the 1985-1995 time period.

The LO_2 and LH_2 propellant densities and respective tank pressures used in the studies and shown below are the same as those in reference 1 for subcooled propellants and are representative of zero net positive suction head at the engine pump inlets.

Propellant	Density, kg/m^3 (lb/ft^3)	Tank pressure, kN/m^2 (psig)
LO_2	1304 (81.4)	137.9 (20)
LH_2	72.1 (4.5)	137.9 (20)
RP-1	801 (50.0)	48.3 (7)

These tank pressures meet propellant vapor pressure and feed system resistance requirements. The RP-1 values correspond to the vapor pressure near normal ambient temperatures plus feed system pressure losses and a low pump NPSH.

The RP-1 fuel tank size required for some wet wing configurations (RP-1 tanks in wing and wing box structures) was large enough that the fuel outlet located on the aft tank bulkhead was further aft than the mode 1 engines pump inlets; therefore, it was necessary to overcome the pressure head difference on these vehicles by incorporating propellant transfer systems that pumped the fuel forward from the wing tanks to a fuselage-mounted service tank and thence to the engine inlets.

The performance data for the various engine configurations analyzed in the dual-mode trajectory performance and vehicle sizing computations are shown in table 3. These performance figures were taken from the parametric data developed in reference 2.

TABLE 3.- ENGINE PERFORMANCE PARAMETERS

Propellant	Type	P_C, MN/m^2 (psia)	C*, m/sec (ft/sec)	ϵ	I_{sp}, vac (sec)
$LO_2/RP-1$ O/F = 2.9	Parallel or dual-fuel (staged combustion)	27.6 (4000)	1796 (5893)	40 55 125 200	351.0 356.5 369.1 375.2
	Parallel (gas generator cycle)	29.3 (4250)	1796 (5893)	42.7 58.4 132.8 212.5	351.0 356.5 369.1 375.2
LO_2/LH_2 O/F = 7.0	Parallel	27.6 (4000)	2240 (7350)	40 55 160 180 200	439.0 445.2 463.3 465.3 466.3
	Dual-fuel	20.7 (3000)	2231 (7320)	40 55 160 180 200	433.2 439.0 456.8 458.8 460.5

Two different mode 1 engine thermodynamic cycles were considered in reference 2, the staged combustion and the gas generator cycle. Initially staged combustion and gas generator engines operating at the same chamber pressure were studied, but the vehicles incorporating gas generator cycle engine proved inferior in spite of the lighter engines because of lower engine specific impulse. Subsequently, the gas generator engines were resized to obtain performance equal to the staged combustion engines by taking advantage of larger expansion ratio nozzles made possible by slightly higher chamber pressures as shown in table 3.

Engine nozzle expansion ratios were varied from 40 to 1 for mode 1 and dual-fuel engines to 200:1 for extended position mode 2 engines. The corresponding gas generator engine nozzle expansions are slightly greater. The effect of expansion ratio on vehicle flight performance for the first and second nozzle positions (expansion ratios ε_1 and ε_2, respectively) was evaluated for two configuration types. The first configuration used five dual-fuel two-position nozzle engines and the second incorporated three single-position nozzle mode 1 engines in addition to two dual-fuel two-position nozzle engines.

The results (fig. 8) show that, for the first configuration, the effect of the initial (nozzle retracted) area ratio is negligible, whereas for the second configuration the improvement in performance with increasing area ratio is significant. For the extended position, the improvement with increasing area ratio is significant for both configurations. Selection of the initial (retracted) area ratio is dictated by performance considerations as well as hardware design limitations influenced by matching the retracted and extended contours and the need to minimize overall engine length. The extended position area ratio is limited by weight and length considerations. For further vehicle design and technology focusing, the expansion ratios of $\varepsilon_1 = 55$ and $\varepsilon_2 = 200$ were selected as being near optimum for SSTO vehicles. This selection is consistent with results of other related studies described in reference 3.

Variations of engine thrust-to-weight ratios with engine thrust are shown in Figure 9 for these expansion ratios. These data are typical results from reference 2. In general, engine thrust levels should be chosen near the levels that give the largest F/W (lightest unit weight) to minimize vehicle weight.

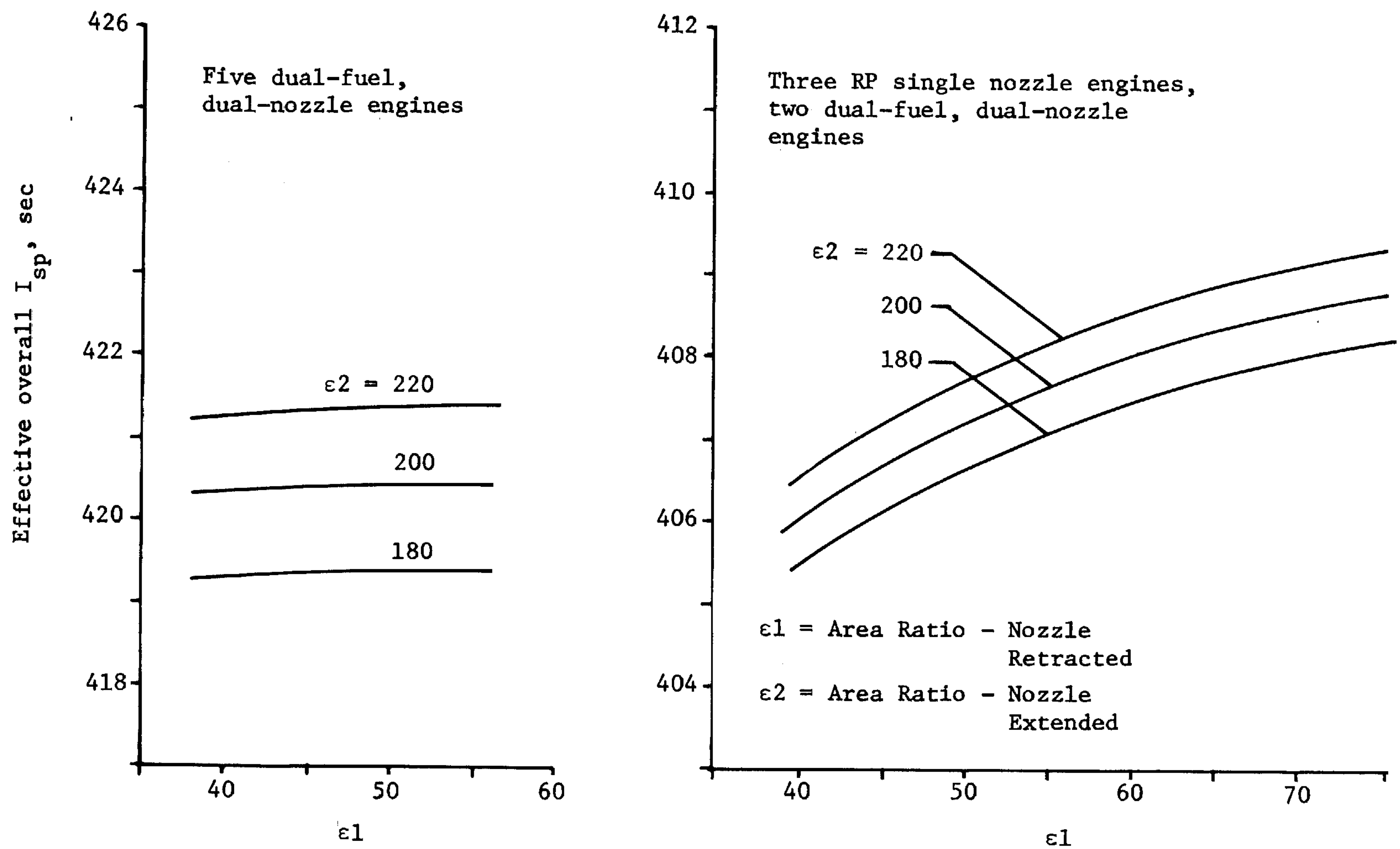


Figure 8.- Effect of nozzle area ratios.

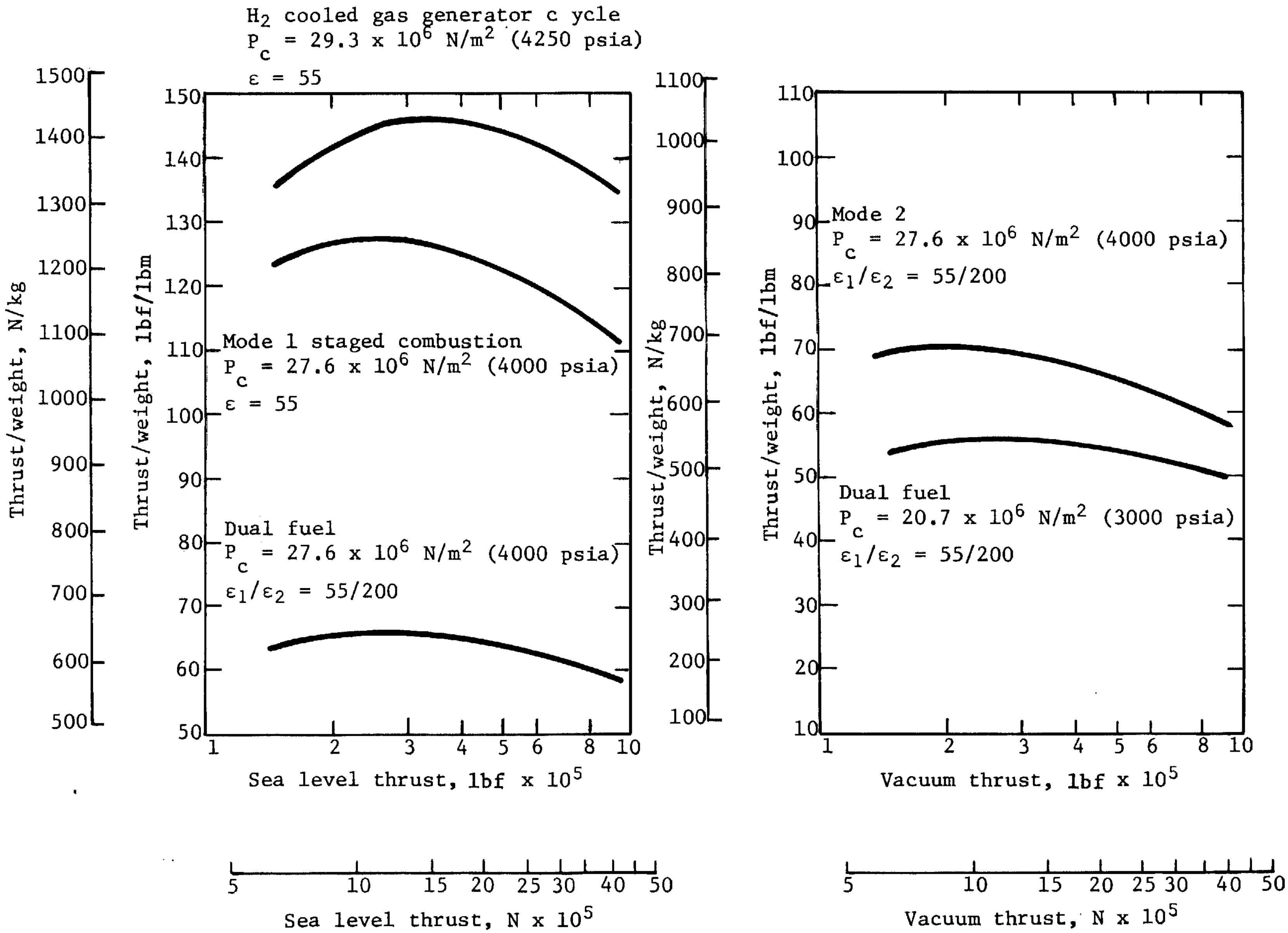


Figure 9.- Thrust/weight versus thrust.

The relative effects on the vehicle dry weight of increased specific impulse or decreased engine weight are important to engine designers and systems analysts. Vehicle sizing analyses using the present VTO vehicles show the following sensitivities:

Engine type	Equivalence
LO_2/RP-1	1% change in I_{sp} is equivalent to -25% change in engine weight, i.e., -81.6 kg/sec (-180 lbm/sec)
LO_2/LH_2	1% change in I_{sp} is equivalent to -13% change in engine weight, i.e., -86.6 kg/sec (-191 lbm/sec)
Dual-fuel	1% change in I_{sp} (average) is equivalent to -8% change in engine weight, i.e., -75 kg/sec (-165 lbm/sec)

Vehicle Design Parametrics

Design parameters were varied to determine the configuration that will yield the minimum vehicle dry weight within the study guidelines and including practical design considerations. The computer program (VISP), used for vehicle sizing analysis, was modified to include sizing equations representing the dual-mode vehicle parametric weight and size, as well as the engine parametric weights furnished by the NASA. All of the vehicle variations of the parametric study represent configurations that meet the same payload requirements and aerodynamic stability guidelines.

The ratio of mode 1 velocity to total velocity $(\Delta V_1/\Delta V^*)$ was varied to determine the effect of changing the relative amounts of RP-1 propellant on vehicle mass properties. Typical weight variations are shown in figure 10 for both parallel-burn and series-burn vehicles. (These data are for the baseline parallel-burn and series-burn vehicles presented later in this report.) The dry weight for the parallel-burn vehicle minimizes at a $\Delta V_1/\Delta V^*$ ratio of 0.41 whereas the gross weight minimizes at about 0.3. The dry weight for the series-burn vehicle is near minimum at a $\Delta V_1/\Delta V^*$ ratio of 0.40 whereas its gross weight minimizes at about 0.2. At the near-minimum dry weight, the series vehicle has mode 1 (RP-1) and mode 2 (dual-fuel) engines that have the same thrust at liftoff. The dual-fuel engine is considered to be the RP-1 engine with a modification that adds

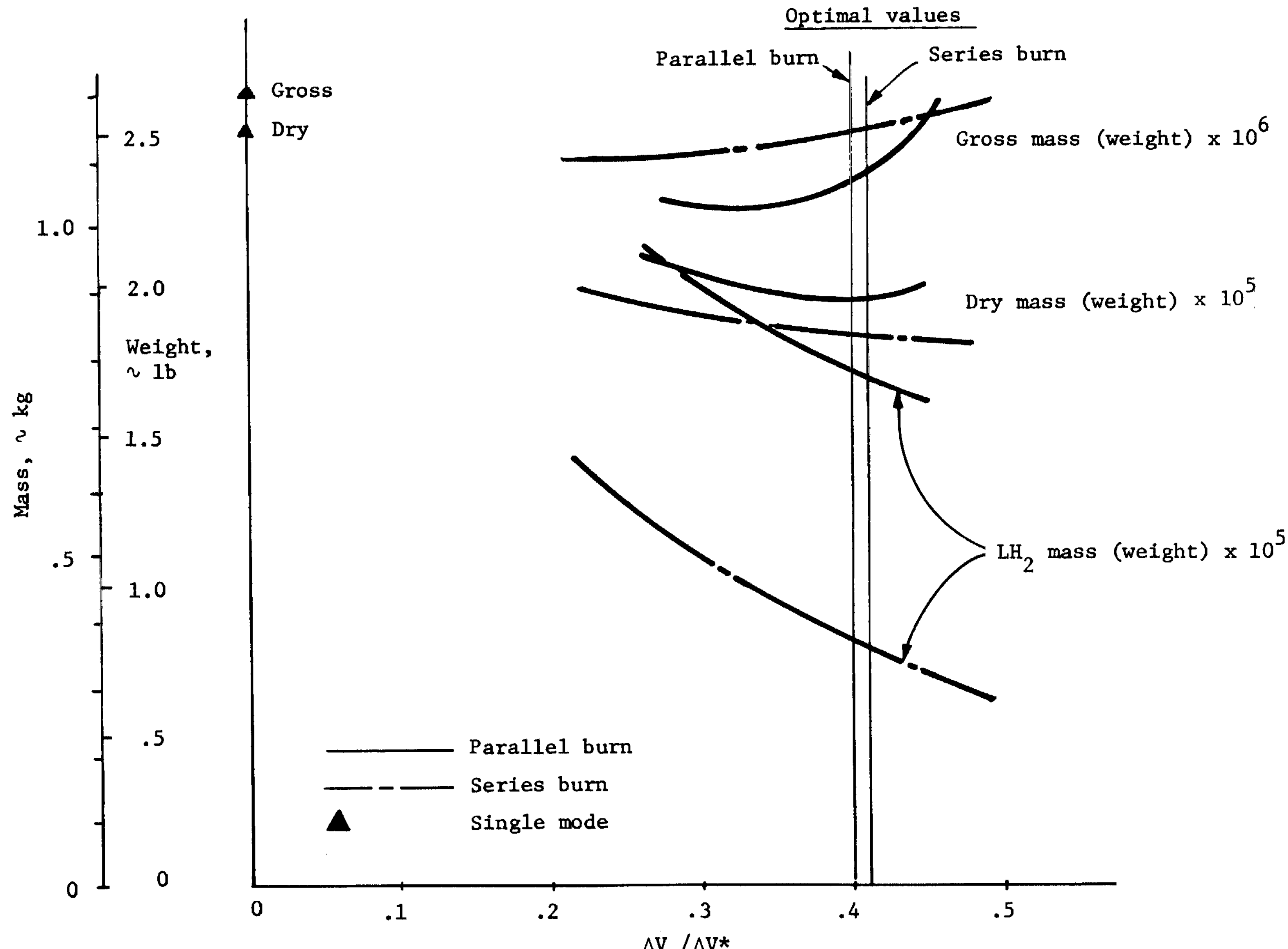


Figure 10.- Weight variation with ΔV_1

the capability for also burning hydrogen fuel, and the two-position nozzle. Figure 10 also shows, for reference, the dry weight and GLOW of the extended performance single-mode vehicle ($\Delta V_1/\Delta V* = 0$). The hydrogen fuel weight variations for the dual-mode propulsion vehicles illustrate the relatively large LH_2 fuel weights of the parallel-burn concept compared to the series-burn concept.

Effects of design variations applied to the series-burn and parallel-burn vehicles are illustrated in figures 11 and 12, showing relative efficiencies in dry weight compared to the baseline configurations. Dry weights are slightly less using up to 12 engines, but such vehicle designs give larger program costs, as discussed later. The use of two-position nozzles on mode 1, RP-1 engines is not warranted because the larger engine weights with two-position nozzles are more than can be compensated by the improved specific impulse at high altitudes. The series-burn data show a weight ratio for a configuration designated pure series. This represents a design wherein the engine utilization strategy was constrained such that all dual-fuel engines were switched from RP-1 fuel to LH_2 fuel at the same flight time, rather than allowing a sequential switchover. The sequential switchover provides a more optimal ascent trajectory. The series-burn data (upper bar) also show the severe penalty if all of the engines are dual-fuel engines, rather than a combination of dual-fuel and RP-1 engines. This again is a result of the large engine weights representing dual-fuel engines that were used in this study. In figure 12, two vehicles with two-position nozzles and with expansion ratios of 40/200 are indicated to be slightly lighter than with initial expansion ratios of 55/200. It is believed, however, that the 40/200 combination is impractical to geometrically package, particularly when this engine is mounted adjacent to a single-position LO_2/RP-1 engine.

Table 4 shows comparative effects on dry weight by changing various parameters. Sensitivity values are shown for some of the design changes illustrated in figures 11 and 12. Further data show that dry weight reductions of 22.6% and 27.2% result when dual-mode propulsion concepts are applied with accelerated technology growth in the other technology areas rather than normal technology goals. Also, a 1% change in LH_2 engine efficiency (from 97% to 98)) results in a 3.4% reduction in vehicle dry weight.

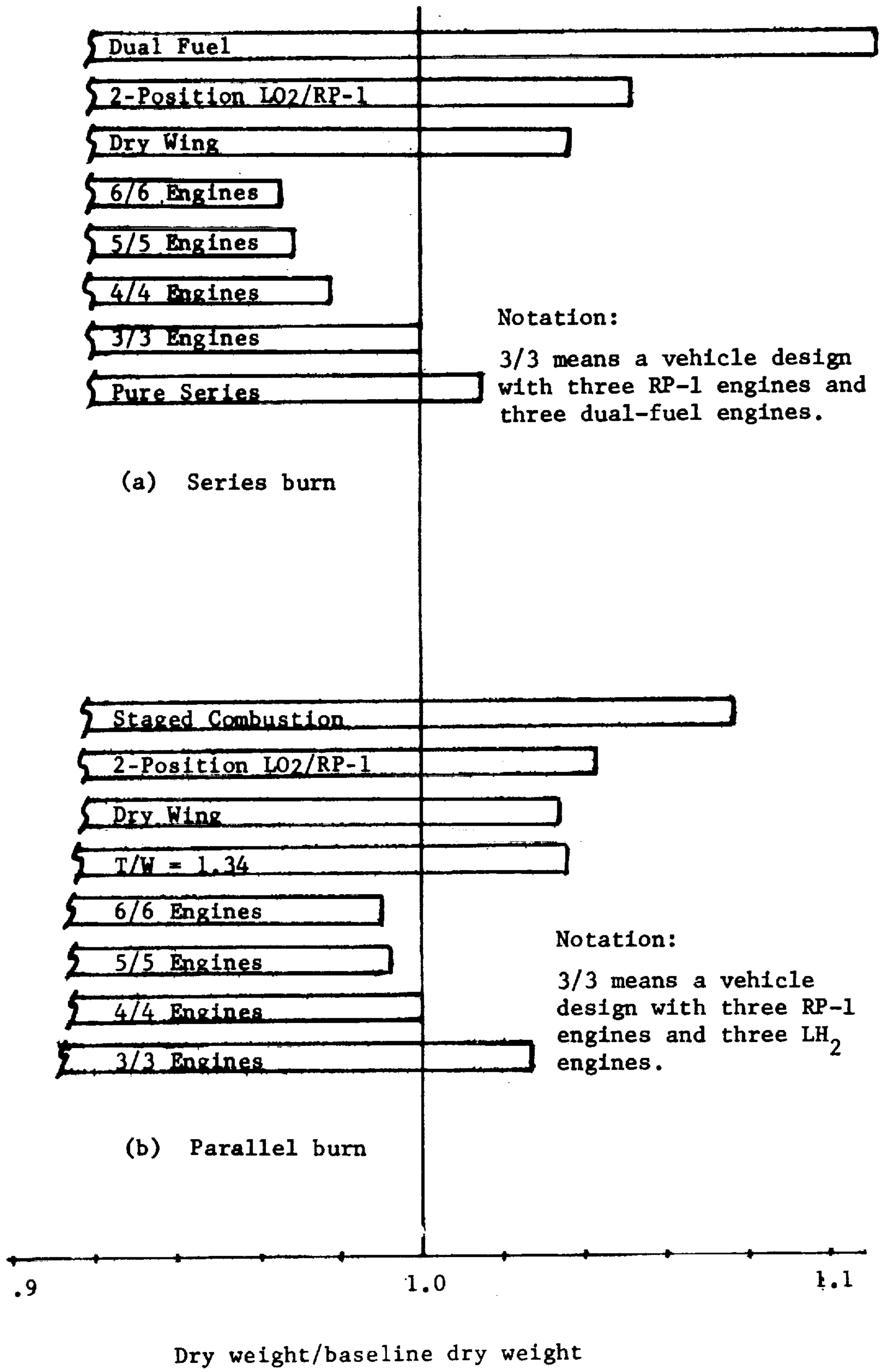


Figure 11.- Effects of design variations on dry weight.

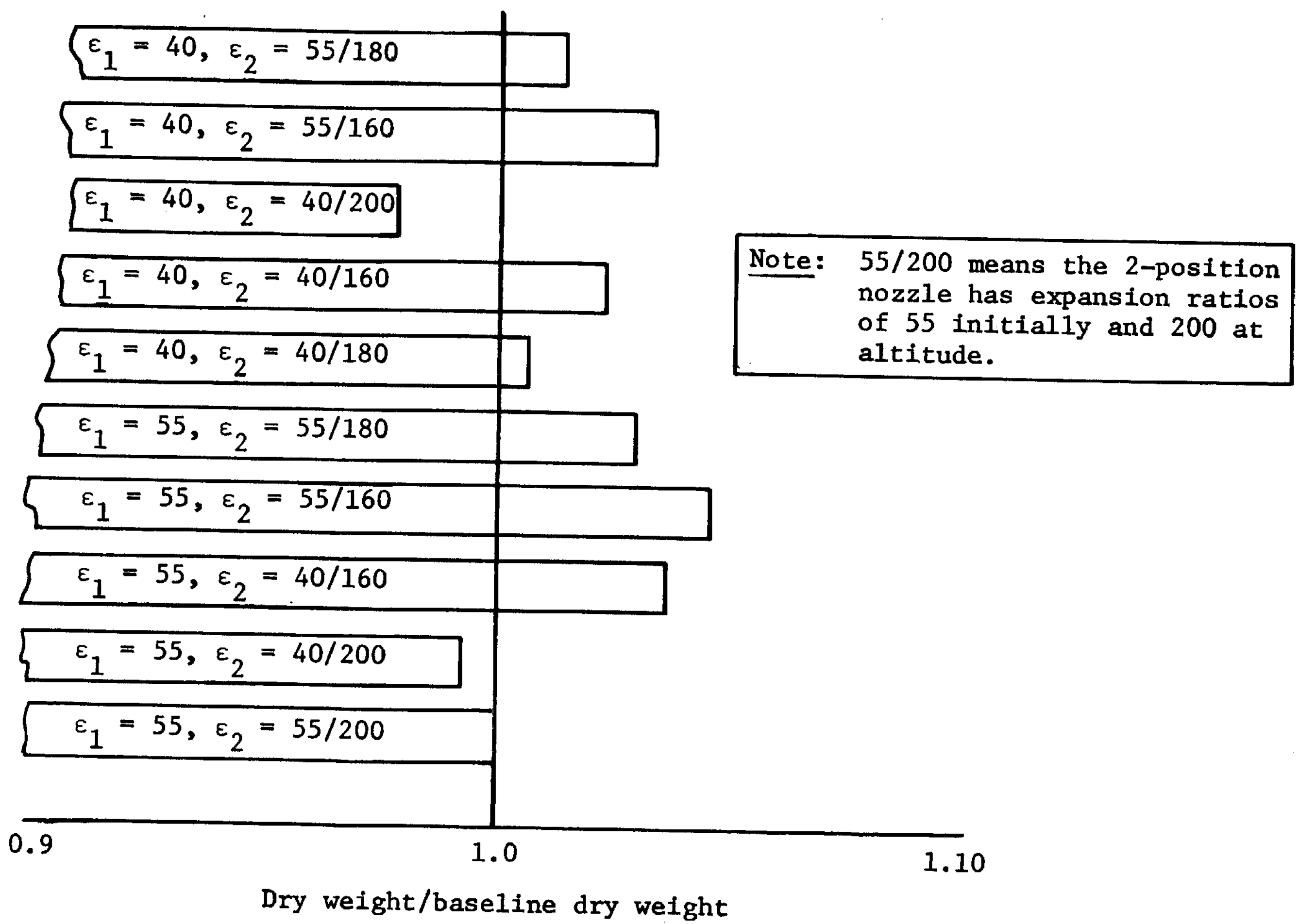


Figure 12.- Engine nozzle expansion ratio effects.

TABLE 4.- VEHICLE WEIGHT SENSITIVITIES

Change		Results in decrease in dry weight, %
From	To	
LO_2/RP-1 Engine:		
Two-position nozzle $\epsilon = 40/125$	One-position nozzle $\epsilon = 40$	3.0
Dry wing configuration	Wet wing configuration	3.7
$(F/W)_{SL} = 1.34$	$(F/W)_{SL} = 1.29$	3.5
Series Mode		
Pure series burn	Sequential series burn	1.6
All dual-fuel engines	Three LO_2/RP-1 Three dual-fuel	11.2
Three LOX + RP-1 Three dual-fuel	Six LO_2/RP-1 Six dual-fuel	4.7
LH_2 density	LH_2 density x 1.0444	0.92
Normal technology, single-mode	Normal technology dual-mode	40.0
Accelerated technology, single-mode	Accelerated technology, dual-mode	27.2
Parallel Mode		
	One percent increase in LOX + LH_2 engine efficiency	3.45
Three LO_2/RP-1 Three LO_2/LH_2	Four LO_2/RP-1 Four LO_2/LH_2	2.7
LH_2 density	LH_2 density x 1.0444	1.75
Normal technology, single-mode	Normal technology dual-mode	42.1
Accelerated technology, single-mode	Accelerated technology, dual-mode	22.6

Figure 13 illustrates arrangements of various engine combinations on the vehicles. The engine arrangements with 5 to 12 engines all fit within the basic configuration base. With more engines, of course, the thrust level of each engine is smaller, and its size is smaller. A shorter engine compartment length (tank dome to end of body) is needed, therefore, yielding a higher volumetric efficiency and hence smaller and lighter vehicle designs.

Table 5 presents values of design parameters that resulted from the parametric evaluations of the series-burn and parallel-burn vehicles.

Vehicle Designs

The dual-mode propulsion vehicle designs using both parallel-burn and series-burn modes are compared in this section. The guidelines for the design are listed in table 1.

General arrangement, parallel-burn vehicle.- The baseline vehicle for the parallel burn propulsion mode is shown in figure 14. The vehicle is 45.55 meters (149.43 ft) long and has a wing span of 34.829 meters (114.269 ft). Four single-position ($\varepsilon = 55$) LO_2/RP-1 gas generator engines are combined with four two-position ($\varepsilon = 55/200$) LO_2/LH_2 engines for a liftoff thrust to weight ratio of 1.29. The wing has leading edge and trailing edge sweep angles of 50° and 20°, respectively, and the vertical tail, 45° and 28°, respectively. The vertical tail is a 10° wedge configuration with the capability of forming a double wedge configuration by actuating the split rudders (speed brakes) inward.

Inboard profile, parallel-burn vehicle.- The parallel-burn propulsion mode vehicle inboard profile is shown in figure 15 showing structural, propulsion, landing gear, OMS, RCS, equipment, and crew subsystems. The LH_2 and LO_2 tanks are in the body whereas the RP-1 propellant is stored in the central portion of the wing. The four LO_2/RP-1 gas generator rocket engines are in line just aft of the aft spar of the wing box. The engines (table 6) have a single-position nozzle ($\varepsilon = 55$) with a vacuum thrust of 1 808 647 N (406 660 lb). The RP-1 boost pumps located on the four wing tank outlets feed the lower engines. The four LO_2/LH_2 engines are two-position ($\varepsilon = 55/200$) engines of 2 050 425 N (460 954 lb) vacuum thrust each. The dual-mode vehicles have a different OMS packaging concept from the single-mode vehicles of reference 1. The OMS tanks are located in the engine compartment above the wing carrythrough box and the two engines are outboard of the four LO_2/RP-1 engines.

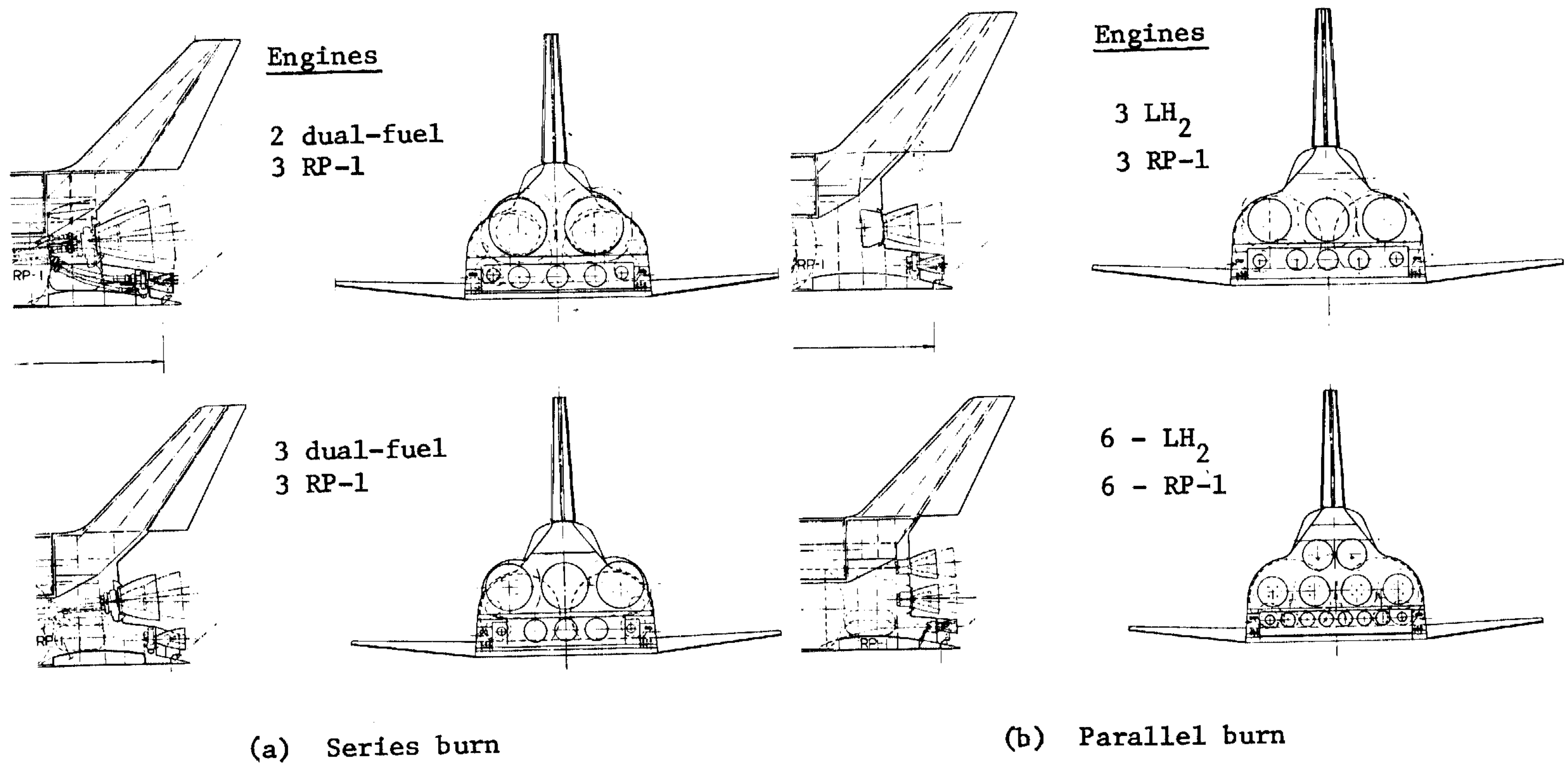


Figure 13.- Vehicle arrangements with various engines.

TABLE 5.- PARAMETERS FOR MINIMUM DRY WEIGHT

	Series burn	Parallel burn
Liftoff acceleration, g	1.29	1.29
Expansion ratio, ϵ_1	55	55
Expansion ratio, ϵ_2	55/200	55/200
Mode 1 engine cycle	Staged combustion	Gas generator
Number of engines	Three LO_2/RP-1 Three dual-fuel	Four LO_2/RP-1 Four LO_2/LH_2
$\Delta V_1/\Delta V$*	0.41	0.40
$\frac{\text{Weight of RP-1 fuel}}{\text{Total propellant weight}}$	0.18	0.09
$\frac{\text{Weight of mode 1 propellants}}{\text{Total propellant weight}}$	0.71	0.36*

*Weights of the RP-1 and the portion of LO_2 consumed by the RP-1 are used in the numerator.

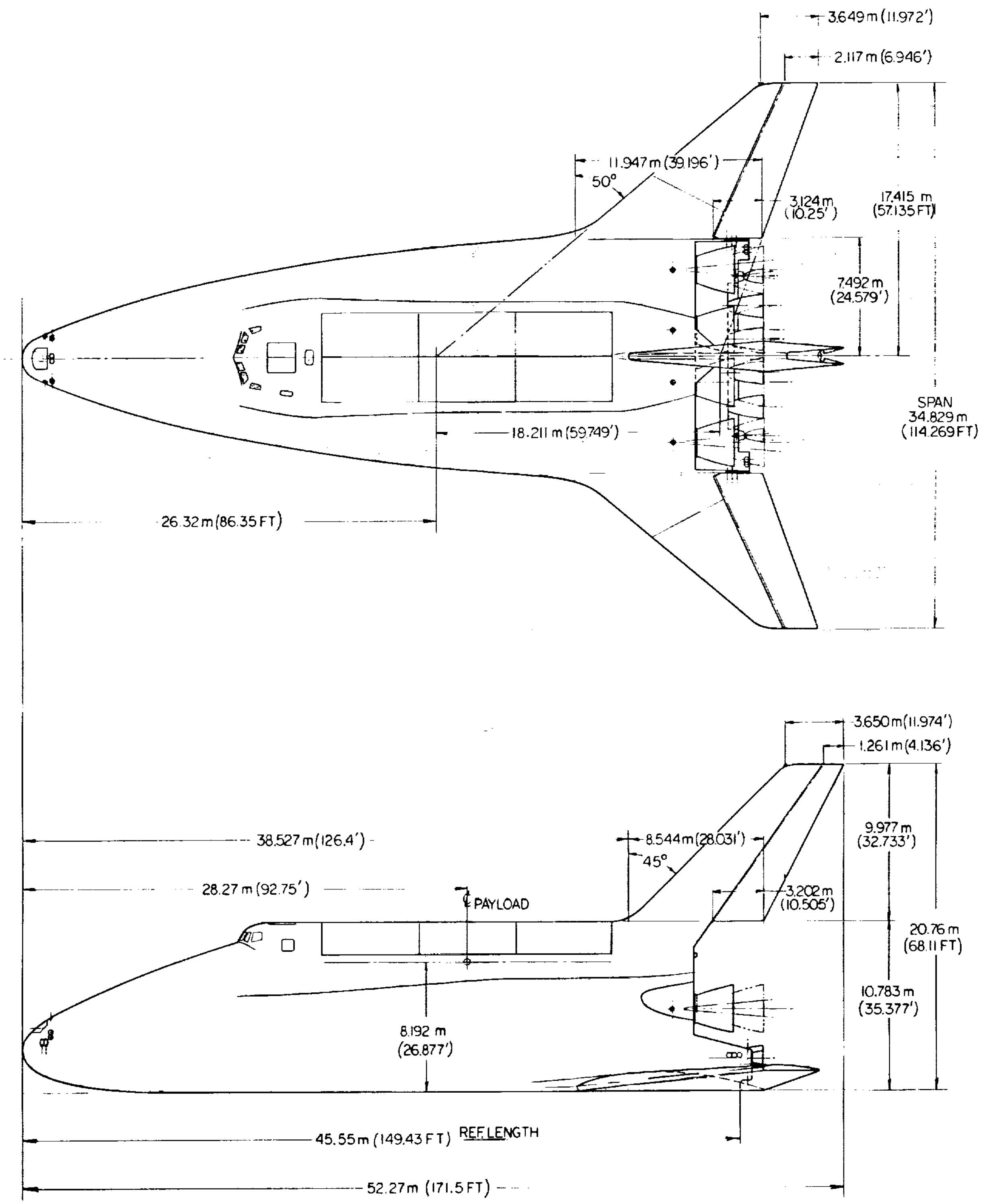


Figure 14.- Parallel-burn vehicle, general arrangement.

AREAS

BODY PLAN AREA	533.3 m^2	(5,740 FT^2)
WING, THEORETICAL	380.7 m^2	(4,098 FT^2)
WING, EXPOSED	154.8 m^2	(1,666 FT^2)
ELEVON	52.0 m^2	(560 FT^2)
VERTICAL TAIL	60.8 m^2	(655 FT^2)
RUDDER	22.3 m^2	(240 FT^2)
BODY WETTED AREA	1,524.1 m^2	(16,406 FT^2)

VOLUMES

LH_2 TANK	1,122.8 m^3	(39,652 FT^3)
LOX TANK	610.6 m^3	(21,564 FT^3)
RP-1 TANK	110.3 m^3	(3,894 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)

WEIGHTS			C.G. % REF. LENGTH
PAYLOAD	29,483 kg	(65,000 lb)	62.07
DRY WEIGHT	88,314 kg	(194,700 lb)	
LANDING W/O PAYLOAD	91,334 kg	(201,358 lb)	67.14
LANDING WITH PAYLOAD	120,817 kg	(266 358 lb)	65.90
ASCENT PROPELLANT	923,405 kg	(2,035,760 lb)	
GROSS LIFT-OFF WEIGHT	1,060,929 kg	(2,338,948 lb)	69.26

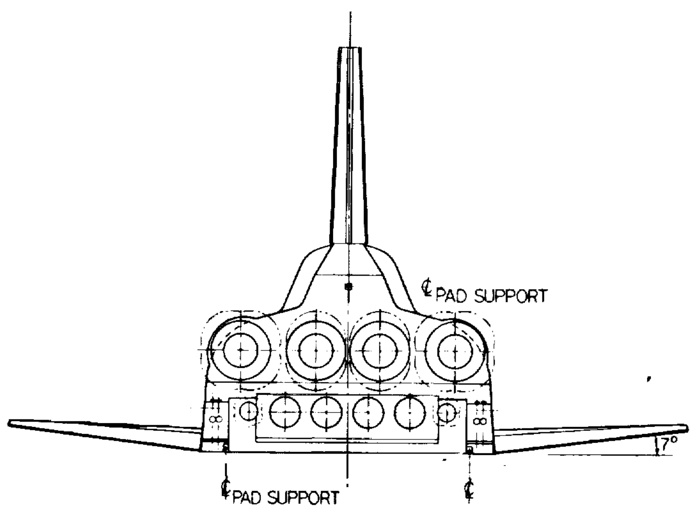


Figure 14.— Continued

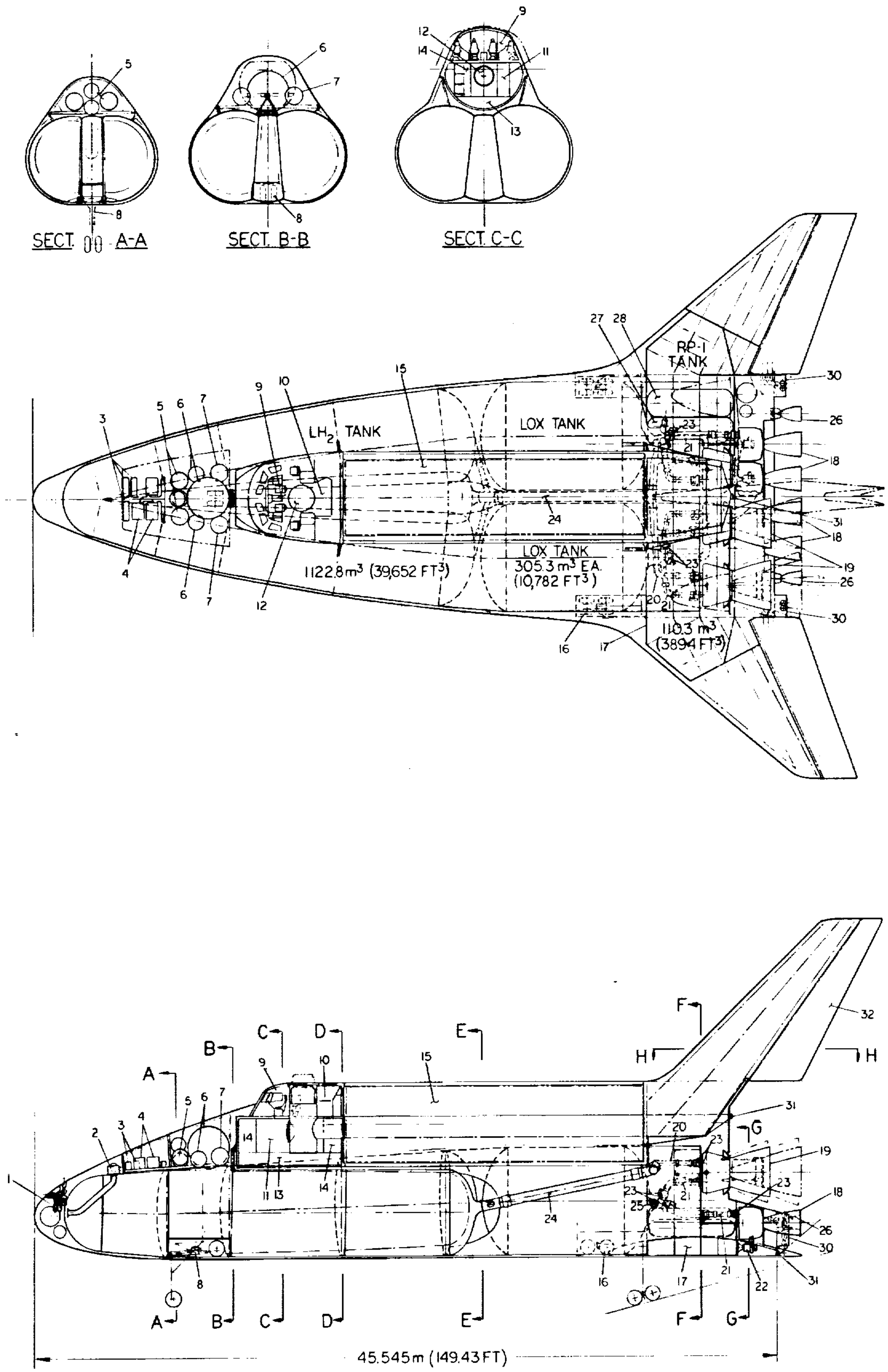
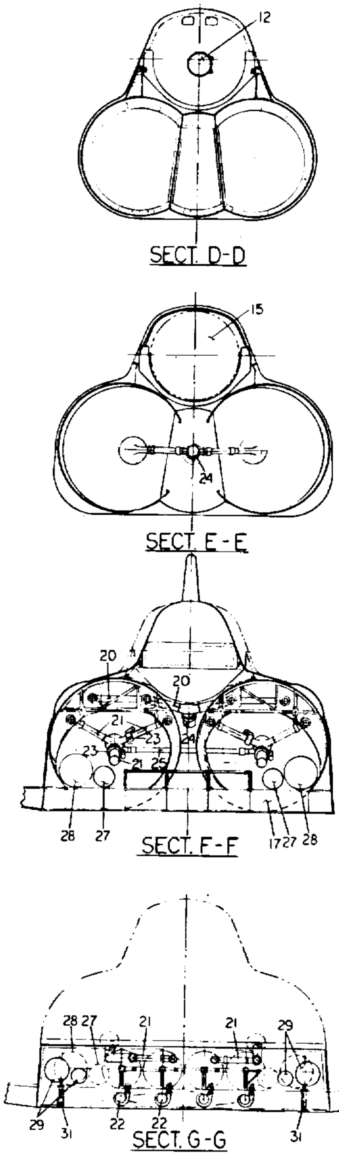


Figure 15.- Parallel-burn vehicle, inboard.



NOMENCLATURE

1. FORWARD RCS MODULE
2. LH_2 TANK VENT AND PRESSURIZATION VALVES
3. ELECTRICAL POWER SYSTEM, FUEL CELLS
4. POWER SYSTEM, APU'S
5. FUEL CELL PROPELLANTS ($LOX-LH_2$)
6. APU PROPELLANT ($LOX-LH_2$)
7. PRESSURANTS (HE)
8. NOSE LANDING GEAR
9. FLIGHT DECK
10. OPERATIONS DECK
11. REST AND PASSENGER AREA
12. AIR-LOCK AND DOCKING MODULE
13. ECLSS - SYSTEM
14. AVIONICS
15. PAYLOAD BAY
16. MAIN LANDING GEAR
17. WING CARRY-THROUGH STRUCTURE/RP-1 INTEGRAL TANK
18. MAIN PROPULSION ENGINE, LOX-RP-1, $\epsilon = 55$, FIXED NOZZLE, NOT GIMBALLED
19. MAIN PROPULSION ENGINE, $LOX-LH_2$, $\epsilon = 55/200$, EXTENDABLE NOZZLE, GIMBALLED
20. LH_2 FEEDLINES
21. LOX FEEDLINES
22. RP-1 BOOST PUMPS
23. PROPELLANT PREVALVE
24. LH_2 MAIN FEEDLINE
25. LOX TANK INTERCONNECT LINE
26. OMS ENGINE, $LOX-LH_2$, $\epsilon = 400$
27. OMS PROPELLANT TANK, LOX
28. OMS PROPELLANT TANK, LH_2
29. RCS PROPELLANT TANKS, $LOX-LH_2$
30. AFT RCS MODULES
31. PAD SUPPORT HARD POINTS
32. SPLIT RUDDER

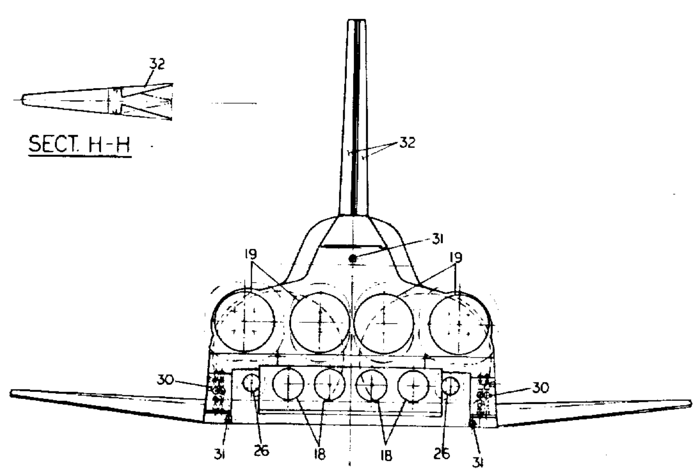


Figure 15.- Continued

TABLE 6.- ENGINE PERFORMANCE DATA

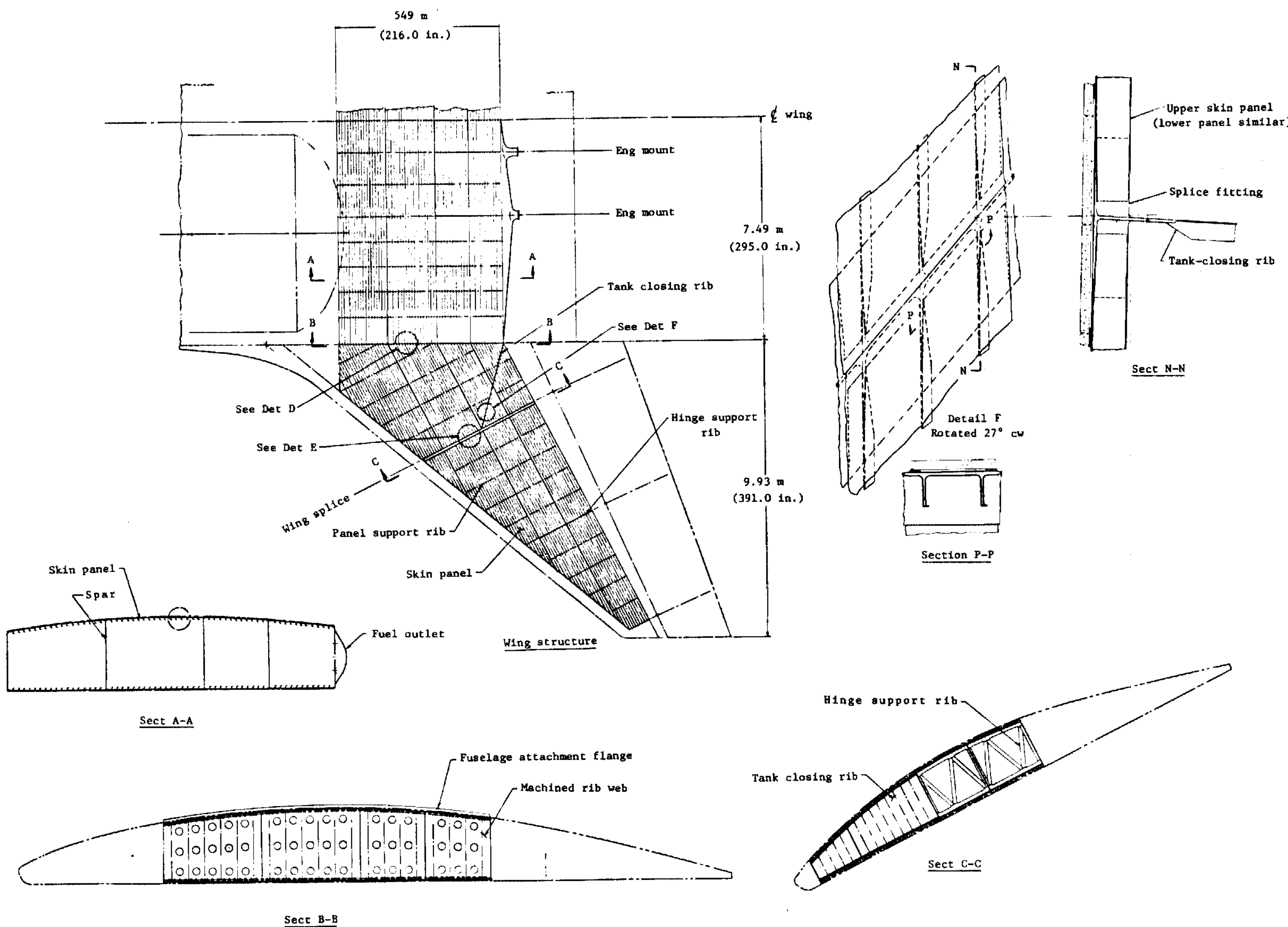
Nozzle Type	Parallel Burn		Series Burn	
	Mode 1	Mode 2	Mode 1	Dual fuel
Number per vehicle	4	4	3	3
Engine weight - kg (lbm)	1145 (2524)	3062 (6750)	2024 (4463)	3868 (8527)
LO_2 flow rate - kg/sec (lbm/sec)	385 (848)	392 (865)	574 (1264)	574/407 (1264/897)
Fuel flow rate - kg/sec (lbm/sec)	133 (292)	56 (123)	198 (436)	198/58 (436/128)
Chamber pressure - 10^6 N/m^2 (psia)	27.6 (4000)	27.6 (4000)	27.6 (4000)	27.6/20.7 (4000/3000)
Expansion ratio	58.4	55/200	55	55/200
Exit area - m^2 (in^2)	1.97 (3047.5)	7.27 (11 277)	2.76 (4281)	10.0 (15 540)
Exit diameter - m (in.)	1.58 (62)	3.04 (120)	1.87 (74)	3.57 (141)
Thrust, SL - 10^3 N (10^3 lbf)	1609 (361)	1754 (394)	2416 (543)	2416 (543)
Thrust, vacuum - 10^3 N (10^3 lbf)	1809 (407)	2050 (461)	2698 (606)	2100 (472)
I_{sp}, SL - sec	317.2	399.0	319.5	319.5
I_{sp}, vacuum - sec	356.5	466.5	356.5	460.5

Structural arrangement.- The structural arrangement and load paths are identical to the previous single-mode propulsion vehicles. The only significant change is the use of the structural wing box cavity to store RP-1 propellant. Figure 16 shows the details of the wing box tankage area as well as the revised structural splice. The splice is outboard of the tank area so that the wing box-tank is an assembly that can be built, tested for leaks, and then installed in the final vehicle assembly. The composite wing skin structure is bonded to titanium fittings at the wing splice section.

Configuration layout, series burn.- The series-burn vehicle configuration shown in Figure 17 is similar to the parallel burn configuration with the following major changes: the RP-1 propellant is housed in both body tanks and in the wing box structure. The RP-1 propellant is pumped from the wing box to the two body tanks and the feedlines drain the body tanks. The rocket engines (table 6) are three two-position (ε = 55/200) dual-fuel engines plus three single-position (ε = 55) LO_2/RP-1 engines.

Mass properties.- The vehicle mass properties are based on advanced technology projections combined with the dual-mode engine weights provided by the NASA (ref. 2). Vehicle structural unit weights are compatible with loads extrapolated from the finite element analysis performed in reference 1.

The parallel burn vehicle mass properties are presented in table 7. The vehicle represents a 22.5% decrease in dry weight compared to the single-mode VTO vehicle. The series burn vehicle mass properties are presented in table 8. This vehicle represents a 27.2% decrease in dry weight compared to the single-mode VTO vehicle. Vehicle center of gravity data are presented in table 9.


549 m
(216.0 in.)
℄ wing
Eng mount
Eng mount
7.49 m
(295.0 in.)
Tank closing rib
See Det F
See Det D
See Det E
Hinge support
rib
9.93 m
(391.0 in.)
Wing splice
Panel support rib
Skin panel
Wing structure
Skin panel
Spar
Fuel outlet
Sect A-A
Fuselage attachment flange
Machined rib web
Sect B-B
Upper skin panel
(lower panel similar)
Splice fitting
Tank-closing rib
Sect N-N
Detail F
Rotated 27° cw
Section P-P
Hinge support rib
Tank closing rib
Sect C-C

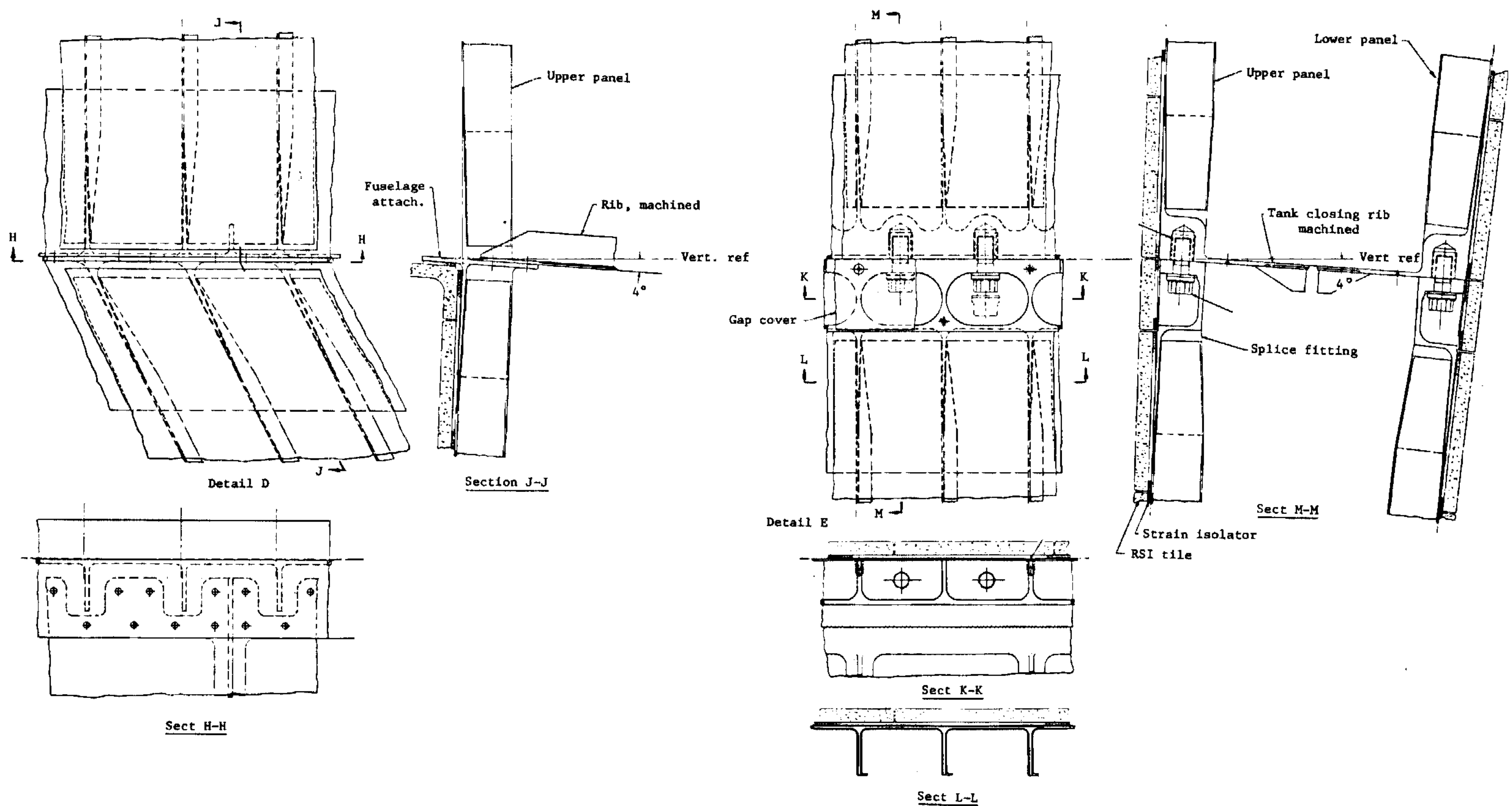


Figure 16.- Wing structures.

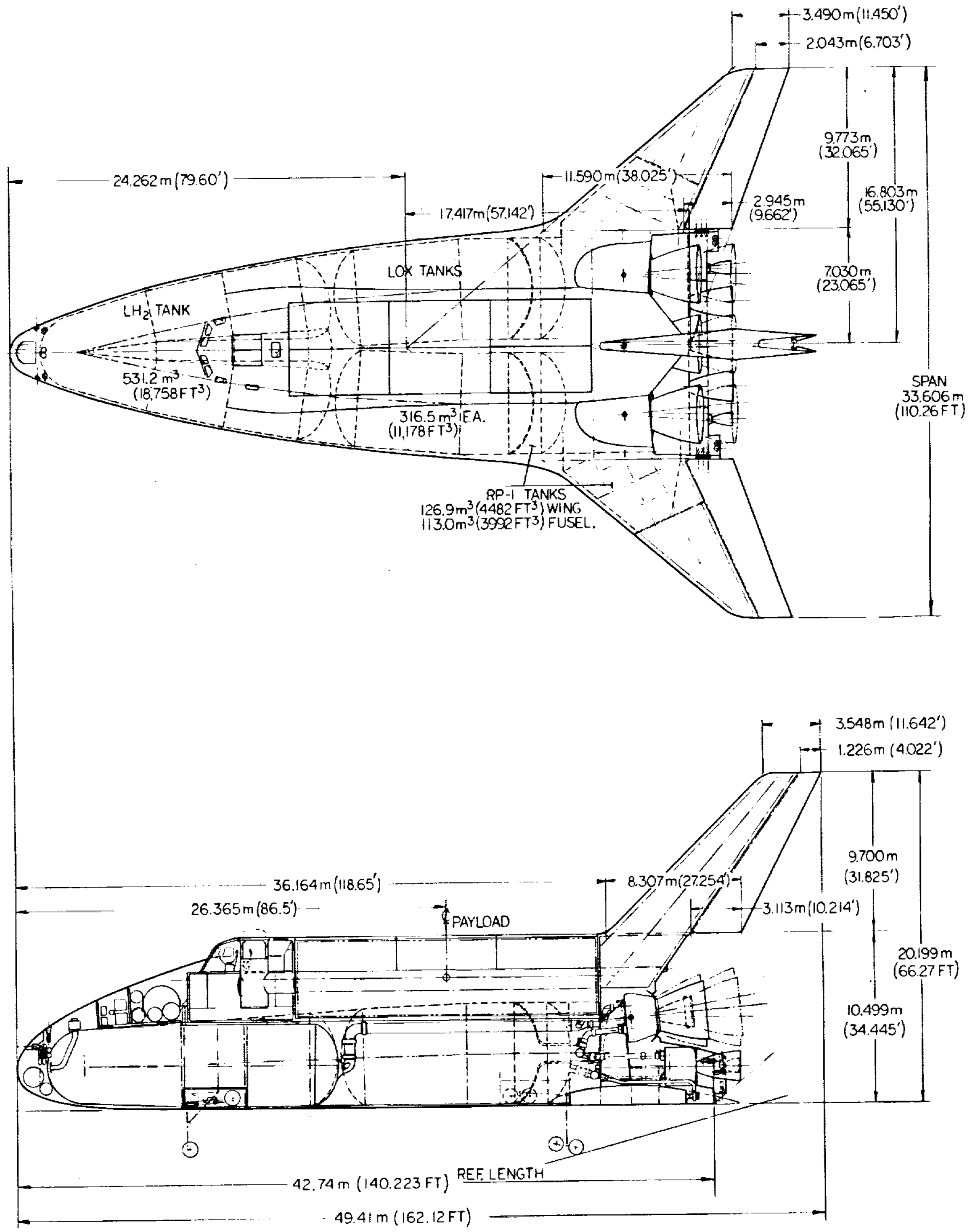


Figure 17.- Series-burn vehicle, layout.

AREAS		
BODY PLAN AREA	472.4 m^2	(5,084 FT^2)
WING, THEORETICAL	351.3 m^2	(3,781 FT^2)
WING, EXPOSED	147.4 m^2	(1,586 FT^2)
ELEVON	48.8 m^2	(525 FT^2)
VERTICAL TAIL	57.5 m^2	(619 FT^2)
RUDDER	21.0 m^2	(226.5 FT^2)
BODY WETTED AREA	1,314.4 m^2	(14,148 FT^2)

VOLUMES		
LH_2 TANK	531.2 m^3	(18,758 FT^3)
LOX TANKS	633.0 m^3	(22,356 FT^3)
RP-1 TANKS	239.9 m^3	(8,474 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)

WEIGHTS			C.G. % REF. LENGTH
PAYLOAD	29,483 kg	(65,000 lb)	61.69
DRY WEIGHT	82,994 kg	(182,970 lb)	
LANDING W/O PAYLOAD	85,956 kg	(189,500 lb)	68.00
LANDING WITH PAYLOAD	115,439 kg	(254,500 lb)	66.39
ASCENT PROPELLANT	1,010,401 kg	(2,227,553 lb)	
GROSS LIFT-OFF WEIGHT	1,143,083 kg	(2,520,068 lb)	65.45

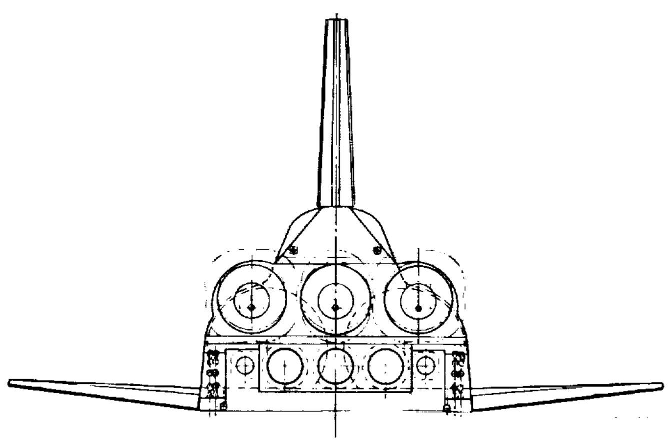


Figure 17.— Continued

TABLE 7.- PARALLEL BURN, MASS PROPERTIES SUMMARY

Code	System	Mass, kg		Weight, pounds	
1.0	Wing group	4 931		10 872	
2.0	Tail group	1 175		2 590	
3.0	Body group	24 445		53 893	
4.0	Induced environmental protection	15 915		35 087	
5.0	Landing and auxiliary systems	3 357		7 401	
6.0	Propulsion ascent	20 092		44 296	
	6.1 Engine accessories		1 048		2 312
	6.2 Feedlines		2 216		4 885
	6.3 Engines		16 828		37 099
7.0	Propulsion-RCS	1 444		3 183	
8.0	Propulsion-OMS	953		2 100	
9.0	Prime power				
10.0	Electrical conversion and distribution	2 653		5 849	
11.0	Hydraulic conversion and distribution	1 074		2 367	
12.0	Surface controls	1 315		2 898	
13.0	Avionics	1 965		4 333	
14.0	Environmental control	1 721		3 795	
15.0	Personnel provisions	499		1 100	
18.0	Payload provisions	270		595	
19.0	Margin	6 505		14 341	
	Dry weight	88 314		194 700	
20.0	Personnel	1 199		2 644	
23.0	Residuals and gases	1 822		4 015	
	Landing weight	91 335		201 359	
22.0	Payload	29 483		65 000	
	Landing with payload	120 818		266 359	
23.0	Residuals dumped	6 057		13 353	
25.0	Reserve fluids	2 459		5 421	
26.0	Inflight losses	1 613		3 555	
27.0	Ascent propellant	923 405		2 035 760	
	27.1 LH_2		77 451		170 751
	27.2 LO_2		761 841		1 679 572
	27.3 RP-1		84 113		185 437
28.0	Propellant-RCS	999		2 202	
29.0	Propellant-OMS	5 578		12 298	
	GLOW	1 060 929		2 338 948	

TABLE 8.- SERIES BURN, MASS PROPERTIES SUMMARY

Code	System	Mass, kg		Weight, pounds	
1.0	Wing group	4 433		9 774	
2.0	Tail group	1 104		2 433	
3.0	Body group	21 858		48 189	
4.0	Induced environmental protection	13 844		30 520	
5.0	Landing and auxiliary systems	3 194		7 041	
6.0	Propulsion ascent	20 982		46 258	
	6.1 Engine accessories		1 036		2 283
	6.2 Feedlines		2 270		5 005
	6.3 Engines		17 676		38 970
7.0	Propulsion-RCS	1 444		3 183	
8.0	Propulsion-OMS	924		2 038	
9.0	Prime power				
10.0	Electrical conversion and distribution	2 561		5 645	
11.0	Hydraulic conversion and distribution	992		2 186	
12.0	Surface controls	1 263		2 785	
13.0	Avionics	1 965		4 333	
14.0	Environmental control	1 721		3 795	
15.0	Personnel provisions	499		1 100	
18.0	Payload provisions	270		595	
19.0	Margin	5 940		13 091	
	Dry weight	82 994		182 970	
20.0	Personnel	1 199		2 644	
23.0	Residuals and gases	1 763		3 886	
	Landing weight	85 956		189 500	
22.0	Payload	29 483		65 000	
	Landing with payload	115 439		254 500	
23.0	Residuals dumped	7 017		15 469	
25.0	Reserve fluids	2 345		5 169	
26.0	Inflight losses	1 613		3 555	
27.0	Ascent propellant	1 010 401		2 227 553	
	27.1 LH_2		36 639		80 775
	27.2 LO_2		789 841		1 741 302
	27.3 RP-1		183 921		405 476
28.0	Propellant-RCS	953		2 102	
29.0	Propellant-OMS	5 316		11 720	
	GLOW	1 143 084		2 520 068	

TABLE 9.- CENTER OF GRAVITY LOCATIONS

Condition of vehicle	$X_{c.g.}$, % of body length	
	Series	Parallel
Dry	68.5	67.5
Landing	68.0	67.1
Landing with payload	65.6	65.5
Liftoff	65.4	69.3
Body length	42.74 m (140.22 ft)	45.54 m (149.43 ft)

LIFE-CYCLE COSTS

Approach and Guidelines

The life-cycle costs (LCC), which include the DDT&E, production, and operations phases of the total systems program, were calculated for each of the candidate vehicle concepts with the aid of a computerized cost model (COCOM). The model included cost estimating relationships (CER) that account for vehicle weight and geometry characteristics in the various program phases. Work breakdown structures, system development schedules, traffic models, and operations schedules were established as bases for the cost analyses. The same cost relationships and schedules as were developed and used in reference 1 continued to be used in this study for consistency in relative values of costs and figures of merit.

The CERs for dual-mode propulsion, as identified for the present study, are presented later in this report. Also, the research and technology (R&T) costs for dual-mode propulsion are presented later. These R&T costs are regarded as sunk costs and therefore are not included in the life-cycle costs.

An overall program schedule for the SSTO project is shown in figure 18. This schedule correlates with milestones given for this study that designated the start of Phase A, the ATP (authority to proceed), and the IOC (initial operational capability). The schedule permits a time span of up to 10 years for supporting research and technology (R&T) activities before ATP. In the event that dual-mode propulsion is selected as a systems goal for focusing NASA projects, the R&T activities would include propulsion programs that would provide a sound technical base for the later DDT&E of dual-mode engines. During the five years from the start of Phase A to ATP, the design of the flight vehicle is developed and long-lead time orders are prepared. The development of the appropriate main rocket engines begins soon after Phase A go-ahead, as this is a long-lead time activity.

The main engine DDT&E extends from 1983 through 1991. Engine manufacturing is scheduled to start in 1989. An estimated engine delivery schedule based on VTO configurations with six series-burn and eight parallel-burn engines is shown in table 10. Five vehicles are used in the flight operations.

The launch processing system development starts after the ATP and is to be complete in 1992. An operational checkout period is planned from mid-1992 through mid-1993. On completion of the checkout effort, the system will be available for operations beginning with the FMOF (first manned orbital flight) in 1993.

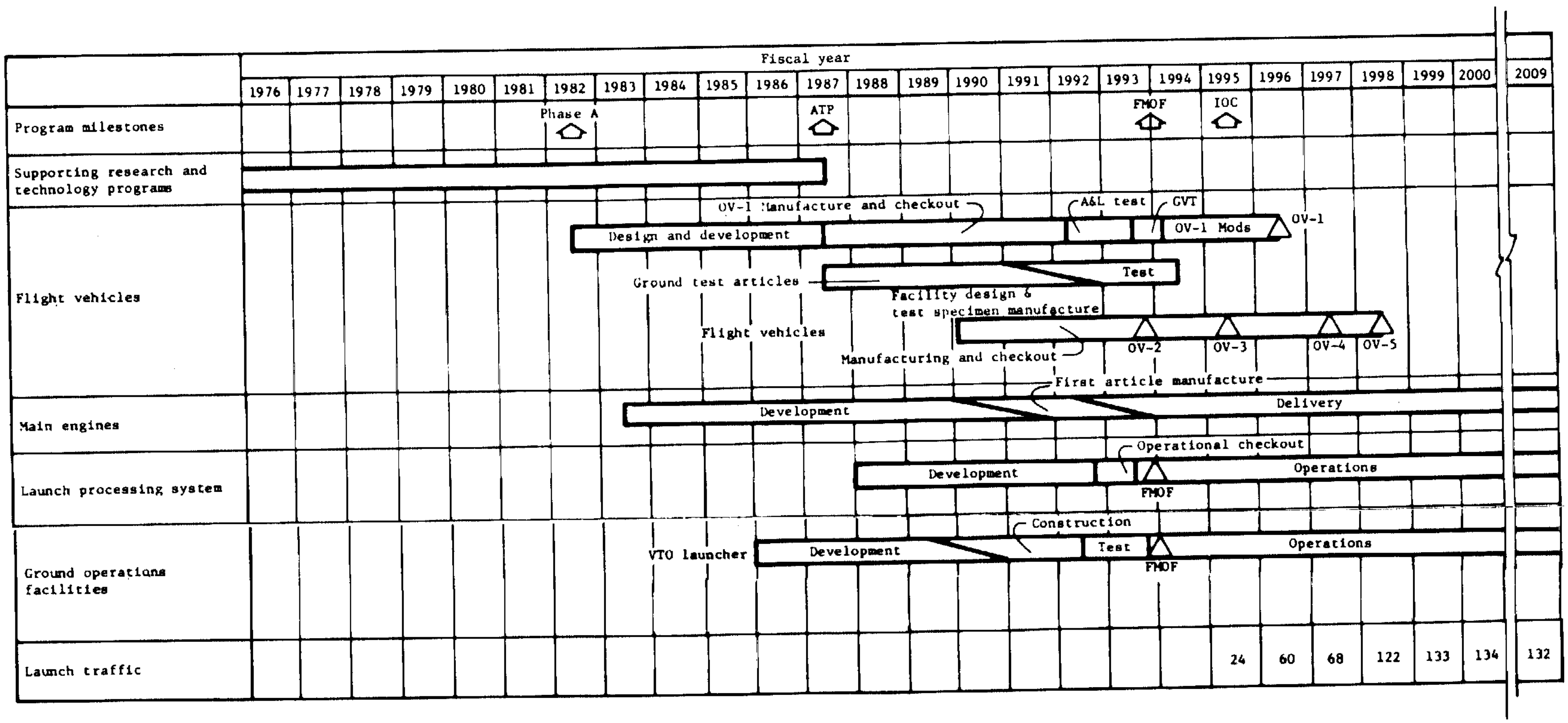


Figure 18.- System development schedule.

TABLE 10.- ENGINE DELIVERY SCHEDULE

	Series	Parallel
Basic requirements		
5 vehicles x number of engines per vehicle	30 engines	40 engines
Spare engines, 20%	6 engines	8 engines
Component spares, 20%	6 equivalent engines	8 equivalent engines
Major overhaul, 50%	15 equivalent engines	20 equivalent engines
Vehicle test articles		
1-1/2 equivalent vehicles + 30% spares	12 engines	15 engines
Total (engines and equivalent engines)	69	91

Year	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Series burn	4	8	8	8	8	8	8	8	5	4	0
Parallel burn	4	8	10	10	10	10	10	10	10	5	4

The Ground Operations Facilities require development of a vertical takeoff launcher and normal runways for landing. The initial development effort starts in early 1986. Construction extends from mid-1989 to mid-1992. A 1½-year test period has been scheduled before the FMOF. The SSTO system is to be completely tested and fully operational in 1995.

The operational traffic model for the SSTO program was derived in reference 1 for use in analyzing life-cycle costs. This model, used again in this dual-mode propulsion study, consists of 1710 launch attempts spread over a 15-year period from 1995 through 2009 (table 11). The launch and ground operations are anticipated to use automatic checkout equipment and computerization that permit 60-hour turnaround times. The main engines, designed for a 200-cycle life, require minimal scheduled maintenance between flights.

The COCOM program generates the life-cycle costs (LCC) on a year-by-year basis using fiscal year 1976 dollars. Costs are quoted based on 10% annual discounting, as well as fiscal year 1976 dollars. These costs include a 10% fee. Guidelines for cost estimating included the anticipated costs of propellants as follows:

Propellant	Cost per kg (lb), $ FY 1976
Liquid hydrogen (subcooled)	$2.2 ($1.0)
Liquid oxygen (subcooled)	$0.04 ($0.02)
RP-1	$0.13 ($0.06)

Engine Cost Estimating Relations

The relative merits of dual-mode propulsion compared to single-mode (all LO_2/LH_2) requires a comparison of relative total program costs, including main engine costs. Definitive costs of the various dual-mode candidates have not been derived as yet. Nevertheless, for this study, CERs for the engine DDT&E and production phases were selected as functions of thrust level based on data from a 1971 engine cost study (NASA/OART working paper MA-71-3) as well as expert engineering judgement including consistency with the engine costs used in reference 1.

TABLE 11.- TRAFFIC MODEL

Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Number of launch attempts	24	60	68	122	133	134	133	126	128	118	140	130	131	131	132

These engine CERs are functions of vacuum thrust, as illustrated in figure 19. The equations are as follows:

Cost estimating relation ($Millions)

Engine type	DDT&E	Production
LO_2/LH_2	(1) $= 1.3(50 + 1.405F^{0.422}) - 183.4$	(3) $= 1.3(350 + 0.475F^{.7})N^{-0.074} \times 10^{-3} + 0.5$
LO_2/RP-1	(2) $= 1.3(50 + 0.865F^{0.422}) - 83.4$	(4) $= 1.3(270 + 0.024F^{.8})N^{-0.074} \times 10^{-3} + 2.5$
Dual-fuel	(A) $= 0.55 \times$ (2)	(C) $= 1.15 \times$ (3)
Dual-fuel	(B) $= 1.55 \times$ (2)	

where F is the vacuum thrust (lb) and N is the number of engines per vehicle. The factor 1.3 is used to adjust the costs for escalation from 1971 to 1976 costs. The exponent of N is based on a 95% learning curve for engine production; the production CER yields an average cost per unit.

For the dual-fuel engine, two equations are used, representing lower and upper extremes. The CER A is based on the approach that an RP-1 engine is developed, then additional development is needed to add a capability for switching the fuel from RP-1 to LH_2 and to add an extendible (two-position) nozzle. It is assumed that, with the additional features, the basic RP-1 development test does not need to be rerun. In essence, in this approach the dual-fuel engine is the RP-1 engine with the addition of a LH_2 modification, with the additional cost represented by CER A. The CER B is based on the extreme approach that the complexities of the dual-fuel engine requires not only the addition of the LH_2 cycle and extendible nozzle, but also requires duplicate development, tests, and evaluations of RP-1 components to achieve the high performance of the RP-1 cycle in the dual-fuel environment. Costs are shown in subsequent tables to show the cost spread from CER A to CER B.

Figure 19 shows a point representing the DDT&E costs currently quoted for the main engine now being developed for the Space Shuttle (SSME = Space Shuttle Main Engine, F = 2090 kN, 470 klbf). A CER curve has been drawn through this point parallel to curve 1 . The level of CER 1 was selected with considerations that a LO_2/LH_2 engine for SSTO would cost less to develop than the SSME engine inasmuch as the SSTO hydrogen engine would be similar to the SSME in thrust level and design, and also would have the technology growth associated with normal research and SSME product improvements over the next 10 years. If the SSTO were to use

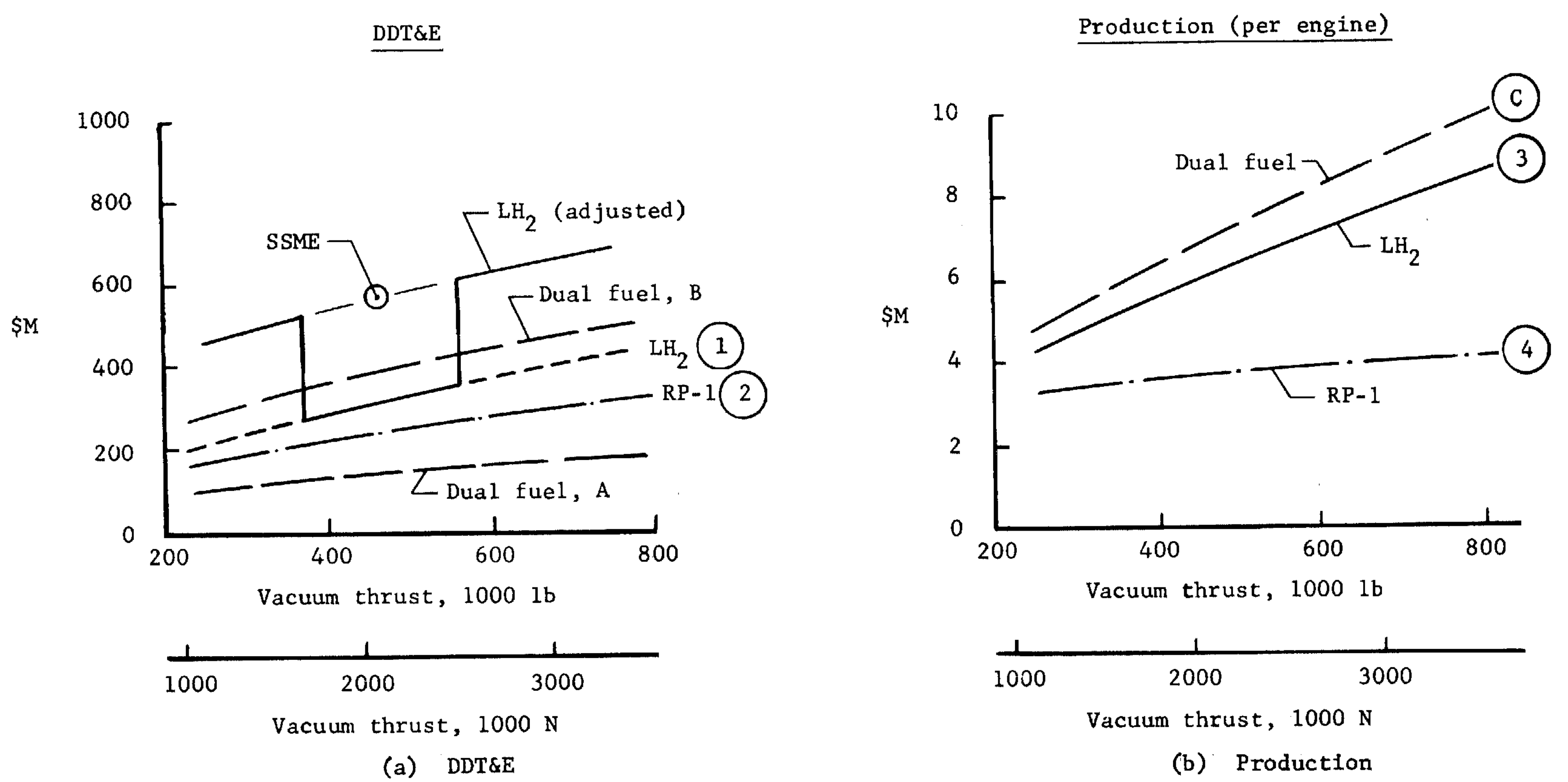


Figure 19.- Main engine costs.

hydrogen engines with thrust levels more than 20%, say, from SSME thrust levels, the advantages of the similarity to SSME could not be realized. The DDT&E costs then would more nearly be represented by the CER which passes through the SSME point. The CER for LO_2/LH_2 engines is therefore chosen, as shown in figure 19, with a discontinuity where the thrust is 20% from the SSME thrust. The incremental cost at the discontinuity is $260 million. For the dual-fuel engines, also, where the hydrogen vacuum thrust deviates more than 20% from that of the SSME, an increment of $185 million was added to CERs A and B. These incremental values were only applied in the cost analysis to select the numbers of engines for the series and parallel burn vehicles. If these increments were as small as 10% ($40 million), the selected numbers would not change, demonstrating that the discontinuity assumed here is not affecting our general decisions and conclusions.

A conclusion from this activity is that a more erudite analysis of engine costs for candidate engine types is needed. These analyses should be based on current knowledge of engine characteristic designs, their development and production processes and costs, together with relevant technology and cost projections from the 1980 to 1990 time period.

SSTO Program Costs

Cost data for DDT&E, production, and operations are presented in tables 12, 13 and 14, respectively, for the reference single-mode VTO vehicle and for the series-burn and parallel-burn vehicles. The life-cycle costs, summarized in table 15, are given in fiscal year 1976 dollars and in discounted dollars at a 10% rate.

These data show that the program costs for these vehicles with dual-mode propulsion are less than for the extended-performance single-mode vehicle. The cost savings (fiscal year 1976 dollars) is at least $435 million (parallel-burn vehicle) up to $812 million (series-burn vehicle, CER A). Savings range to 8.4%. Program costs for the series-burn and parallel-burn vehicles deviate no more than 4.2% from each other, indicating that the LCC is not a strong driver in selecting series-burn or parallel-burn modes.

Table 16 shows costs of selected items for comparison between the series-burn and parallel-burn vehicles. The DDT&E costs for engines are about 12% of the DDT&E costs for the vehicle and other support. Engine production and spares costs for the parallel-burn vehicle are about 13% more than for series, whereas LH_2 costs are more than twice as much.

TABLE 12.- DDT&E COSTS

Cost element	Fiscal year 1976 $ millions		
	Single-mode propulsion	Dual-mode propulsion	
		Series*	Parallel
Program management	303	302	299
Systems engineering and integration	539	539	534
Air vehicle design	2 002	2 150*	2 043
Ground support equipment	296	296	296
Training	172	172	172
Systems test and evaluation**	1 098	982	1 015
Logistics	45	45	45
Facilities	466	466	466
Fee	415	415	410
Total	5 336	5 367*	5 280

* 2.5 equivalent air vehicles

**Based on CER B for dual-fuel engine DDT&E

TABLE 13.- PRODUCTION COSTS

Cost element	Fiscal year 1976 $ millions		
	Single-mode propulsion	Dual-mode propulsion	
		Series	Parallel
Structures	199	152	158
Thermal protection	25	19	20
Landing gear	15	12	13
Propulsion	259	197	217
Avionics	101	101	101
ECLS	28	28	28
Power, hydraulics	137	132	133
Final assembly and checkout	191	158	168
Sustaining engineering	30	25	27
Sustaining tooling	38	32	33
Fee	102	85	90
Total	1 125	941	988
First article cost	283	237	250

TABLE 14.- OPERATIONS COSTS PER FLIGHT

Cost element	Fiscal year 1976 $ millions		
	Single-mode propulsion	Dual-mode propulsion	
		Series	Parallel
KSC civil service	0.092	0.092	0.092
Launch operations	0.861	0.670	0.747
Flight operations (JSC)	0.704	0.704	0.704
Refurbishment	0.077	0.077	0.077
Engines	0.147	0.105	0.119
Totals	1.881	1.648	1.739

TABLE 15.- LIFE-CYCLE COSTS

Cost Item	Single Mode		Series Burn		Parallel Burn	
	FY '76 $M	Discounted $M	FY '76 $M	Discounted $M	FY '76 $M	Discounted $M
DDT&E	5336	1588	5106 to 5367	1519 to 1597	5280	1569
Production	1125	227	941	189	988	200
Operations	3216	239	2818	211	2974	219
Total	9677	2054	8865 to 9126	1919 to 1997	9242	1988
First Article Cost	283	----	239	----	250	----

TABLE 16.- COST COMPARISON

Item	Series FY '76 $M	Parallel FY '76 $M
DDT&E Costs		
Engines	435 to 696	573
Vehicle and support	4671	4707
Production Costs		
Vehicle set of engines	34	39
Operations Costs		
LH_2 costs	144	300
Engine spares	180	204
RP-1 costs	42	19

Variations of cost with numbers of engines are shown in table 17. These data were calculated by resizing vehicles for each of the engine combinations, including variations in $\Delta V_1/\Delta V^*$ for optimal sizing. The weight and size characteristics of the optimal vehicles were then used as input to the COCOM cost model. The results show that the total cost is least for the series vehicle with three dual-fuel engines and three RP-1 engines, and for the parallel vehicle with four LH_2 engines and four RP-1 engines. The series vehicle with fewer than six engines would show larger total costs because of the larger required thrust level.

Other perturbations on SSTO dual-mode design parameters and subsequent cost calculations were studied. Two major results were that the gas generator cycle (parallel burn) yielded a LCC savings of $29 million over the staged combustion cycle, and vehicles with RP-1 tanks in the wing box and wing structures yielded LCC savings of $36 to $50 million over dry wing designs. The basic series-burn and parallel-burn vehicle designs therefore use wet wings and for the parallel burn, RP-1 engines with the gas generator cycle are used. Additional LCC cost sensitivities are tabulated in table 18 based on perturbed vehicle designs. All perturbations showed program cost variations of less than 6% from the basic LCCs for dual-mode propulsion.

The cost analysis has shown a significant program cost reduction for dual-mode systems compared with the reference single mode system. The analysis also showed that the costs for series-burn and for parallel-burn concepts were about the same, but that better CERs for the various engine types would be desirable to aid in future decisions.

TABLE 17.- SENSITIVITY OF LIFE-CYCLE COSTS TO ENGINE CONFIGURATION

Cost item	Engine configuration*	Series Burn		Parallel Burn	
		FY '76 $M	Discounted $M	FY '76 $M	Discounted $M
DDT&E	3/3	5106 to 5367	1519 to 1597	5670	1649
	4/4	5203 to 5432	1548 to 1615	5280	1569
	5/5	5159 to 5365	1535 to 1596	5467	1612
Production	3/3	941	189	969	196
	4/4	964	194	988	200
	5/5	988	198	1012	205
Operations	3/3	2818	211	2960	218
	4/4	2843	213	2974	219
	5/5	2864	214	2994	220
Total	3/3	8865 to 9126	1911 to 1997	9599	2063
	4/4	9010 to 9239	1955 to 2022	9242	1988
	5/5	9011 to 9217	1947 to 2008	9473	2037

*For series burn, 3/3 denotes three dual-fuel engines and three LO_2/RP-1 engines
For parallel burn, 3/3 denotes three LO_2/LH_2 engines and three LO_2/RP-1 engines

TABLE 18.- LIFE-CYCLE COST SENSITIVITIES

Item varied	Type of variation	Increase (decrease) in life-cycle costs, \$M			
		Series		Parallel	
		FY '76	Discounted	FY '76	Discounted
Hydrogen costs	Increase from \$2.2/kg (\$1/lb) to \$4.4/kg (\$2/lb)	144	11	300	23
$\Delta V_1 / \Delta V^*$	Increase from 0.41 to 0.49 (series) 0.40 to 0.45 (parallel)	140	31	6	1
	Decrease from 0.41 to 0.28 (series) 0.40 to 0.38 (parallel)	293	64	9	1
Engine Performance	I_{sp} increase** and engine weight decrease	-264	- 62	-375	-81
	I_{sp} decrease** and engine weight increase	499	118	456	98
	Decrease nozzle efficiency from 0.98 to 0.968 (LH_2 engine)	--	--	155	33
LH_2 Density	Increase from 72.1 kg/m^3 (4.5 lb/ft^3) to 75.3 kg/m^3 (4.7 lb/ft^3)	- 16	- 4	- 33	- 8

**See following table for specific changes

Engine parameter	Series		Parallel	
	LO_2/RP-1 engine	Dual-fuel engine	LO_2/RP-1 engine	LO_2/LH_2 engine
Weight increase	20%	20%	20%	10%
Weight decrease	- 5%	- 5%	- 5%	-10%
I_{sp} increase	7 sec	7 sec 1) 5 sec 2)	7 sec	9 sec
I_{sp} decrease	- 7 sec	- 7 sec - 5 sec	- 7 sec	- 5 sec

1) Mode 1
2) Mode 2

ACCELERATED TECHNOLOGY RESEARCH PROGRAMS

The previous accelerated technology assessments (ref. 1) identified technology areas offering the greatest cost and performance benefits for SSTO, VTO, LOX/LH_2 propellant vehicles that could result from focused R&T and additional funding. The additional funding represented R&T funding above normally expected levels. Technology parameters were selected that offered a potential for significant improvement in vehicle dry weight. These parameters related to the primary technology areas of materials, structures, and propulsion as well as secondary technologies taken as a whole and vehicle design criteria and design margin requirements. Research and technology programs that could be implemented to pursue the improvements in the parameters were also identified.

The overall effects on vehicle size and weight were calculated for each technology improvement and the costs determined. Cost and performance benefit figures of merit were then determined for the various technology improvements to form the basis for assessments of the merits of accelerated technologies.

Twelve research programs (table 19) were selected for assessment of the potential benefits of accelerated funding and emphasis. Seven of the twelve programs relate to advancements in materials, structures, and system support areas. The remaining five programs relate to propulsion; one program addresses auxiliary (OMS/RCS) propulsion, one is the use of supercooled high density propellants, and the last three of special interest here relate to the main engines.

Results of the previous accelerated technology assessments revealed that the structures, TPS, and subcooled propellant programs were prime candidates for accelerated activities and the benefits derived from them are included in the vehicle designs discussed in this report. The propulsion programs, which focused primarily on LO_2/LH_2 main engine improvements, did not show reasonable payoffs from accelerated funding. That is, the benefits to vehicle size and cost would not offset the relatively high research costs associated with these programs, in part because the SSME has already attained a high level of technology. However, the main engine areas of investigation are similar to those areas requiring focused effort and additional funding to develop dual-mode propulsion.

These dual-mode propulsion research and technology programs are identified as programs 6, 7, and 8 in table 19 using the same titles as in reference 1. Each program will consist of a concept design analysis and optimization phase, and component and subsystem test phases. The projected research and technology costs for these programs over and above the previously projected $10 million

TABLE 19.- ACCELERATED TECHNOLOGY PROGRAMS

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

per year "normal" propulsion R&T costs are shown in Table 20 for the parallel-burn approach and the series-burn approach. Estimated annual funding levels of these R&T costs and associated time spans of the required overall activities are given in figure 20. The accelerated R&T efforts are scheduled to start early in 1977 and to complete in 1985, overlapping the start of the prototype engine development by approximately three years. The objectives, activities, and type of testing required for the three main propulsion R&T programs are discussed in the following sections.

Main Engine Injectors/Chambers/Nozzles

The objective of this program will be to establish high-pressure LO_2/RP-1 engine technology through intensive research of candidate components that may comprise the thrust chamber assembly. If dual-fuel engines are to be used, additional effort will be required to ensure hardware configuration and performance compatibility with both propellant combinations. Activities are outlined in the following subparagraphs.

Thrust chamber assembly analysis and design.-

(1) Develop injector pattern to improve performance, reduce pressure drop, improve combustion stability, and reduce required chamber length.

(2) Develop injector structural design to accommodate pattern changes and to minimize weight. This effort will include investigation of new manufacturing techniques, combustion chamber size, shape and structural configuration to reduce weight, improve performance, and maintain sufficient cooling.

(3) Explore applicable engine cycles to improve performance and, in particular, to extend engine life and reuseability. The design optimization will include examination of oxidizer and fuel-rich preburners or gas generators and component integration to reduce valves, lines, etc.

(4) Evaluate the injector and combustion chamber technology improvements derived for primary thrust chambers as applied to gas generators and preburners. In addition, investigate higher performing fuel-rich and oxidizer-rich designs. Injector pattern development with reduced pressure drop will contribute to higher subsystem efficiency and reduced weight.

(5) Conduct compatibility/integration analysis and design studies for both dual-fuel propellant combinations. The new LO_2/RP-1 technology derived above and SSME LO_2/LH_2 experience will be used.

TABLE 20.- R&T COSTS FOR FOCUS ON DUAL-MODE PROPULSION

	Parallel burn engines		Series burn engines	
	LO_2 + RP-1	LO_2 + LH_2	LO_2 + RP-1	Dual-fuel
Cooling	$12.0M	$7.8M	$12.0M	$ 7.8M
Pumps	$14.0M	None (use SSME technology plus normal growth)	$14.0M	$ 5.0M
Injector/Chamber/Nozzles	$20.0M	None	$20.0M	$ 5.0M
Fuel switchover	None	None	None	$ 9.0M
Totals	$46.0M	$7.8M	$46.0M	$26.8M
	$53.8M		$72.8M	

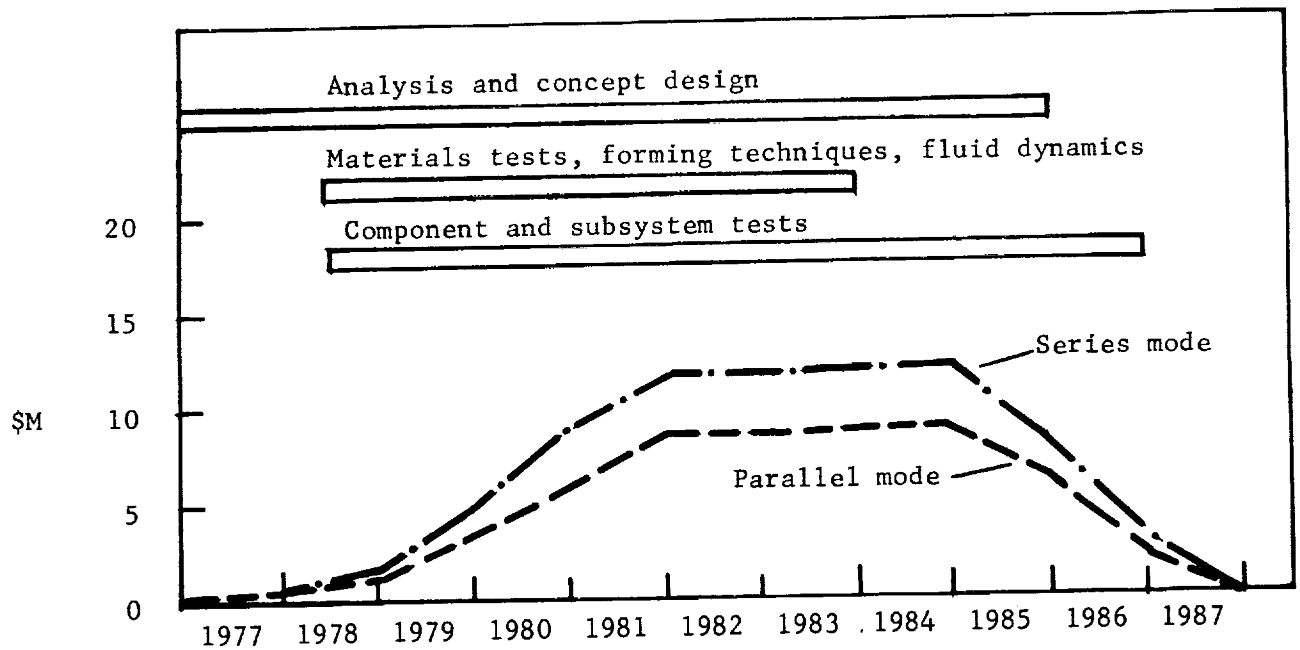


Figure 20.- Dual-mode propulsion R&T programs and cost.

Research and laboratory tests.-

(1) Investigate higher strength metals and composite materials to establish applicability, material characteristics, and design criteria.

(2) Develop new manufacturing and forming techniques paralleling the design concepts.

Subsystem tests.-

(1) Build and test components and subassembly hardware representing the most promising concepts and cycle features.

(2) Although no new major facilities will be necessary, test fixtures, new instrumentation, and modification of existing facilities will be required.

(3) Conduct specific tests to demonstrate hardware compatibility, and performance and operational feasibility using both dual-fuel propellant combinations. Switchover from hydrocarbon fuel to hydrogen will be demonstrated and the characteristics defined.

Main Engine Pumps

This R&T program will be directed toward achieving the extremely high LO_2 and RP-1 pump discharge pressures necessary to obtain the desired 27.6 mN/m^2 (4000 psia) chamber pressures. Efforts will also be directed toward turbine and propellant pump improvements that increase efficiencies, improve component life, and reduce weight. Activities are as follows.

Turbopump assembly design analysis.-

(1) Optimize propellant impeller, diffuser, and blade design. Particularly emphasize cavitation phenomena definition and suppression.

(2) Investigate turbine cooling extensively to extend life and to improve performance by allowing higher turbine inlet gas temperatures.

(3) Pursue pump bearing development and seals improvements (possibly through seal elimination).

Research and laboratory tests.-

(1) Accomplish new materials research for application to pumps, turbines, and drive mechanisms.

(2) Investigate new manufacturing and forming processes.

Subsystem tests.- Manufacture and test components and subassembly test hardware using existing facilities. Some modification of existing facilities, some new fixtures, and additional instrumentation will be required.

Main Engine Cooling

The primary objective of this program will be directed toward weight reduction and performance improvement through chamber, nozzle, and turbine cooling improvement. If dual-fuel engines are to be used, regenerative cooling with LO_2 is preferred. If a parallel-burn technique is used with dedicated LO_2/LH_2 and gas generator cycle, hydrogen cooled LO_2/RP-1 engines and improved LH_2 cooling at higher pressures is required.

Thrust chamber assembly and turbine design analysis.-

(1) Reduce system pressure losses by developing better cooling techniques. Lower pressure losses reduce pump discharge pressures and power requirements, resulting in smaller lighter pumps, turbines, and preburners or gas generators.

(2) Investigate oxidizer or both propellants as the coolant. Because of density, higher liquid oxygen pump discharge pressures are easier to attain than those with liquid hydrogen. The system can be optimized for minimum engine weight or higher chamber pressures.

(3) Research new materials and coatings toward minimizing the heating effects on engine hardware thus reducing cooling requirements and giving longer life.

Research and laboratory tests.-

(1) Test new materials and coatings for effectiveness and to establish design criteria.

(2) Test propellants to better define their fluid properties, heat transfer characteristics, and cooling capabilities.

(3) Conduct model heat transfer tests of representative cooling configurations.

Subsystem tests.- Conduct single component and subassembly tests of the best designs using LO_2, LH_2, or both propellants as coolants.

MERIT ASSESSMENTS OF DUAL-MODE PROPULSION

The accelerated technology assessments of reference 1 include the identification and development of figures of merit (FOM). These FOMs aided in the assessment by providing quantitative data for comparisons of the cost/performance benefits of the various technology areas. Different types of FOMs were selected as meaningful, including vehicle weights, program (LCC) costs, transportation costs, R&T costs, and the ratio of LCC savings to R&T costs. Selected FOMs were ranked according to their relative nominal values; the technology areas that exhibited FOMs in the upper three quartiles were recommended for accelerated research beyond "normal" R&T. In addition to the expected (nominal) values, estimates of maximum and minimum values were made representing 95% confidence intervals. The present study to assess the relative merits of dual-mode compared to single-mode propulsion uses the same approach.

The advantage of dual-mode over single-mode propulsion was isolated from effects of applying other accelerated technology in the FOM analysis. The VTO single-mode vehicle, sized with accelerated technology, was used as a reference vehicle, and dual-mode vehicles were also sized with the same accelerated technologies. This reference vehicle already exhibits substantial reductions in size over the corresponding "normal" technology, single-mode vehicle. It was, therefore, interesting to calculate effects of applying dual-mode propulsion with all other technolgies "normal." These "normal" technology results, with and without dual-mode propulsion, gives FOMs that can be compared with those of reference 1. The following paragraphs present FOMs using both the accelerated technology reference and the "normal" technology reference.

The weights and costs of the three types of vehicles, all using accelerated technology, are shown for comparison in table 21. This table includes a merit index, which is the transportation cost; that is, cost per unit weight of payload delivered to earth orbit. These data, again, demonstrate advantages of dual-mode over single-mode propulsion. They reflect use of the expected values of weight, performance, and cost parameters. A comparison of the percentage weight improvements that result from application of dual-mode propulsion is illustrated in figure 21. The weight gains are shown to be larger percentages if other technology areas have normal growth rather than accelerated technology growth projections. Further, the series mode has somewhat better dry weight gains than does the parallel mode, although the parallel mode has better GLOW gains.

A set of FOMs is presented in table 22 for the propulsion technology area pursuing dual-mode concepts. Again, the reference vehicle for the incremental values of the various weight, cost, and FOMs is the accelerated performance single-mode VTO vehicle. (The reference vehicle for the corresponding table 41 of reference 1 is the "normal" technology VTO vehicle.) The percentage variations on engine specific impulse and weight represent the 95% confidence intervals selected for the sensitivity analyses (table 18). The upper and lower limits of I_{sp} and weight were applied to vehicle resizing and program recosting. These limits, together with the maximum and minimum estimates of R&T costs, yield the maximum/minimum values of FOMs for comparison with the expected values.

TABLE 21.- COMPARISON OF VEHICLE CONCEPTS, WEIGHTS AND COSTS (ALL WITH ACCELERATED TECHNOLOGY)

	Vehicle		
		Dual mode	
	Single mode	Series	Parallel
Dry weight			
kg	114 029	82 994	88 314
lb	251 390	182 970	194 700
GLOW			
kg	1 207 219	1 143 084	1 060 929
lb	2 661 463	2 520 068	2 338 948
Total program costs, dollars in billions			
Fiscal year 1976	9.67	8.87 to 9.13	9.24
Discounted 10%	2.05	1.92 to 2.00	1.99
Merit index*, dollars/kg (dollars/pound)			
Fiscal year 1976	63.8 (28.9)	55.9 (25.4)	59.0 (26.8)
Discounted 10%	4.7 (2.2)	4.2 (1.9)	4.3 (2.0)

*(operations costs)/(number of flights)(payload)

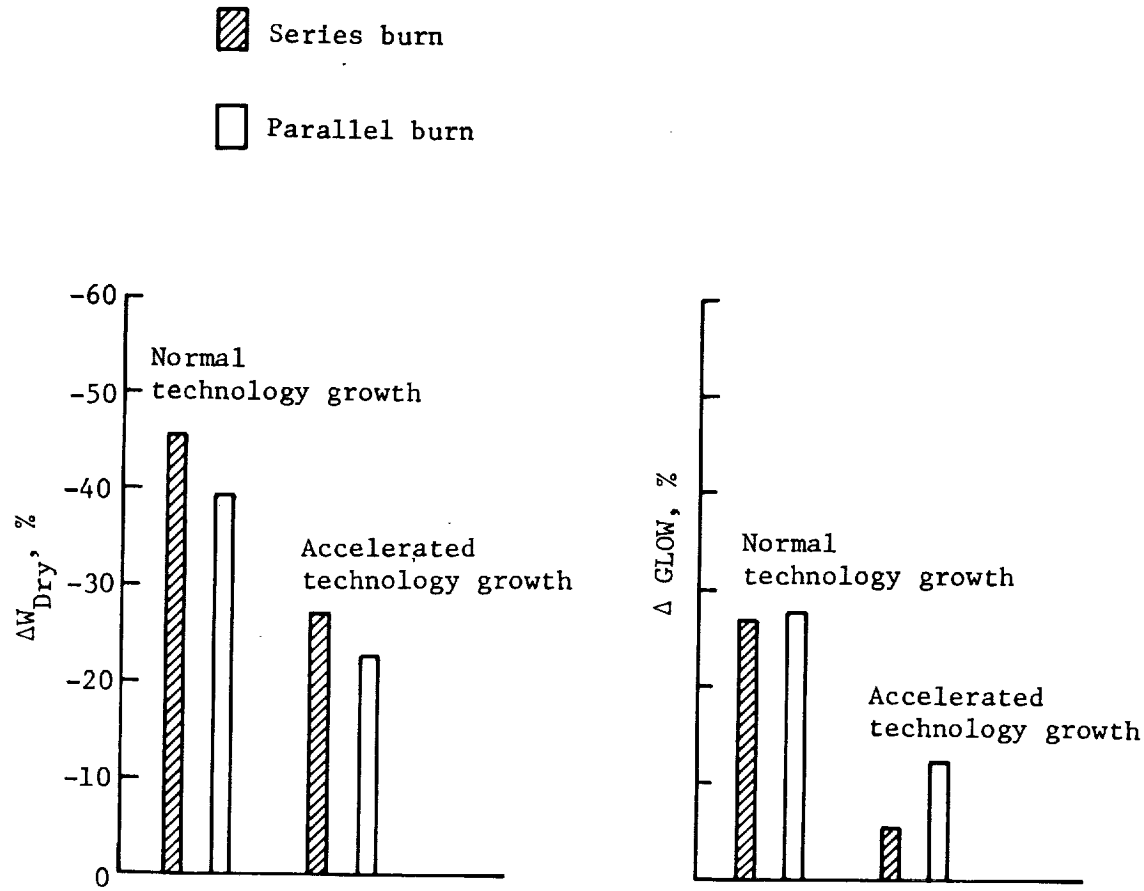


Figure 21.- Dual-mode vehicle weight reductions to single-mode VTO vehicles.

TABLE 22.- FIGURES OF MERIT

Technology program	Technology values: I_{sp}, sec; W, kg (lbm)	Technology values: $\pm$ Tolerance	$\Delta\$R_D$ $M (max / min)	ΔW_{dry} kg (lbm)	ΔGLOW kg (lbm)	$\Delta\$$ DDT&E$_D$ $M	$\Delta\$$ Prod$_D$ $M	$\Delta\$$ Ops$_D$ $M	$\Delta\$$ LCC$_D$ $M (max / min)	$\Delta\$LCC_D - \$R_D$ $M	$\frac{\Delta\$LCC}{\Delta\$R}$	$\frac{\Delta\$LCC_D}{\Delta\$R_D}$ (max / min)
Dual-mode propulsion												
1. Parallel burn												
RP-1 engine, I_{sp}	356.5	$\pm$ 2%										
W	1145 (2524)	+ 20% - 5%	32.8 (44.6 / 25.1)	-25 537 (-56 300)	-146 057 (-322 000)	19	27	20	66 (147 / -32)	33.2 (122 / -77)	8.1	2.0 (5.9 / -1.3)
LH_2 engine, I_{sp}	466.5	+1.9% -1.1%										
W	3062 (6750)	+ 10% - 10%										
2. Series burn												
RP-1 engine, I_{sp}	356.5	$\pm$ 2%										
W	2024 (4463)	+ 20% - 5%				69	38	28	135 (172 / 16)	90.7 (138 / -44)	11.2	3.0 (5.1 / 0.5)
			44.3 (60.3 / 34.0)	-30 858 (-68 030)	- 49 895 (-110 000)	to	to	to	to	to	to	to
Dual-fuel engine, I_{sp}	460.5	$\pm$1.1%				-9*	38	28	57 (119 / -61)	12.7 (85 / -121)	7.6	1.3 (3.5 / -1.0)
W	3868 (8527)	+ 20% - 5%										

*Negative because of CER for engine uses 1.55 factor. Other negative values result from low projections of minimum engine performance.

The Δs are relative to the accelerated technology single-mode VTO vehicle.

The ratio of LCC savings to research costs, $\Delta\$LCC/\Delta\$R$, is a primary FOM for assessing technology benefits, and is shown for both discounted and fiscal year 1976 dollars in the right hand columns of table 22. The net funding FOM, $\Delta\$LCC - \Delta\$R$, is also tabulated (discounted). The expected (nominal) values of these FOMs for parallel burn are within the ranges of expected values for series burn. Furthermore, the maximum/minimum limits are approximately the same, but exhibiting a potential negative payoff when the low performance, high weight engine technology is assumed. These costs and figures of merit are illustrated in figures 22 and 23.

In figure 22, the life-cycle cost savings and R&T costs are shown for the expected (nominal) values and maximum/minimum limits. The upper and lower boundaries of each bar represent the possible LCC savings whereas the right and left boundaries represent possible R&T costs to achieve the technology goals of dual-mode propulsion (taken as 95% probability limits). These incremental saving and costs are relative to the single-mode accelerated technology VTO vehicle, as before. Possible LCC savings can be more than twice the expected values, although there is a small risk (less than 1/10) of a negative payoff if the research goals are not achieved and engine performance is well below expected values. The dashed line was derived in reference 1 to differentiate technology areas with FOMs in the upper two quartiles from those in the lower two quartiles, using the single-mode normal growth VTO as a reference. Technologies, such as dual-mode propulsion represented in figure 22, that have LCC savings near this line or above it are technologies with potentials for good cost/performance benefits. Dual-mode propulsion meets these criteria.

Furthermore, using $\Delta\$LCC_D/\Delta\$R_D$ as the reference FOM (figure 23), dual-mode propulsion again exhibits substantial program payoffs for the research dollars used. It is exceeded in merit only by the areas designated as integration engineering, miscellaneous structures, and wing and vertical tail structures described later. (Refer to table 42 of reference 1). Data are presented in table 23 for the FOMs showing the benefits of dual-mode propulsion applied with the accelerated technology reference, and, in addition with the normal technology reference for comparison with reference 1 results.

Table 23 first shows FOMs for applying dual-mode propulsion, in combination with selected accelerated technology programs, to the accelerated technology vehicle. The upper row is the expected value data from table 22 giving the basic merits of dual-mode propulsion with the other accelerated technologies with good potential payoffs. The lower row of table 23 shows that if R&T activities in

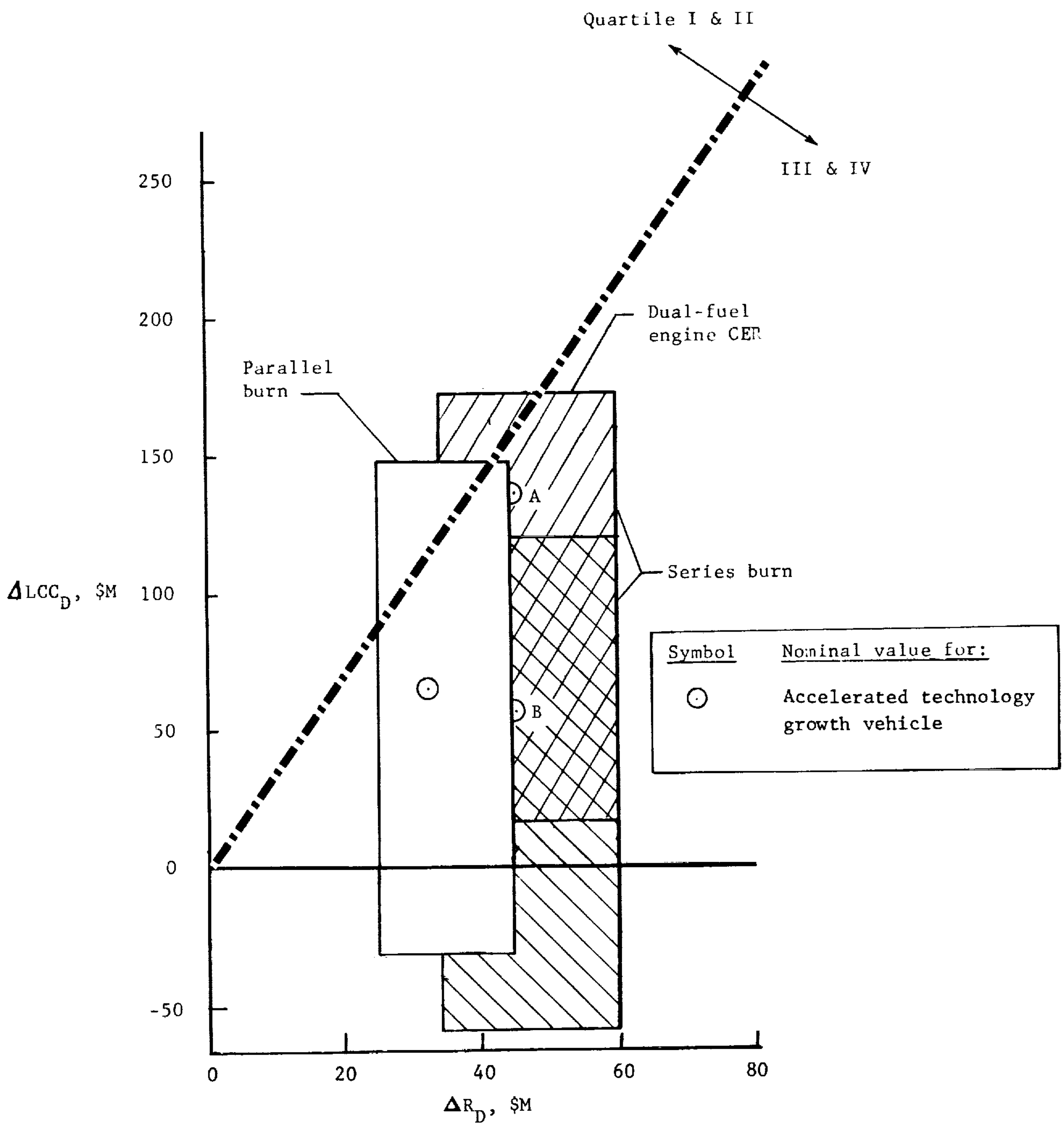


Figure 22.- Life-cycle cost figures of merit

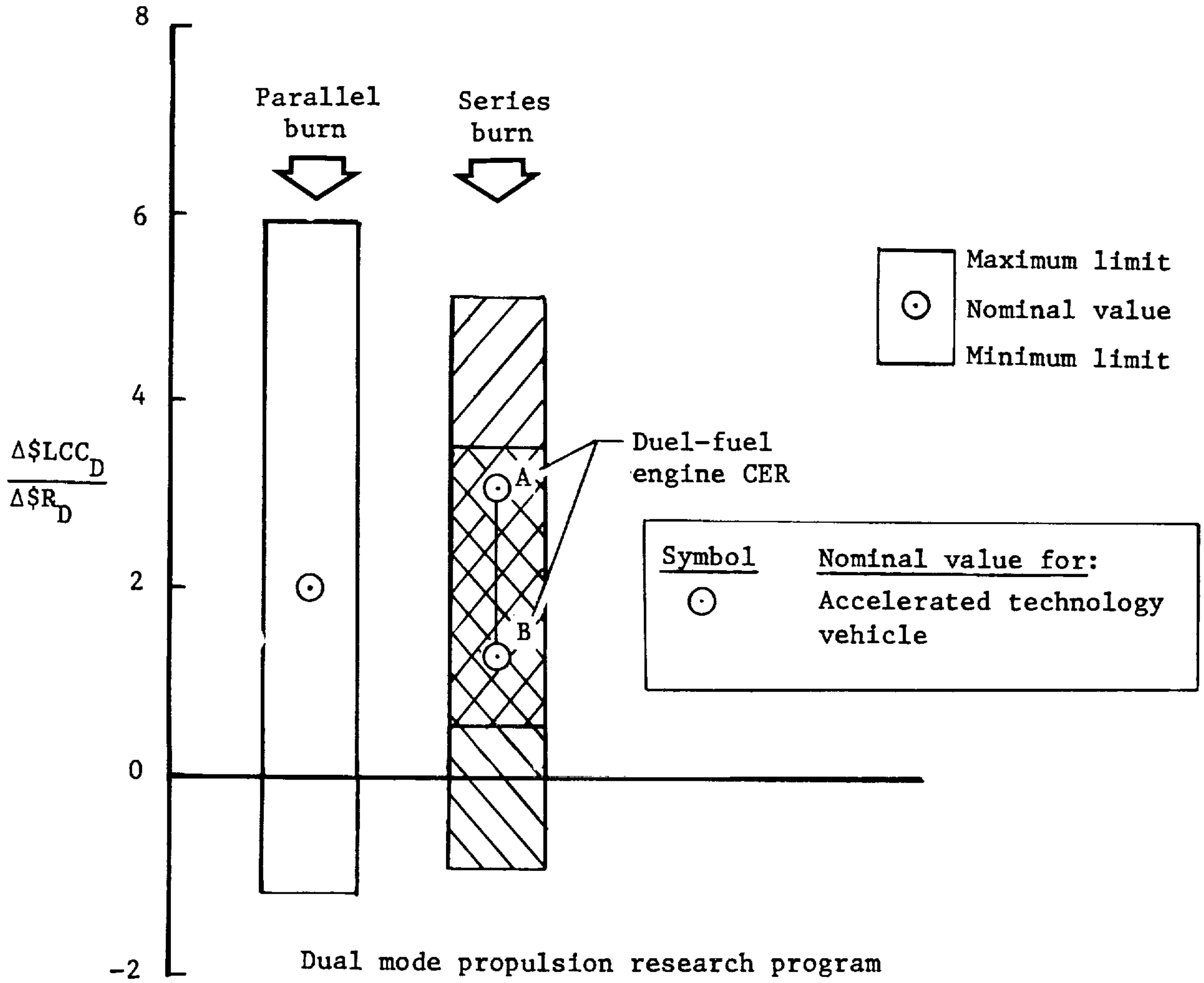


Figure 23.- Figures of merit comparison.

TABLE 23.- FIGURES OF MERIT FOR ACCELERATED TECHNOLOGY PROGRAM COMBINATIONS

Technology level with dual-mode propulsion	Reference vehicle and technology level	Propulsion mode	ΔW_{dry}, kg (pounds)	ΔGLOW, kg (pounds)	$\Delta \$R_D$ \$M	$\Delta \$LCC_D$ \$M	$\frac{\Delta \$LCC_D}{\$R_D}$	$\Delta \$LCC_D - \Delta \$R_D$ \$M	$LCC_D + \Delta \$R_D$ \$M
Accelerated technology growth VTO vehicle (programs 1, 2, 3, 4, 5, 10, 11 and 12)*	Accelerated technology growth VTO vehicle without dual-mode propulsion	Series	- 30 858 (- 68 030)	- 49 895 (- 110 000)	44.3	57 to 135	1.3 to 3.0	12.7 to 90.7	1984 to 2041
		Parallel	- 25 537 (- 56 300)	- 146 057 (- 322 000)	32.8	66	2.0	33.2	2021
"Normal" technology growth vehicle	"Normal" growth without dual-mode propulsion	Series	- 92 899 (-204 808)	- 519 678 (-1 145 695)	44.3	201 to 262	4.5 to 5.9	157 to 218	2082 to 2143
		Parallel	- 79 534 (-175 343)	- 534 193 (-1 177 695)	32.8	174	5.3	141	2159

*Identified in table 19.

the other technology areas are normal growth, accelerated, dual-mode propulsion will yield good cost/performance benefits, as previously mentioned.

A summary of evaluations of relative merits of technology programs is presented in table 24. The data are taken from reference 1, except for the addition of data for dual-mode propulsion. The last column indicates the excellent potential merit of dual-mode propulsion with its FOM of about 5 ranking no less than third on the list of technology programs.

A table was presented in reference 1 to identify high yield and critical technology areas for both normal and accelerated growth. This table is reproduced in table 25, herein, with the addition of dual-mode propulsion. This R&T area is considered as an activity within the main engine propulsion area, and requires accelerated growth to reach its R&T goals within the time span for a 1995 IOC specified for this study. It is an R&T area with potentially high yield for both series or parallel burn concepts. A high performance RP-1 engine and a dual-fuel engine are required to be funded for R&T to realize the capability to design and develop the series burn vehicle. A high performance RP-1 engine is required to be funded to design and develop the parallel-burn vehicle, and assuming continued product improvement of the SSME hydrogen-fueled engine.

The RP-1 fuel was used in this study as representative of high density fuels that might prove beneficial in future advanced space transportation systems. Fuels that may be selected include various synthetic hydrocarbon fuels and methane. Furthermore, additional engine concepts for single-mode and dual-mode propulsion continue to be examined, including engines with linear nozzles and new dual-fuel concepts.

There is a need, therefore, to continue analysis of cost and performance benefits of R&T in various technology areas. This research analysis can ensure the best focusing of funding and research towards SSTO goals. The high yield R&T program identified as integration engineering (program 12) performs this function, among others, and continues to be highly recommended for accelerated growth.

TABLE 24.- COSTS AND BENEFITS OF ACCELERATED RESEARCH

Technology program	Δ$ (Millions)		
	R_D	LCC_D	$\frac{LCC_D}{R_D}$
Miscellaneous structures	4.5	31	6.9
Wing and tail structures	16.4	98	6.0
Propellant tanks	9.0	43	4.8
Thrust structures	4.5	20	4.4
Subsystems weights	4.8	17	3.5
Subcooled propellants	17.5	49	2.8
Thermal protection systems	10.5	23	2.2
Main engine LO_2/LH_2 propulsion	84.0	81	<1
OMS/RCS propulsion	26.8	9	<1
Main engine dual-mode			
Series	44.3	201 to 262	4.5 to 5.9
Parallel	32.8	174	5.3

Note: All are referenced to normal technology growth VTO vehicle (ref. 1)

TABLE 25.- HIGH YIELD AND CRITICAL TECHNOLOGY ASSESSMENTS

Technology area	"Normal" growth (focused)		Accelerated growth	
	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		
Dual-mode propulsion			X Parallel-burn concept: high performance LO_2/hydrocarbon engine required X Series-burn concept: high performance dual-fuel engine required	
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.

CONCLUSIONS

A fundamental goal of this study of dual-mode propulsion was to identify its potential cost and performance benefits applied to future earth-orbit transportation systems with vertical take-off and horizontal landing. These systems used completely re-useable, single-stage-to-orbit (SSTO) vehicles and had mission requirements similar to Space Shuttle, which the SSTO could re-place in 1995. Both parallel-burn and series-burn propulsion concepts using RP-1 and LH_2 fuels were analyzed, based on engine characteristics defined by another current NASA-sponsored study.

The benefits of dual-mode propulsion were identified by parametric analyses of its impacts on vehicle size and program costs, and by defining specific vehicle characteristics for near-optimum designs based on minimum weight and cost considerations. Figures of merit were used to assess the potential of the dual-mode propulsion concepts and their relations to single-mode systems.

The major results of the study are as follows:

(1) Single-stage-to-orbit concepts have exceptionally worth-while cost and performance merits as advanced earth-orbital trans-portation systems;

(2) The application of dual-mode propulsion concepts can significantly enhance the cost and performance benefits;

(3) The amount of enhancement using dual-mode depends on the levels of technology in other important areas (such as material, structures, surface insulation, and LH_2 propulsion). The merit of dual-mode propulsion is larger when applied with "normal" tech-nology projections than when applied with "accelerated" technology projections;

(4) Important merit indicators of parallel burn vehicle con-cepts compare with those of series-burn concepts within 6%. The results also show a dry weight and hydrogen cost advantage for series burn, and a GLOW and R&T cost advantage for parallel burn. The life-cycle cost and life-cycle cost savings per dollar of re-quired research were about the same for both concepts. Within the guidelines and tolerances of this study, therefore, both show about the same merit and are beneficial compared to single-mode propulsion concepts;

(5) Areas of dual-mode propulsion technology which need to be pursued to realize the goals required for SSTO vehicles are as follows:

(a) High chamber pressure, high efficiency hydrocarbon engines;

(b) Pumps for all propellants to achieve pressure and performance goals;

(c) Cooling of chambers and nozzles with LO_2 and LH_2 in conjunction with radiation cooling techniques;

(d) Nozzle extension with or without engine shutdown;

(e) Dual-fuel engine switchover from hydrocarbon to hydrogen fuel, preferably without engine shutdown.

(These are in addition to those high yield and critical technologies described in reference 1.)

(6) Inasmuch as dual-mode propulsion showed significant potential for cost savings, more near-term R&T effort is indicated to pursue better definitions of engine concepts, engine costs, and dual-mode vehicle concepts;

(7) Reduction of operations costs is a major goal for cost-effective advanced transportation systems. Dual-mode propulsion studies should therefore include analysis of relative costs of launch operations with various types of engines;

(8) Other engine concepts and high density fuels for applications to advanced transportation systems continue to be offered for potential assessment studies. These include, for example, linear engines, new dual-fuel concepts, and synthetic and methane fuels. Integration engineering is highly recommended as a continuing, accelerated program to ensure focusing of these and other R&T activities toward technology areas with best cost and performance benefits.

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