ARTICLE NO. 78-972R

Optimization of Rocket Propulsion Systems for Advanced Earth-to-Orbit Shuttles

Alan W. Wilhite*
NASA Langley Research Center, Hampton, Va.

A computerized preliminary design system is used to evaluate potential main liquid-rocket propulsion systems for advanced technology winged single-state-to-orbit launch vehicles. Evaluated are tradeoffs between ascent flight trajectory performance and flight vehicle sizing driven by engine mass and propellant requirements. Numerous mission, flight, and vehicle-related requirements and constraints are satisfied in the design process. With the design system, five dual-mode propulsion system concepts are compared to a baseline hydrogen and oxygen system in terms of the changes in vehicle dry mass and gross mass.

Nomenclature

c.g.	= center of gravity position $= x/l_b$
I_S	= engine specific impulse, s
$\overline{I_S}$	= propulsion system effective specific impulse $= \Delta V_r / g\ln R_m$, where ΔV_r is a reference ideal velocity equal to 8950 m/s
l_b	= body length, m
O/F	= oxidizer-to-fuel ratio
R_e	= hydrocarbon thrust fraction, sea-level thrust from fixed-nozzle hydrocarbon engines divided by total thrust
R_f	= hydrocarbon propellant fraction, ratio of mass of hydrocarbon fuel and its associated liquid oxygen to total propellant mass
R_m	= ascent mass ratio $= \dfrac{\text{initial vehicle mass}}{\text{burnout mass}}$
T/W	= engine thrust divided by engine weight
$\overline{T/W}$	= effective T/W, total propulsion system thrust divided by total weight
x	= longitudinal body station, m
ϵ	= engine nozzle expansion ratio
ρ	= propellant density, kg/m^3
$\bar{\rho}$	= total propellant (fuel + oxidizer) effective (bulk) density, kg/m^3

Subscripts

sl	= sea level
vac	= vacuum

Introduction

TO enhance the potential for full utilization of space in the future, studies are being conducted of future space transportation systems and the associated technology requirements. The single-stage-to-orbit (SSTO) shuttle is one concept being studied due to its inherent operational advantages and its sensitivity to technology advancements. A key technology area for this concept is the main propulsion system (which includes engines, installation structure, tankage, plumbing, and propellants), since it accounts for approximately 50% of the dry mass and over 90% of the gross liftoff mass. This fact provides a strong incentive to refine propulsion systems. Innovative propulsion schemes have recently been studied to increase overall vehicle system performance despite the fact that the Space Shuttle Main Engine (SSME) brings rocket propulsion near its optimum in terms of engine performance (specific impulse). Initial studies by Salkeld and Beichel[1,2] have shown that dual-mode propulsion, in which both a hydrocarbon and hydrogen fuel are burned, has significant benefits on single-stage shuttles due to the higher propellant bulk density (lower tank volume requirement) in spite of a lower engine performance. Since these initial studies, various dual-mode propulsion engine concepts have been studied in detail: a staged-combustion hydrocarbon engine, a hydrogen-cooled gas-generator hydrocarbon engine, and a dual-fueled engine which initially burns a hydrocarbon fuel and, at an optimized point in flight, transitions to burn hydrogen fuel.[3] Two additional concepts have been studied which burn both fuels simultaneously: the linear aerospike engine[4] and the dual-expander engine.[5] The engine characteristics used in this study are based on those presented in the referenced literature, which may not be achieved with actual hardware.

Since it is not apparent which system is superior by consideration of engine characteristics alone, each system is incorporated into a baseline single-stage-to-orbit vehicle in order to define the relative merits. A computerized preliminary design system is used to trade off dual-mode engine performance, propellant bulk density, and engine mass on the overall vehicle system in terms of dry mass and gross mass.

Analysis

The evaluation of potential SSTO propulsion schemes requires the consideration of the total vehicle system utilizing each scheme and the trade of numerous conflicting requirements such as flight performance, engine mass, and propellant bulk density. The method used is similar to the one developed in Ref. 6 where the performance results obtained from a point mass trajectory optimization program are combined with a vehicle sizing program to establish changes in both dry mass and gross mass resulting from propulsion system variations on a baseline vehicle.

Baseline SSTO Vehicle

The SSTO concept used in this study is a vertical-takeoff horizontal-landing vehicle similar to the one described in Ref. 7. This vehicle meets the mission, payload, and operational requirements which are essentailly the same as space shuttle

Presented as Paper 78-972 at the AIAA/SAE 14th Joint Propulsion Conference, Las Vegas, Nev., July 25-27, 1978; submitted Sept. 28, 1978; revision received Aug. 17, 1979.

Index categories: LV/M Propulsion and Propellant Systems; Launch Vehicle Systems.

*Aerospace Engineer, Space Systems Division.

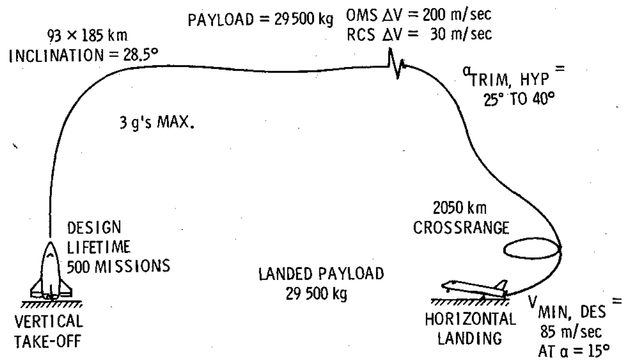

Fig. 1 Single-stage-to-orbit (SSTO) operational mode and design requirements.

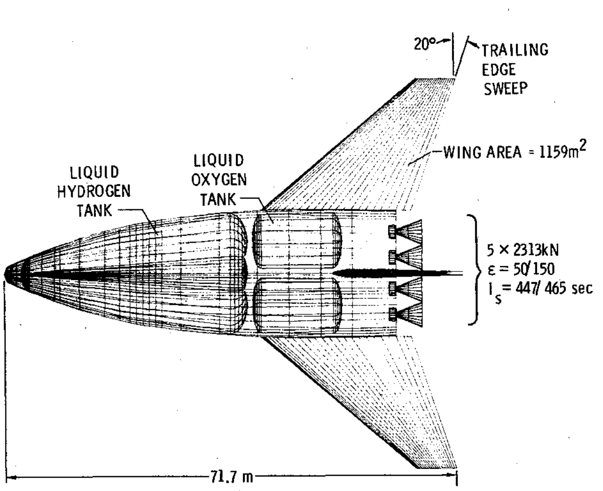

Fig. 2 Baseline SSTO vehicle.

requirements shown in Fig. 1. Consistent with an assumed initial operational data of 1995, improvements in structural, subsystem, and propulsion technologies beyond current levels have been utilized based on expected normal technology advancement. For this study, the baseline vehicle deviates from that of Ref. 7 in that all the hydrogen-fueled engines are assumed to have two-position nozzles, which is near-optimum in terms of dry mass and gross mass, as shown in Ref. 6. The resulting vehicle is shown in Fig. 2.

Propulsion Systems and Characteristics

Since the initial studies on the advantages of dual-mode propulsion by Salkeld and Beichel,[1,2] various propulsion schemes have been proposed for incorporating dual-fuel advantages into an SSTO vehicle. Several of these propulsion systems have been analyzed in detail. In Ref. 3, four engine concepts were analyzed: 1) a hydrogen-cooled gas-generator hydrocarbon engine; 2) a staged-combustion hydrocarbon engine; 3) a dual-fueled engine which burns both hydrocarbon and hydrogen fuel in series; and 4) a modified SSME, which burns only hydrogen fuel, with a two-position nozzle to provide a high-expansion ratio at high-altitude and vacuum conditions for increased specific impulse. For this study, one propulsion scheme is the gas-generator hydrocarbon engines which are burned in parallel (simultaneously) with the modified SSME's at liftoff. At transition, the hydrocarbon engines are shut down, the nozzles of the modified SSME are extended to give a higher expansion ratio, and the hydrogen fuel continues to burn to orbital injection. The second scheme is identical to the first, except the gas-generator engines are replaced by the staged-combustion engines. The third scheme is a combination of staged-combustion engines burned in parallel with the dual-fueled engines. Only the hydrocarbon fuel is burned at liftoff and then the hydrocarbon engines are shut down, the nozzles of the dual-fueled engines are extended to provide a high-expansion ratio, and the fuel is switched from hydrocarbon to hydrogen. Since this is a serial burn of fuels, this scheme is called series burn.

A fourth engine examined is the hybrid linear aerospike engine[4] which employs a parallel burn of the fuels by the use of a split combustor with hydrogen used in the inner combustor and a hydrocarbon fuel in the outer combustor. At transition, the hydrocarbon fuel combustor is shut down, which effectively provides a higher expansion ratio for the hydrogen fuel without the moving parts of an extendable nozzle as previously described. It is a hybrid engine, since it employs a gas-generator cycle for the hydrocarbon-fuel burn and a staged-combustion cycle for the hydrogen-fuel burn.

The last engine studied is the dual-expander engine.[5] It also employs a parallel-burn mode but in a novel fashion. The dual-expander engine employs central and annular combustion chambers which discharge into a common bell-type nozzle. At lift-off, the hydrocarbon fuel is burned in the central chamber while the hydrogen fuel is burned in the annular chamber. At transition, the central chamber is shut down and hydrogen continues to burn in the annular chamber, which effectively provides the high performance of a high-expansion-ratio nozzle.

Characteristics of each of these engine systems are presented in Table 1. The sea-level thrust-to-weight includes other elements of the engine system such as pressurization, feedline systems, and contingency. The fixed-nozzle engines were all assumed to have an expansion ratio of 50 and the dual-fuel engine and modified SSME have an extendable nozzle with an expansion ratio of 150. The hybrid linear aerospike engine was selected from Ref. 4 which presents many options including expansion ratio, thrust fraction, width-to-height ratios, and various engine cycles. The selection was based on previous in-house studies of the various options. The dual-expander selection is based on optimization of the thrust fraction between hydrocarbon and hydrogen-thrust and expansion-ratio options presented in Ref. 5.

Trajectory Analysis

Detailed trajectory analysis was used to identify the variations in ascent performance, as measured by the ascent mass ratio R_m, which results from variations in rocket propulsion system characteristics.[8] The optimized ascent trajectories were computed for a matrix of propulsion system characteristics using a generalized computer program called

Table 1 Propulsion systems

	Propellants	O/F	T/W_{sl} [a]	$I_{s,vac}$	ϵ
Mode 1 staged combustion	LOX/RP	2.9	95	355	50
Hydrogen-cooled, gas generator	LOX/RP/LH	2.9	111	355	50
Dual-fuel engine	LOX/RP/LH	2.9/6	62	355/465	50/150
Mode 2 LOX/LH engine (mod. SSME)	LOX/LH	6	56	447/465	50/150
Linear engine (hybrid, PC = 17.2 MPa)	LOX/RP/LH	2.8/7	74	366/458	40/114
Dual expander	LOX/RP/LH	2.9/7	106	377/452/466	100/50/194

[a] Includes contingency, pressurization, and feed systems.

POST (Program to Optimize Simulated Trajectories),[9] assuming a due-east launch from Kennedy Space Center at a thrust-to-weight ratio of 1.3. The optimization maximizes the burnout mass to meet specified insertion conditions while satisfying various in-flight constraints. Insertion was for the perigee of a 93 × 185 km orbit, while constraints included maximum *g*'s, maximum dynamic pressure, and maximum normal force. Total acceleration was limited to 3 *g* by continuous engine throttling when required. The normal force was limited to a level consistent with the maximum entry normal force (a 2.5 *g* subsonic maneuver), so that the full benefits of aerodynamic lift could be utilized without affecting the wing design.

In the initial trajectory studies, the time of transition was determined to yield a minimum mass ratio. In addition to these trajectories, this transition time was varied to determine the effects of fuel split, R_f, on the mass ratio. For transition times that were delayed to later in the flight, more hydrocarbon fuel was burned but the mass ratio increased. This trade of higher propellant bulk density vs lower effective specific impulse was made with the sizing analysis.

Sizing Analysis

The sizing was used to evaluate the combined effects of ascent trajectory performance (which determined propellant requirements), propellant bulk density, and propulsion system mass on vehicle size. A recently developed computer-aided design system, the Aerospace Vehicle Interactive Design (AVID) system, was used for this task. The AVID system gives the user the capability to interactively execute a number of technology computer programs. Figure 3 illustrates the procedure used in this study. Trajectory and engine characteristics data were used as inputs to the AVID simulation. The vehicle from Ref. 7 was defined geometrically (Fig. 3) and analyzed for volumes and areas. This geometric information and the trajectory and engine data were used in a mass and sizing program. This program estimated the mass of the vehicle by using historical mass estimating relationships similar to Refs. 10 and 11. A check was made on the propellant requirements to meet the ascent performance and the total thrust for the liftoff thrust-to-weight ratio of 1.3 to deliver a shuttle payload (29,500 kg) to orbit. To meet propellant volume requirements, the geometry of the vehicle was photographically scaled; to meet thrust-to-weight requirements, the number of engines were scaled (fractional number of engines resulted from this "rubberized" approach). The mass estimating and scaling were iterated until the requirements were satisfied.

Since the wing was scaled with the body, it was initially assumed that the center-of-gravity position and the entry wing loading remained constant in order to satisfy the aerodynamic requirements. For this study, the center of gravity moved significantly forward for some propulsion schemes due to the higher effective thrust-to-weight of the dual-mode propulsion systems. To simplify the study, wing sizing was only included on the optimum vehicle based on dry mass determined for each propulsion system. The baseline wing (Fig. 2) was sized by the hypersonic trim requirements. To meet the same hypersonic trim requirement for the study vehicles, the trailing-edge sweep was reduced as the center of gravity moved forward. The trailing-edge sweep reduction reduced structural span (wing mass) and helped to linearize the subsonic, longitudinal stability curve. (The stability curve of the baseline vehicle has been shown to be nonlinear due to large trailing-edge sweep in wind-tunnel tests.) As the wing mass was reduced, the center of gravity moved further forward and the wing was resized. With the gas-generator, parallel-burn concept and the dual-expander engine, the trailing-edge sweep was reduced to an acceptable level based on the study in Ref. 12 which determined criteria for a subsonic linear longitudinal stability curve. For these two cases, instead of further reducing trailing-edge sweep, the wing area was reduced to maintain the same level of hypersonic trim.

To analyze the total vehicle design, the AVID system was used for interactive graphics (wing definition), geometry

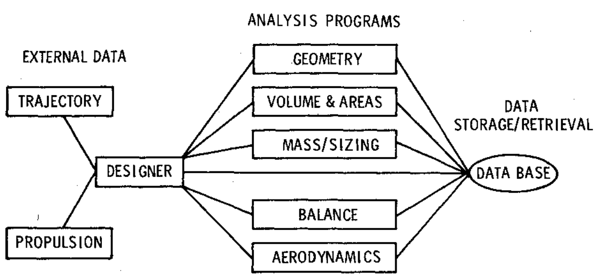

Fig. 3 Aerospace Vehicle Interactive Design (AVID) propulsion system.

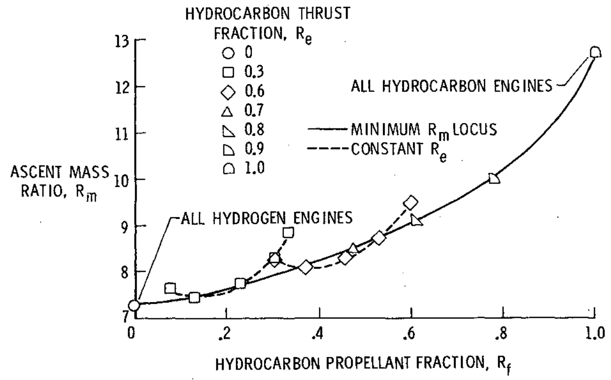

Fig. 4a Trajectory results of the parallel burn concept with staged combustion engines.

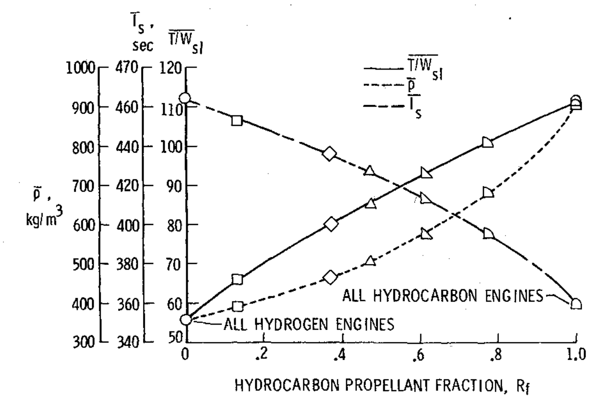

Fig. 4b Key sizing parameters of the parallel burn concept with staged combustion engines.

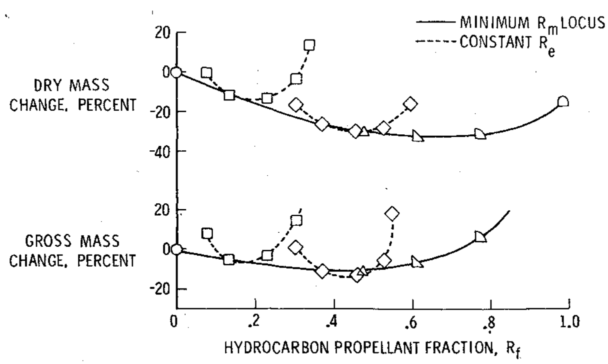

Fig. 4c Sizing results of the parallel burn concept with staged combustion engines.

analysis, mass estimation/sizing, balance, and hypersonic trim analysis. A typical design sequence took several hours to iterate through these technology programs to define an acceptable vehicle which met all the requirements.

Results and Discussion

Vehicle sizing results are presented as percent changes relative to the baseline vehicle with all-hydrogen two-position nozzle engines (modified SSME's) which has been shown to be near-optimum for both dry mass and gross mass in Ref. 6.

Figure 4 shows the results of systematically replacing the modified SSME's with staged-combustion hydrocarbon engines. At liftoff, both engine systems are burned in parallel at an expansion ratio of 50. At transition, the hydrocarbon engines are shut down, and the modified SSME's continue to burn, but at an expansion ratio of 150. The trajectory results (Fig. 4a) show a performance curve that was generated by a locus of the minimum mass ratio values which was determined for various thrust-fraction values. This mass ratio curve is monotonically increasing with the fraction of hydrocarbon thrust and propellant, which is due to a lower effective specific impulse I_s. Although I_s is decreasing with increasing hydrocarbon propellant fraction, both effective engine thrust-to-weight and propellant bulk density are increasing to counteract this decrease in performance (Fig. 4b). Using the trajectory results and engine mass data in the vehicle sizing analysis, approximately a 32% reduction in dry mass and 6% reduction in gross mass was computed using a hydrocarbon-thrust split of 0.8 ($R_f = 0.61$). Thus the trade of I_s vs T/W and ρ in dual-fuel concepts can be substantially favorable.

Also in Fig. 4, the transition time is perturbed from that which resulted in a minimum mass ratio at a thrust fraction of 0.3 and 0.6. By delaying the time of transition, more hydrocarbon propellant is burned, but there is a performance penalty (high R_m). As shown in Fig. 4c, a slight decrease in both dry mass and gross mass (approximately a 1% reduction) occurs by delaying transition time.

In the second parallel-burn case (Fig. 5), hydrogen-cooled gas-generator hydrocarbon engines are burned in parallel with

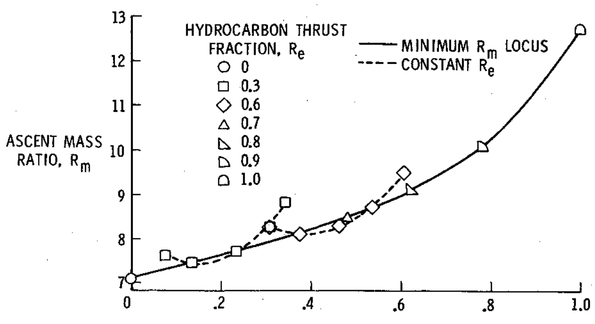

Fig. 5a Trajectory results of the parallel burn concept with gas generator engines.

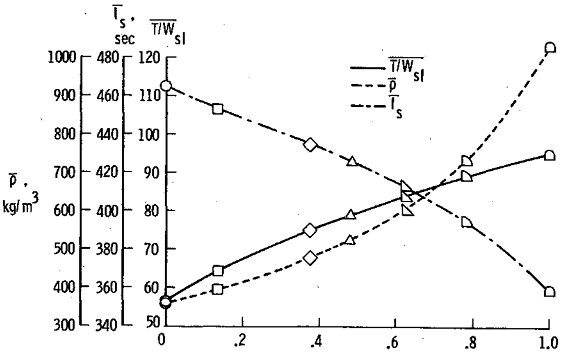

Fig. 5b Key sizing parameters of the parallel burn concept with gas generator engines.

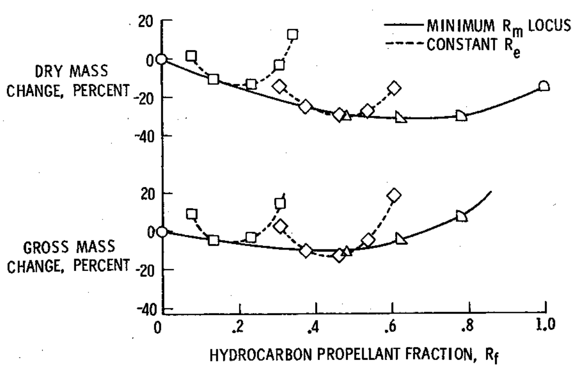

Fig. 5c Sizing results of the parallel burn concept with gas generator engines.

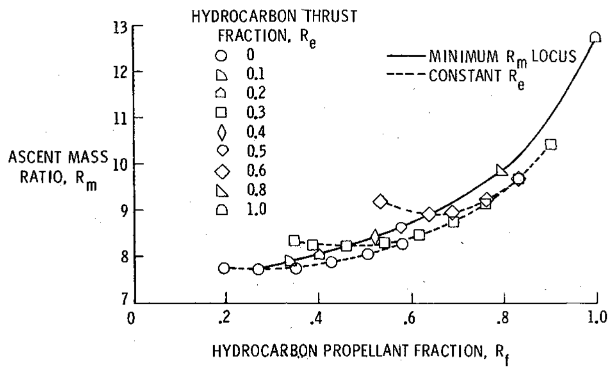

Fig. 6a Trajectory results of the series burn concept.

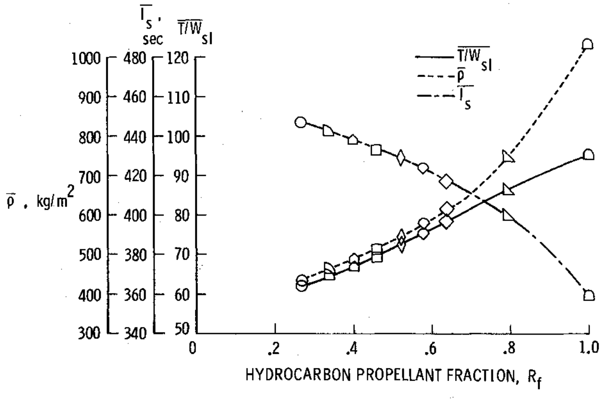

Fig. 6b Key sizing parameters of the series burn concept.

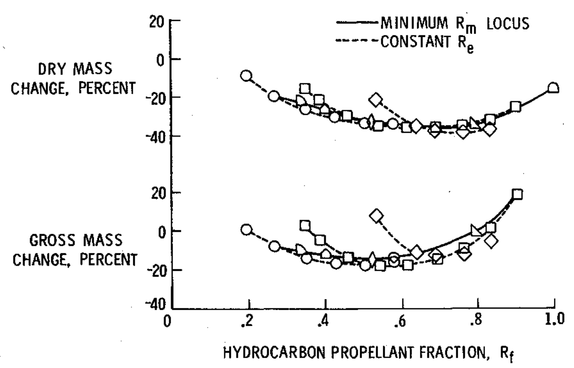

Fig. 6c Sizing results of the series burn concept.

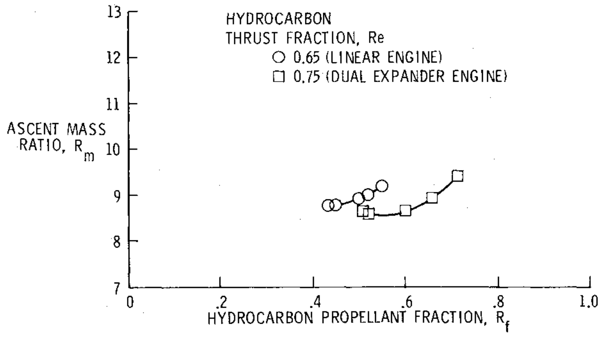

Fig. 7a Trajectory results of the linear and dual expander engine.

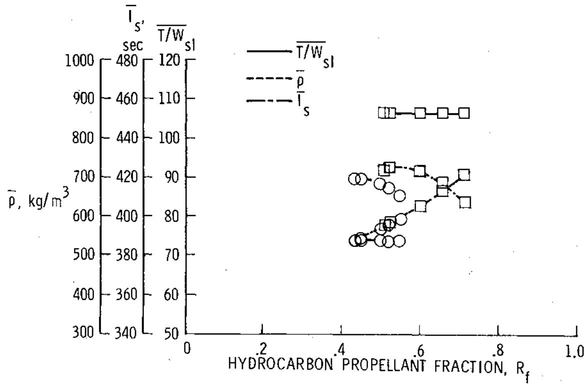

Fig. 7b Key sizing parameters of the linear and dual expander engine.

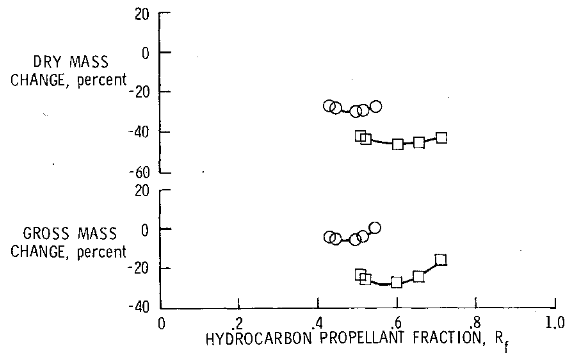

Fig. 7c Sizing results of the linear and dual expander engine.

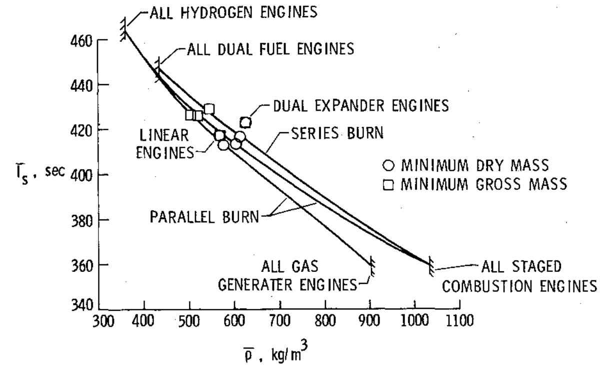

Fig. 8a Comparison of propulsion systems specific impulse.

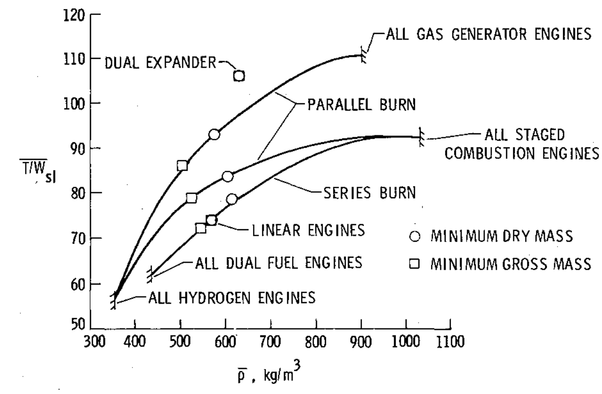

Fig. 8b Comparison of propulsion systems thrust-to-weight ratio.

the modified SSME's instead of the staged-combustion engines. Although the specific impulse (and performance) of the gas-generator engines is identical to the staged-combustion engines, the gas-generator engines burn hydrogen in the gas-generator cycle. This cycle therefore produced a lower overall hydrocarbon-propellant fraction and bulk density than the staged-combustion engine, but the gas-generator engine has a higher effective engine thrust-to-weight. Due to this counterbalance of engine mass and bulk density, reduction in both dry mass and gross mass, as compared to the baseline vehicle, is nearly the same as the staged-combustion parallel-burn concept.

The next system studied was the series-burn concept (Fig. 6). The staged-combustion engines are burned with a dual-fuel engine. At liftoff, both engines burn a hydrocarbon fuel at an expansion ratio of 50. At transition, the staged-combustion engines are shut down, the dual-fuel engines switch from hydrocarbon to hydrogen fuel, and the nozzles are extended to an expansion ratio of 150. The results show that replacing the modified SSME's with the dual-fuel engine reduces the dry and gross masses 36% and 18%, respectively, over the baseline vehicle (Fig. 6c).

The linear aerospike engine and the dual-expander engines are also dual-fueled engines, but they burn the hydrocarbon and hydrogen fuel in parallel at liftoff. Although various options exist for each of these engines, only the option which resulted in minimum vehicle dry and gross masses is presented in Fig. 7. The vehicle sizing with the linear aerospike engine shows a 30% and 6% reduction in dry and gross masses, respectively, and with the dual expander, a 48% and 28% reduction.

Figure 8 shows the trends of the three key parameters associated with each propulsion concept: bulk density, effective specific impulse, and effective thrust-to-weight ratio. Minimum dry and gross masses of the vehicle are provided as a guide to the realistic range of the key parameters. The linear aerospike engine is comparable with the series-burn concept in $\bar{I}_s$ at the minimum dry mass point, but it has a lower $\overline{T/W}$ and $\bar{\rho}$. The staged-combustion parallel-burn concept is lower in $\bar{I}_s$ and $\bar{\rho}$ at the minimum dry mass point than the series burn, but has a higher $\overline{T/W}$. The gas-generator, parallel-burn concept has the identical $\bar{I}_s$ as the staged-combustion parallel-burn concept (Table 1). It has a higher $\overline{T/W}$, but a lower $\bar{\rho}$. Since these four propulsion concepts simply trade the three key parameters, no one has a clear advantage. The advantage of the dual-expander engine is obvious since it has a higher $\bar{I}_s$, $\overline{T/W}$, and $\bar{\rho}$ as compared to all of the other propulsion concepts. Figure 9 summarizes these results for the propulsion system concepts in terms of dry and gross mass reductions over the baseline vehicle.

With SSTO vehicles, all the propulsion system is integrated into the vehicle and must be carried from liftoff to orbit. Because the propulsion system is placed in the extreme end of the body, many SSTO vehicles have a hypersonic trim problem due to aft c.g. locations. As shown in Fig. 2, for the baseline vehicle with a c.g. of 0.74, the wing area is large and has a trailing-edge sweep of 20 deg. Both the large wing area

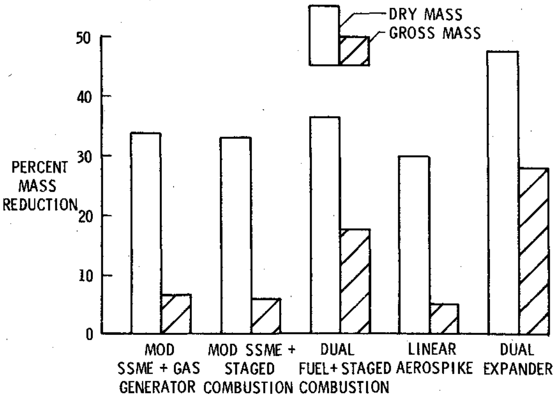

Fig. 9 Comparison of minimum dry mass vehicles.

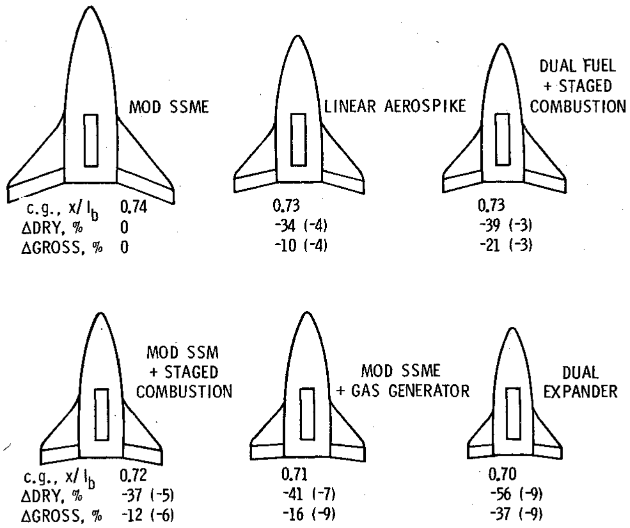

Fig. 10 Sizing comparisons including effects of wing sizing due to c.g. changes—parentheses denote changes due to wing sizing.

and trailing-edge sweep adversely affect the vehicle mass. Incorporating the dual-mode propulsion concepts in the vehicle with their higher T/W causes the c.g. to move forward and the wing area and trailing-edge sweep can be reduced. Reducing wing area and trailing edge also reduces vehicle mass aft of the c.g., thus the c.g. can be moved further forward. The additional effect of sizing the wing to the correct c.g. can be significant, as illustrated in Fig. 10. The dual expander has the greatest effect on c.g. with a 4% forward shift from the baseline vehicle. With this forward c.g. shift, wing sizing iterations for the dual expander produced an additional 9% reduction in both dry and gross mass.

Conclusions

All the dual-mode propulsion systems studied have a significant potential benefit when applied to the SSTO class of vehicles. Since the gas-generator hydrocarbon engines show approximately an equal benefit over the staged-combustion engines, this cycle should be pursued for near-term applications due to its higher level of technology readiness.

Of the propulsion systems considered, the dual-expander engine offers the greatest potential for reducing vehicle mass, but further studies and technology advances must be made to bring this concept to a technology level comparable to the conventional rocket engines. On the other hand, the linear aerospike engine does not show any advantage over conventional bell-nozzle engines for a vertical-takeoff high-aerodynamic-performance launch vehicle. These conclusions are based on recently published characteristics of dual-mode propulsion studies which may not be achieved with actual hardware.

Finally, the dual-mode propulsion concepts have been shown to be beneficial to single-stage-to-orbit vehicles, due not only to their high-bulk density propellant but also to their high-thrust-over-engine-weight ratio as compared to an all-hydrogen fueled system.

References

[1] Salkeld, R., "Mixed-Mode Propulsion for the Space Shuttle," *Astronautics & Aeronautics*, Vol. 9, Aug. 1971, pp. 52-58.

[2] Salkeld, R., and Beichel, R., "Reusable One-Stage-to-Orbit Shuttles: Brightening Prospects," *Astronautics & Aeronautics*, Vol. 11, June 1973, pp. 48-58.

[3] Luscher, W. P. and Mellish, J. A., "Advanced High-Pressure Engine Study for Mixed-Mode Vehicle Applications," NASA CR-135141, 1977.

[4] Diem, H. G. and Kirby, F. M., "Linear Aerospike Engine Study," NASA CR-135231, 1977.

[5] Beichel, R., "The Dual-Expander Rocket Engine—Key to Economical Space Transportation," *Astronautics & Aeronautics*, Vol. 15, Nov. 1977, pp. 44-51.

[6] Eldred, C. H., Rehder, J. J., and Wilhite, A. W., "Nozzle Selection for Optimized Single-Stage Shuttles," International Astronautical Conference, IAF-76-162, Oct. 1976.

[7] Haefeli, R. C., Littler, E. G., Hurley, J. B., and Winter, M. G., "Technology Requirements for Advanced Earth-Orbital Transportation Systems," Final Report, NASA CR-2866, 1977.

[8] Rehder, J. J., "Effect of Propulsion System Characteristics on Ascent Performance of Dual-Fueled Single-Stage Earth-to-Orbit Transports," NASA TP-1115, Dec. 1977.

[9] Brauer, G. L., Cornick, D. E., and Stevenson, R., "Capabilities and Applications of the Program to Optimize Simulated Trajectories (POST)," NASA CR-2779, 1977.

[10] Space Shuttle Synthesis Program (SSSP), NASA CR-114987, 1970.

[11] Glatt, C. R., "WAATS—A Computer Program for Advanced Transportation Systems," NASA CR-2420, 1974.

[12] Spreeman, K. P., "Design Guide for Pitch-Up Evaluation and Investigation at High Subsonic Speeds of Possible Limitations Due to Wing Aspect Ratio Variations," NASA TM X-26, 1959.