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Advanced Rocket Propulsion Technology Assessment for Future Space Transportation

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Single-stage and two-stage launch vehicles were evaluated for various levels of propulsion technology and payloads. The evaluation included tradeoffs between ascent flight performance and vehicle sizing that were driven by engine mass, specific impulse, and propellant requirements. Numerous mission, flight, and vehicle-related requirements and constraints were satisfied in the design process. The results showed that advanced technology had a large effect on reducing both single- and two-stage vehicle size. High-pressure hydrocarbon-fueled engines that were burned in parallel with two-position nozzle hydrogen-fueled engines reduced dry mass by 23% for the two-stage vehicle and 28% for the single-stage vehicle as compared to an all-hydrogen-fueled system. The dual-expander engine reduced single-stage vehicle dry mass by 41%. Using advanced technology, the single-stage vehicle became comparable in size and sensitivity to that of the two-stage vehicle for small payloads.

Nomenclature

AVID	= aerospace vehicle interactive design
COTV	= cargo orbital-transfer vehicle
I_{sp}	= engine specific impulse, s
IOC	= initial operational capability
MOD SSME	= modified SSME with two-position nozzle
MOTV	= manned orbital-transfer vehicle
O/F	= oxidizer-to-fuel ratio
P/L	= payload
SSME	= Space Shuttle main engine
TPS	= thermal protection system
T/W	= engine thrust/engine weight
ΔDRY	= fractional change in dry mass
ΔP	= fractional change in parameter
ϵ	= engine nozzle expansion ratio
$\bar{\rho}$	= propellant bulk density

Subscripts

sl	= sea level
vac	= vacuum

Introduction

OVER the past several years, many studies have been directed toward the full utilization of space to benefit man and his environment. Once the dreams of using space for practical applications start to become a reality with the Space Shuttle, many new ideas will blossom, and the age of space industrialization will begin. Even today, plans are being developed for large space structures for communications and Earth resource monitoring that will require many Shuttle flights. There are even more ambitious studies for space industrialization which produce projections of traffic increasing rapidly between Earth and low-Earth orbit. This rapid growth offers a growing challenge to transportation systems.

Recently, studies have been specifically directed toward an examination of the technologies associated with these advanced transportation systems; this examination has produced several viable candidates for elements of a total system.[1-3] The focus has been on systems that could become operational in the 1990-2000 time frame. This paper discusses the results of projecting technology to this time frame and applying new technology to both two- and single-stage vehicles.

Future Space Transportation

To achieve future space industrialization, a matrix of advanced vehicles, as shown in Fig. 1, will probably be required.[3] This matrix consists of four vehicle classes. For the large amount of material associated with space industrialization, a heavy-lift launch vehicle will be required. This vehicle will deliver cargo to low-Earth orbit. Since many of the projected missions will need geosynchronous orbit capability, a cargo orbital-transfer vehicle will be required that could have either an electric or a low-thrust chemical propulsion system. The goal for these vehicles will be to minimize the transportation cost per kilogram of cargo. To support space industry with personnel and priority cargo, a small, flexible, express launch vehicle will be required. It will be matched, most probably, with a rapid-transit manned orbital-transfer vehicle. As opposed to the heavy-lift vehicles, the overall technology goal for these priority cargo vehicles will be to minimize cost per flight instead of cost per kilogram because of the flexibility and number of flights required in this transportation support role.

The purpose of the present study is to determine the effects of propulsion technology for the two types of launch vehicles considered in the advanced transportation matrix of vehicles.

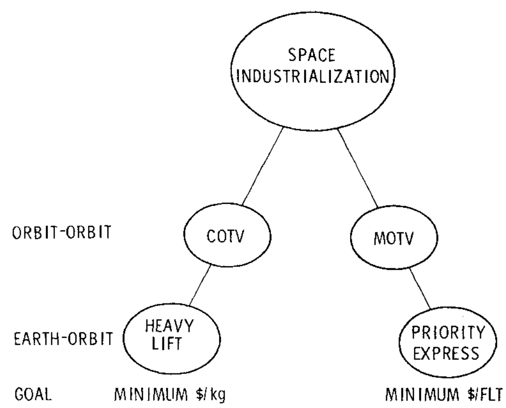

Fig. 1 Advanced space transportation systems.

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Table 1 Propulsion systems

	Propellants	O/F	T/W_{sl} [a]	$I_{sp,vac}$	ϵ
SSME, $\epsilon = 50$	LOX/LH	7	62	447	50
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
Dual expander	LOX/RP/LH	2.9/7	106	377/452/466	100/50/194

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

Analysis

The evaluation of potential propulsion schemes for advanced launch vehicles requires the consideration of the total vehicle system and the trade between numerous conflicting requirements such as flight vehicle performance, engine mass, specific impulse, and propellant bulk density. The method used is similar to the one developed in Ref. 4, where performance results obtained from a point-mass trajectory-optimization program were combined with a vehicle sizing program to establish changes in both dry mass and gross mass resulting from propulsion system variations on a set of baseline vehicles.

Baseline Vehicles

The baseline vehicles and mission requirements used in this study were similar to the ones developed in a recent study.[3] The single-stage vehicle was a vertical-takeoff, horizontal-landing vehicle with the same mission and operational requirements as those of the Space Shuttle. A cold structure that required a thermal protection system was used, and the propellant tankage was integral to the body structure.

The two-stage concept was similar in structure to the single-stage vehicle, but the booster had a greatly reduced thermal protection system, since the staging velocity was constrained to 2150 m/s. This feature allowed the basic load-carrying structure in the booster to be used as a heat sink for the thermal pulse. At liftoff the engines of both stages burned in parallel, with the booster crossfeeding the propellant to the orbiter. This parallel burn mode reduced the size of the propulsion system required by the booster compared to series burn concepts where the orbiter propulsion system is not used until staging. The thrust split between the booster and the orbiter was adjusted, so that both vehicles had the same initial thrust-to-weight ratio as the single-stage vehicle. After staging, the booster cruised back to the launch site with conventional turbojet engines.

Propulsion Technology

Four different propulsion systems (or schemes) were evaluated for the two classes of launch vehicles. First, the Space Shuttle main engine (SSME) with an expansion ratio of 50:1 was considered as current technology instead of the present value of 77.5:1, since the smaller expansion ratio was near optimum for this class of advanced launch vehicles. The second system that was considered used the SSME's in combination with modified SSME's (MOD SSME). The MOD SSME's had two-position nozzles which were assumed to be the result of normal growth technology, since they are likely to be developed as a performance improvement for the Space Shuttle. For the single-stage vehicle, both the fixed-position nozzle and the two-position nozzle engines were burned at liftoff. At high altitude, the single-position nozzle engines were shut down, and the two-position nozzle engines were extended to the higher expansion ratio to increase specific impulse. The optimum number of SSME's and MOD SSME's resulted from a trade between decreased engine thrust-to-weight ratio and increased specific impulse associated with the two-position nozzle. Optimization of this propulsion system was illustrated in Ref. 4. For the two-stage vehicle, the booster was equipped with the fixed-nozzle SSME's, and the orbiter was equipped with the MOD SSME's.

In a higher technology scenario, the fixed-nozzle SSME's were replaced by a new hydrocarbon engine with an expansion ratio of 50:1. The hydrocarbon engine was a hydrogen-cooled, gas-generator, high-pressure (4000-psi) engine studied in Ref. 5, which is considered to require only a modest technology advancement program. The MOD SSME's were burned in parallel with the hydrocarbon-fueled engines at liftoff. At transition, the hydrocarbon engines were shut down, and the nozzles of the MOD SSME's were extended. Burning both hydrogen and hydrocarbon fuels has been shown to result in a significant reduction in dry mass in spite of the decrease in specific impulse because of the benefits of increased engine thrust-to-weight ratio and propellant bulk density.[4]

The fourth propulsion system studied for the single-stage vehicle was the dual expander which burns two fuels in the same engine.[6] The dual-expander engine employs central and annular combustion chambers which discharge into a common bell-type nozzle. At liftoff, the hydrocarbon fuel was burned in the central chamber, while the hydrogen fuel was burned in the annular chamber. At transition, the central chamber was shut down, and hydrogen fuel continued to burn in the annular chamber. Without the hydrocarbon fuel burning, the expansion ratio for the hydrogen cycle was increased, which provided a higher specific impulse. This engine depends on advanced technology, and developmental programs will have to be greatly accelerated for this engine to exist in the 1990 time frame.

A summary of the characteristics of each of these engine systems is given in Table 1.

Structures and Subsystem Technologies

To determine the mass of the structures and subsystems of the vehicles, a mass estimation approach similar to those in Refs. 7 and 8 was used. Historical data from aircraft, current expendable launch vehicles, the Space Shuttle, and many of the Space Shuttle phase B studies for a completely reusable two-stage system were used. The historical mass trend data were used for scaling trends, but the absolute mass values were corrected to match current Space Shuttle component masses. These results were used to establish the level for current technology. To project the reductions in mass that are expected from normal-growth technology to the 1990s, results from Refs. 1-3 were used. These projections were for technology that is expected to evolve from current levels of funding for the Space Shuttle and spinoffs from commercial and military aircraft programs. The mass of wing, tail, nose, intertank adapters, and payload bay structures was reduced by 30% with the substitution of composite materials for aluminum.[3] To estimate the mass of tanks, a pressure design approach was taken to determine skin thickness. Additional structures such as frames and other nonoptimum factors such as welds and manholes were estimated by correcting the pressure design estimates to historical data from Saturn, phase B Shuttle studies, and the Space Shuttle external tank.

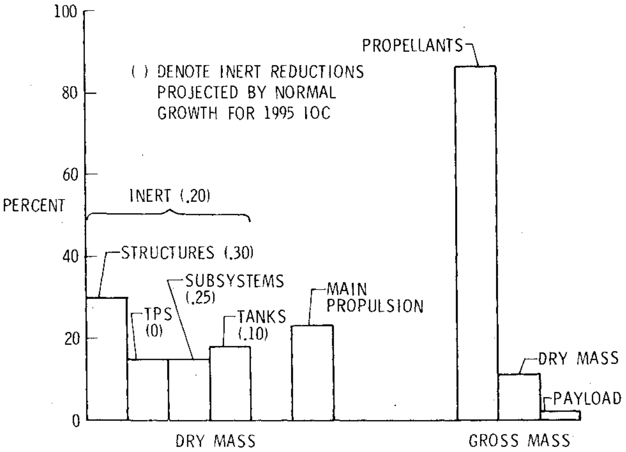
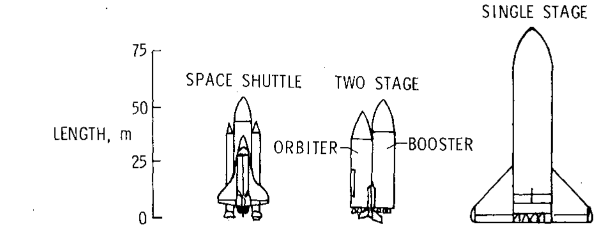


Fig. 2 Typical mass breakdown of a single-stage launch vehicle with hydrogen engines.



EXPANSION RATIO	77.5	50/50	50
DRY MASS, metric tons	274	237	522
GROSS MASS, metric tons	2051	1670	4781

Fig. 3 Comparison of launch vehicles using current technology, SSME propulsion, 30-MT payload.

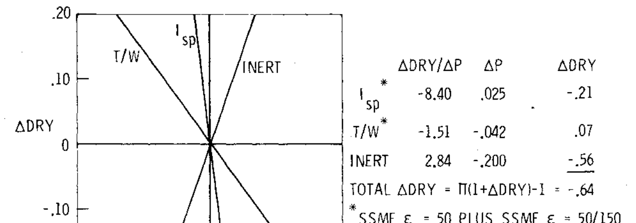


Fig. 4 Effects of normal growth technology on a SSTO vehicle, 30-MT payload.

Aluminum structure was assumed for normal growth, so only a 10% mass reduction was realized by reducing nonoptimum factors using optimum design techniques. There was no mass reduction assumed for the thermal protection system basically because of the infancy of this technology. The various subsystems were reduced by a factor of 25% because of the reduced mission stay time of the advanced vehicles and reduced crew size (from three to two). The advanced vehicles were assumed to be transportation vehicles only and not laboratory platforms like the Space Shuttle, which was designed for long orbital stay times.

These reductions in mass, referred to as inert mass reductions in this paper, averaged an overall value of 20% for the systems considered. The mass breakdown on these components for a typical single-stage vehicle with hydrogen engines is illustrated in Fig. 2. The other elements that comprised the remainder of the vehicle were mainly propulsion elements and propellants which accounted for approximately 80% of the gross mass of the vehicle. As will be shown, propulsion was the key technology for reducing vehicle mass and, therefore, transportation costs.

Trajectory, Mass, and Sizing Analysis

Optimized ascent trajectories were computed for the various propulsion systems using a generalized computer program called Program to Optimize Simulated Trajectories (POST). For the single-stage vehicle, results from Ref. 4 were used which optimized the point of transition, the thrust split between engines, and the propellant split when dual-fuel systems were used. The two-stage system transition or staging condition was assumed to be at a velocity of 2150 m/s to minimize the thermal protection required for the booster. For both single- and two-stage vehicles, initial thrust-to-gross weight was assumed to be 1.3; the insertion was at a perigee of 93 by 185-km orbit; and constraints were used for maximum *g*'s, dynamic pressure, and normal force. The trajectory results provided only an indication of performance (specific impulse) differences for the various propulsion systems. To evaluate the combined effects of ascent performance, propulsion system mass, and propellant bulk density, it was necessary to integrate the propulsion system parameters into the set of launch vehicles. A recently developed computer-aided design system, the various Aerospace Vehicle Interactive Design (AVID) system,[9] was used for this task. For this study, only the mass and sizing analyses of the system were used. Using the baseline geometry of the vehicle, the component mass of each of the various systems that comprise the vehicle was computed based on historical mass estimating relationships. The propellant requirements to meet the ascent flight performance and the initial thrust-to-weight ratio were checked. To meet propellant volume requirements, the geometry was photographically scaled, and to meet thrust-to-weight requirements, the number of engines was scaled. The various other systems of the vehicle were also scaled accordingly. The mass estimating and scaling were iterated until all the mission requirements were satisfied.

Results

To determine the effects of technology improvements on the launch vehicles, both the single- and two-stage vehicles were sized with today's Shuttle technology for the Shuttle payload of 30 MT, as shown in Fig. 3. As would be expected, the two-stage vehicle is similar in both dry mass and gross mass to the Shuttle. Phase B Shuttle studies were directed toward two-stage fully reusable vehicles, but because of funding constraints, two vehicles could not be developed. The single-stage vehicle, because of its performance sensitivity at the current technology level, is a very large vehicle with dry mass and gross mass being approximately double that of the Shuttle.

The effects of incorporating normal-growth technology into the single-stage vehicle are illustrated in Fig. 4. This figure was developed by linearizing the results (obtained by the detailed sizing analysis using AVID) of the sensitivity of dry mass to perturbations in technology. This figure and Fig. 6 are presented only to compare relative vehicle sensitivities to the various anticipated technology changes, since the sensitivities are not expected to be linear for large parameter perturbations. All other results were obtained using the detailed sizing analysis. Figure 4 shows that, by increasing engine specific impulse or engine thrust-to-weight ratio, the dry mass of the single-stage vehicle decreases and, by reducing the inert mass, the dry mass again decreases. The slopes of these curves are listed along with the changes in technology that are expected for each parameter at an initial operating date of 1995. Substituting some of the SSME's with MOD SSME's (40% of total vehicle thrust from MOD SSME's), the specific impulse increased by 2.5% because of the incorporation of a two-position nozzle on the SSME, and the

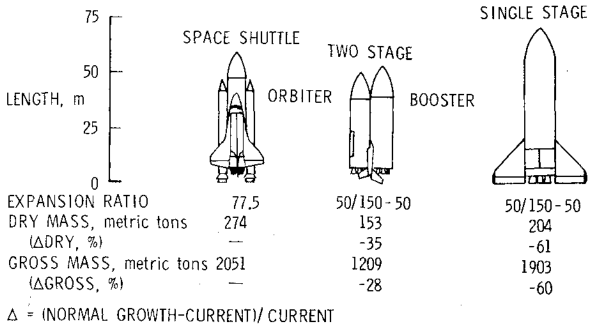


Fig. 5 Comparison of launch vehicles using SSME's/MOD SSME's, 20% inert reduction, 30-MT payload.

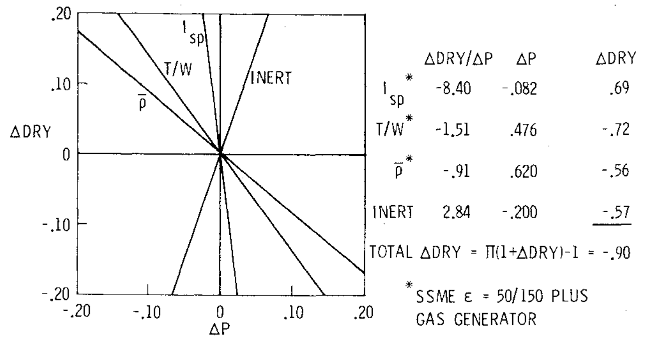


Fig. 6 Effects of mixed-mode propulsion on a single-stage vehicle, 30-MT payload.

dry mass was reduced by 21%. Because of the two-position nozzle, the engine thrust-to-weight ratio decreased by 4.2% which increased dry mass by 7%. Therefore the combination of these enhanced propulsion technologies reduced dry mass by a total of 15% (using the formula on the figure). Dividing the sensitivity slopes for these two parameters indicates that engine thrust-to-weight ratio must not increase by more than 5.5% for a 1% increase in specific impulse for an even trade in vehicle dry mass. The two-position nozzle sensitivity had a ratio of 1.7:1 and thus reduced vehicle dry mass as shown. The inert mass normal-growth technology projection of 20% reduction showed the largest overall reduction in dry mass with a 56% reduction in total vehicle dry mass. By combining all technology advances, the single-stage vehicle showed a large dry-mass reduction of 64% (61% with the detailed analysis).

A comparison of the two- and single-stage vehicles using normal-growth technology (MOD SSME's and 20% inert mass reduction) is made in Fig. 5. The two-stage vehicle showed a considerable reduction in size with a 35% reduction in dry mass and a 28% reduction in gross mass. The single-stage vehicle, because of its performance sensitivity, showed a much larger reduction in size with a 61% reduction in dry mass and a 60% reduction in gross mass.

High-pressure oxygen/hydrogen technology has been extended almost to its theoretical limit with the SSME. Instead of trying to increase performance of this engine system, studies that were initiated by Beichel and Salkeld have shown that vehicle size can be reduced by using a hydrocarbon fuel in combination with a hydrogen fuel which is called mixed-mode propulsion.[10,11] Their studies traded a decrease in specific impulse with an increase in engine thrust-to-weight ratio and propellant bulk density.

Figure 6 illustrates the effects of mixed-mode propulsion on a single-stage vehicle. The dry mass sensitivities to specific impulse, engine thrust-to-weight ratio, and inert mass reductions are identical to those shown in Fig. 4. The bulk density parameter is added to account for the change in propellant density, since a hydrocarbon fuel has been used. By substituting the SSME's with hydrocarbon engines (80% thrust from hydrocarbon engines and 20% thrust from MOD SSME's), impulse performance was degraded by 8.2%, which increased the single-stage dry mass by 69%. The thrust-to-weight ratio of the total propulsion system, on the other hand, increased by 58%, which decreased dry mass by 72%. The additional benefit of the mixed-mode propulsion is the 62% increase in bulk density with a corresponding 56% reduction in vehicle dry mass. The total effect for mixed-mode propulsion results in a 79% reduction in dry mass. Add to these effects the 20% inert mass reduction projected for normal-growth technology, and the total dry mass reduction from linear sizing becomes 90% (72% with the detailed analysis), which is quite dramatic for only a moderate projection of advanced technology. The 18% difference between linear and detailed sizing techniques illustrates the errors that are produced by extrapolating linear techniques. The detailed analysis of the AVID system must be used to model the synergistic effects of changing the propulsion systems.

The effects of propulsion technology for both the single-stage and two-stage vehicles over a range of payload levels using the detailed analysis are presented in Figs. 7a-f. For payloads less than 100 MT, all the payload was returned from orbit. For payloads greater than 100 MT, only 10% of the payload was returned which reduced the required wing and various subsystem masses (shown by the discontinuities of the curves). As shown in Figs. 7a and 7b, both dry mass and gross mass for the single-stage vehicle was significantly reduced, assuming normal technology growth (0.2 inert mass reduction and MOD SSME's) and mixed-mode propulsion with the high-pressure hydrocarbon engines in parallel with the MOD SSME's. The dual-expander engine showed the largest reductions in dry mass and gross mass although significant technology advances are needed for its development. The effects of advanced technology on the two-stage vehicles are shown in Figs. 7c and 7d. Reductions in dry mass and gross mass are significant but not to the same level as the single-stage vehicle. Referring to Fig. 7e, for a payload of 30 MT, the two-stage vehicle with normal-growth inert mass technology and mixed-mode propulsion (P2P3S2) had a dry-mass reduction of 41%; and the single-stage vehicle with the same technology had a 72% reduction. Although the single-stage did not compare as favorably with the two-stage vehicle for the same payload at the current technology level, it was competitive with normal-growth inert-mass technology and mixed-mode propulsion, as shown in Fig. 7e, at a priority payload level (less than 30 MT). At the cargo payload level (greater than 200 MT), the single-stage vehicle was not feasible with today's technology. At normal-growth inert-mass technology with mixed-mode propulsion, the single-stage vehicle showed a large reduction in both dry mass and gross mass (Fig. 7e and 7f), but was still heavier than the two-stage vehicle. In addition to dry-mass and gross-mass reductions, technology growth had a dramatic effect on single-stage vehicle sensitivity to payload. At the current technology level, the single-stage vehicle was very sensitive to payload as compared to the two-stage vehicle. Thus it should not be considered feasible at this technology level, since inert mass growth, which is a chronic problem during the development program of a new concept, could easily eliminate the payload. On the other hand, at the advanced technology level, the single-stage vehicle sensitivity approached that of the two-stage vehicle and became a viable candidate for future launch vehicle systems.

From this study, the single-stage vehicle was selected for the priority mission and the two-stage vehicle for the cargo mission in the matrix of advanced launch vehicles needed for space industrialization. A summary of technology growth effects on the single- and two-stage vehicles is presented in Figs. 8a and 8b. The dry-mass payload sensitivities illustrate that the single-stage becomes attractive for launch vehicle

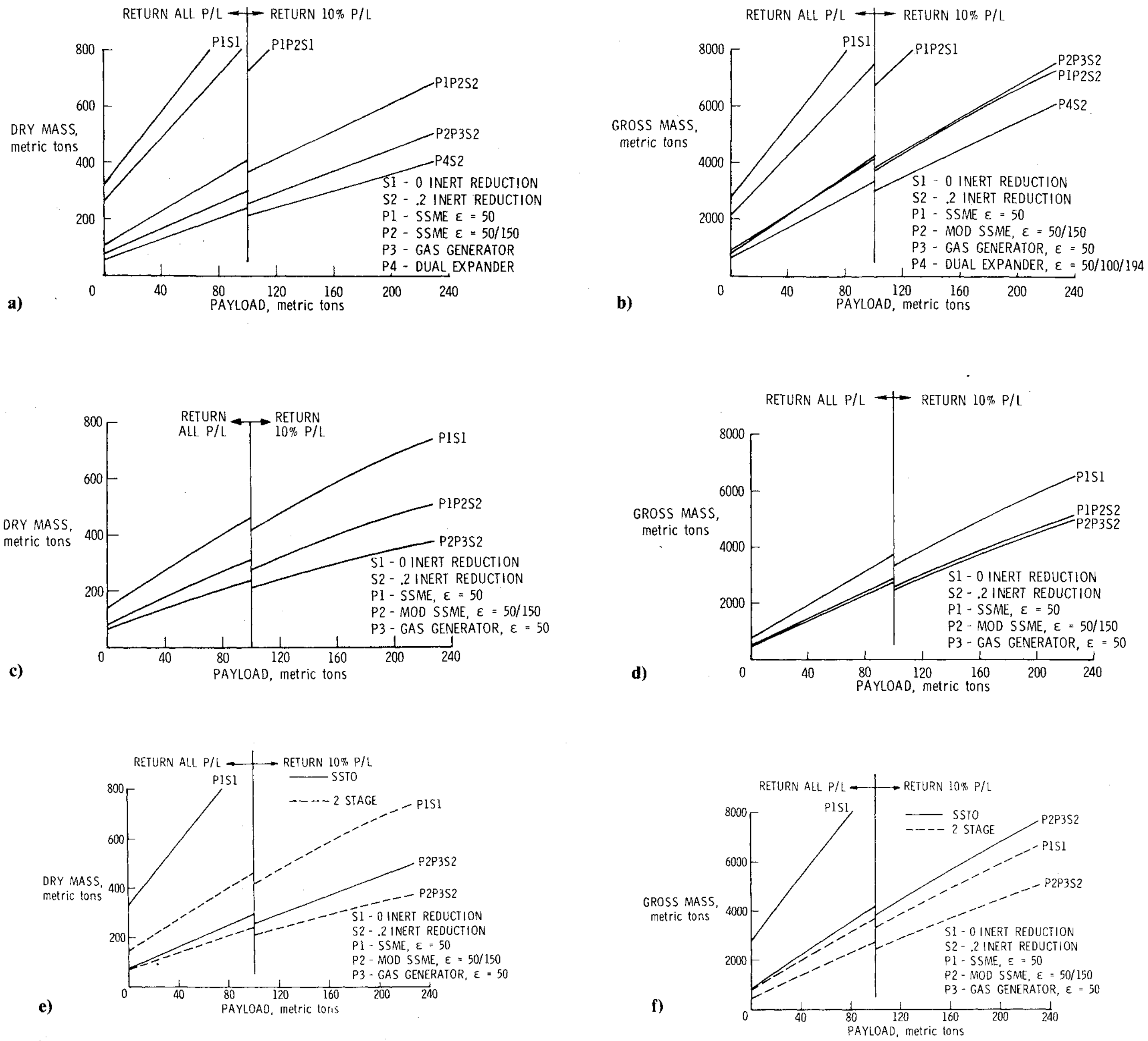


Fig. 7 a) Effects of technology on single-stage vehicle dry mass. b) Effects of technology on single-stage vehicle gross mass. c) Effects of technology on two-stage dry mass. d) Effects of technology on two-stage gross mass. e) Comparison of single-stage to two-stage vehicle dry mass. f) Comparison of single-stage to two-stage vehicle gross mass.

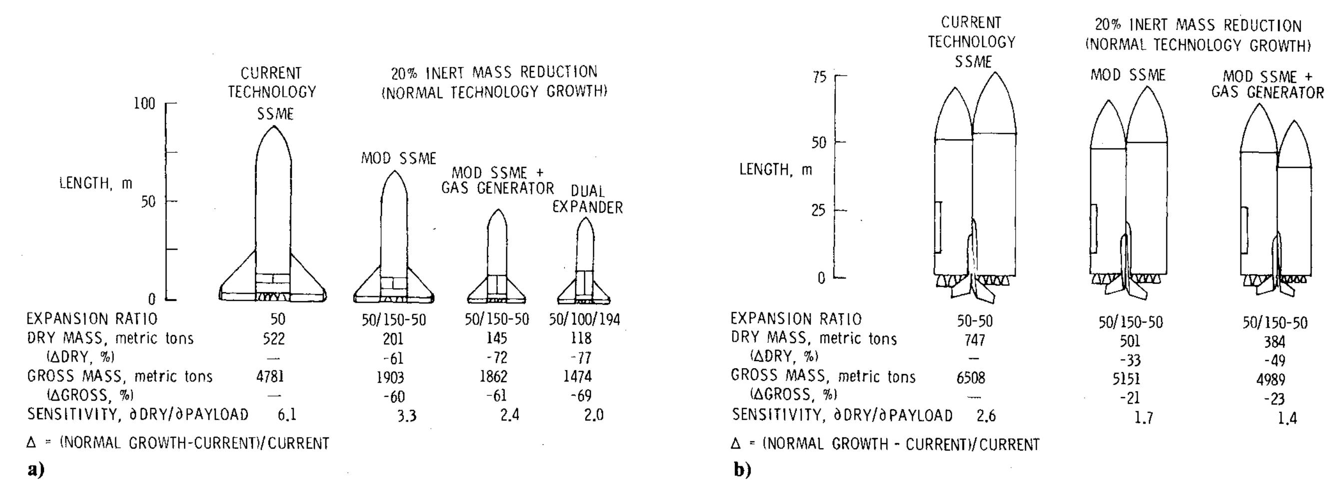


Fig. 8 a) Summary of technology effects on priority single-stage vehicle, 30-MT payload. b) Summary of technology effects on heavy-lift two-stage vehicles, 227-MT payload.

considerations if a moderate level of advanced technology is available for its development. For the normal technology growth vehicles, mixed-mode propulsion with separate engines reduced dry mass by 28% and gross mass by 2% over the all-hydrogen-fueled vehicle. The dual-expander engine reduced dry and gross mass by 41% and 22%, respectively. The two-stage vehicle also shows considerable reductions because of advanced technology, but not to the same extent as the single-stage vehicle. Mixed-mode propulsion with separate engines for the two-stage vehicle reduced dry mass by 23% and gross mass by 3% over the all-hydrogen-fueled vehicle.

Conclusions

Advanced propulsion system technology was shown to have a significant potential benefit when applied to the preliminary design of single- and two-stage launch vehicles. Mixed-mode propulsion in which hydrogen-fueled engines are burned in parallel with hydrocarbon-fueled engines reduced two-stage vehicle dry mass by 23% and single-stage dry mass by 28% as compared to an all-hydrogen-fueled propulsion system. The dual-expander engine reduced single-stage dry mass by 41%, but significant technology advances will be needed before this engine can be developed. Technology advances brought the single-stage vehicle to a comparable size, mass, and sensitivity to that of a two-stage vehicle with similar technology for small payloads.

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