Propulsion Evaluation for Orbit-on-Demand Vehicles

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Future Earth-to-orbit vehicles may be required to reach orbit within hours or even minutes of a decision. A study has been conducted to consider vehicles with such a capability. In Phase I of the study, 11 vehicles are designed to deploy 5000 lb to a polar orbit. Changes in the designs are examined parametrically for increased on-orbit maneuvers, increased payload, and other mission variations. Based on the results, two concepts are selected for Phase II design work: 1) a vertical-takeoff, two-stage system and 2) a horizontal-takeoff, two-stage system with an airbreathing subsonic first stage. Propulsion evaluations indicate that the liftoff thrust-to-weight should be increased to 1.5 for the vertical-takeoff concept, that dual-fuel is marginally useful for the horizontal-takeoff concept, and that using fluorine could improve the vehicles significantly.

Introduction

TRANSPORTATION from Earth to orbit is important for both commercial and military users. Currently, the Space Shuttle[1] can provide such access at a reasonable cost, but future requirements will lead to the need for new vehicles. One characteristic that may be required is the capability to launch within hours of a decision. The Orbit-on-Demand Vehicle (OODV) Study[2] considers vehicles with such a capability.

At the beginning of the OODV Study, likely mission requirements and vehicle concepts in design were not well understood. For this reason, the approach of the study was to first design 11 vehicle systems for a relatively easy baseline mission, to then parametrically examine the effects of increased mission requirements, and to finally select vehicle concepts and mission requirements for two final designs. The examination of the 11 vehicle systems is called Phase I and the final design effort, Phase II.

Baseline Phase I Mission and Technology Assumptions

The baseline mission for Phase I is simply to deploy and return a payload to a 160-n.mi. polar orbit. The payload weight, 5000 lb, is considerably less than that of the Space Shuttle. Additional mission details are in Ref. 2.

The technology level assumed for the OODV study had a significant impact on the resulting vehicle sizes and weights. In selecting the level of each technology, the guideline was to select a capability that could be developed, with a sufficient technology development effort, so that a vehicle could be in operation before the end of the century. Enough information had to be available about a capability to allow quantification. The physics of the technology had to be understood, and a plausible method of applying the technology had to be available. For example, the weights of the rocket engines were based on the Space Shuttle Main Engine (SSME) and previous engine designs.[3] This weight was then reduced 20% based on studies of the use of composite materials in rocket engines.[4-5]

Phase I Designs

The 11 vehicle systems designed for Phase I are shown on Fig. 1. The Space Shuttle is included as a reference. Each system is described in Ref. 2.

The first two vehicle systems use an expendable booster similar to a Titan. The first system is called V-EB-S. The V stands for vertical takeoff, the EB stands for expendable booster, and the S denotes that storable propellants are used for the orbit maneuver system (OMS). The second system is called V-EB-C and uses a cryogenic OMS. The next concept is a vertical-takeoff, single-stage vehicle and is called V-1. A dual-fuel rocket propulsion system is used with three propellants—liquid oxygen (LOX), liquid hydrogen (H), and RP-1. A two-stage, vertical-takeoff concept[6,7] called V-2 is included. The booster is staged at a Mach number of 3 and glides back to the launch site. A concept with two reusable stages and an expendable tank, called V-2DT, is the final in the vertical-takeoff category. Several horizontal-takeoff concepts, denoted by H, are included in the study. The first is the single-stage vehicle H-1. The remaining systems have airbreathing boosters and operational capabilities such as offset launch. A design with supersonic staging is included and called H-2-M3, where M3 indicates staging at a Mach number of 3. A similar concept with staging at a Mach number of 5 is called H-2-M5. Three systems have subsonic boosters. The first has a reusable orbiter staged at subsonic speeds and is called H-2-SUB. A concept with an expendable tank is included and called H-2DT. The final concept, H3, has three stages.

Phase I Design Results

Some of the characteristics of the Phase I designs[2] are given in Table 1. One question of interest is whether the H-2DT and H-3 concepts could use existing airplanes for the subsonic booster. Advanced versions of existing airplanes could probably carry about 400,000 lb to the staging condition. The orbiter and tank of the H-2DT weigh 590,000 lb, so it seems unlikely that this concept could use an existing airplane and achieve a satisfactory capability with foreseeable technology. The orbiter and stage 2 of the H-3 concept weigh 427,000 lb, which indicates it might be possible using an existing airplane as a booster.

The dry weights of the Phase I systems vary considerably. The orbiters for the horizontal-takeoff systems have a considerably higher dry weight than corresponding vertical-takeoff systems. This is due to the shape of the orbiters and the loads encountered. The orbiters for the horizontal-takeoff

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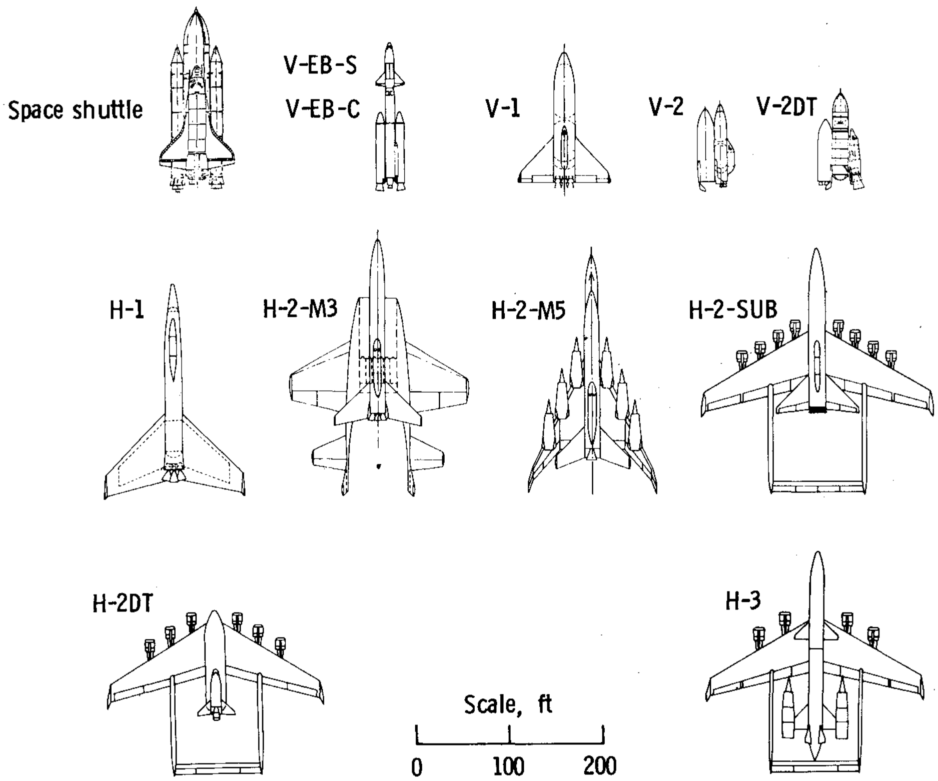

Fig. 1 Orbit-on-demand vehicle concepts.

Table 1 Orbit-on-demand vehicle characteristics

	Dry weight, 10^3 lb			Gross weight, 10^3 lb			Length, ft	
Concept	Booster	Orbiter	system[a]	Booster	Orbiter	System[a]	Orbiter ref.	System[a]
V-EB-S	169	12	181	1274	20	1294	44	150
V-EB-C	168	12	180	1268	20	1288	45	151
V-1	—	86	86	—	1127	1127	126	135
V-2	31	34	65	300	313	613	81	93
V-2DT	20	25	63	187	33	555	47	100
H-1	—	160	160	—	1473	1473	192	221
H-2-SUB	336	96	432	504	756	1260	170	262
H-2-M3	424	89	513	598	604	1202	172	254
H-2-M5	642	73	715	886	423	1309	152	230
H-2DT	262	31	332	393	40	983	47	170
H-3	190	32	352	284	203	711	94	220

[a]System = booster + orbiter + expendable tank or stage 2 but no sled.

systems are slender and have thin wings to reduce the drag of the mated configuration. The orbiters for the vertical-takeoff systems are shaped to keep the surface area small and the body and wing bending resistance high. The horizontal-takeoff systems encounter greater lift loads than the vertical-takeoff systems, which affects both wing and body weights. The wind gusts produce a greater penalty on the horizontal-takeoff vehicles, and they experience runway dynamic loads that the vertical-takeoff vehicles do not encounter.

The dry weight of the airbreathing boosters is much higher than that of the vertical-takeoff boosters. The airbreathing engines are heavy; the wings must provide lift and the landing gear must be designed for the gross weight of the system. The booster weight is also a function of the orbiter gross weight, which is greater for horizontal-takeoff systems than for vertical-takeoff systems. The airbreathing boosters need a smaller propellant fraction than the rocket boosters, which helps to reduce the gross weight of the airbreathing boosters.

Cost estimates of the Phase I systems are presented in Fig. 2. The expendable booster system V-EB-S has low development and production costs, but the operating costs are high. The expendable-tank systems V-2DT and H-2DT have somewhat higher operating costs than fully reusable systems. As expected from the weight trends, the vertical-takeoff systems cost the least. Single-stage concepts cost less than two-stage concepts, and increasing the staging Mach number increases the cost for airbreathing systems.

Parametrics

The gross weight of several systems as a function of the orbit maneuver velocity requirement is shown in Fig. 3. For the baseline mission, the requirement was 800 ft/s. The single-stage concepts V-1 and H-1 grow rapidly with velocity. The expendable-tank concepts V-2DT and H-2DT grow less rapidly, and the two-stage concepts grow at an intermediate rate. The vertical-takeoff systems maintain the advantage of lower gross weight compared to the corresponding horizontal-takeoff systems. The sensitivity of the gross weight suggests that the orbit maneuver requirement for several of the concepts should not exceed 2000 ft/s. Attractive system requirements would be difficult to meet with regard to economics and developmental risk.

Figure 4 shows the payload parametrics for typical concepts.[2] The gross weight doubles as the payload increases from 0 to 30,000 lb. An increase in payload from the 5000 lb used in

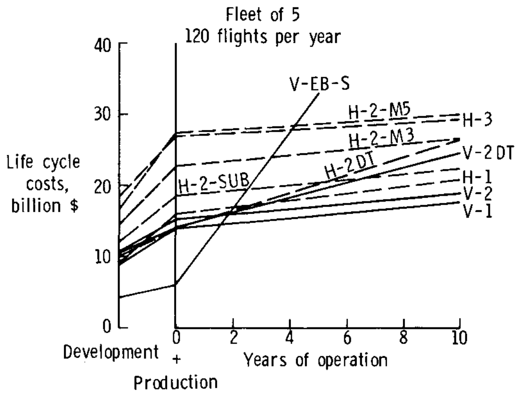

Fig. 2 Cost estimate for Phase I designs.

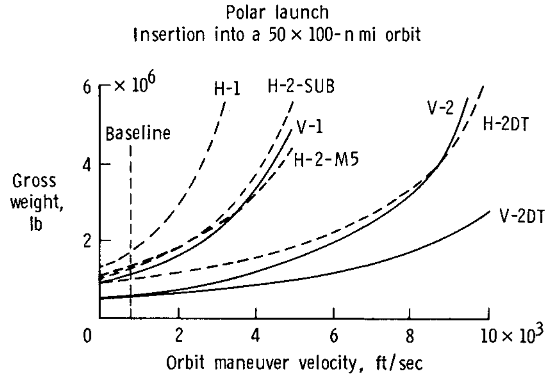

Fig. 3 Orbit maneuver parametrics.

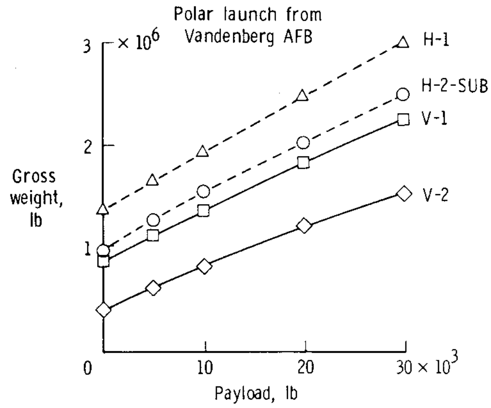

Fig. 4 Payload parametrics.

Phase I appears worthwhile. The utility would increase and the cost and risk increases would be small.

Phase II Designs

Based on the results of Phase I of the study, two concepts were selected for additional analysis: a vertical-takeoff, two-stage concept and a subsonic staged airbreathing booster concept.[2] The vertical-takeoff, two-stage concept was selected because it provides a good compromise of low cost, low development risk, and low weight growth when mission requirements are increased. The small size and low dry weight of both the booster and orbiter are considered worthwhile advantages. The airbreathing-booster concept has some significant mission advantages. It can provide an offset launch to reduce orbital phasing time, abort capability, and ferry. These and other advantages for airbreathing boosters were examined, with the conclusion that a choice between vertical and horizontal takeoff should not be made until the missions are better defined. The subsonic-staging concept was selected because it provides the lowest cost and can do the missions as well as the concepts with higher staging speeds.

The mission requirements for the Phase II designs were modified from the Phase I requirements.[2] The orbit maneuver velocity was increased to 1800 ft/s, and the payload weight was increased to 10,000 lb.

The Phase II design for the vertical-takeoff concept is shown in Fig. 5. As with the Phase I design for the vertical-takeoff concept, the gross and dry weights are lower than those of the horizontal-takeoff concept, and both stages are less than 100 ft long.

The Phase II design of the horizontal-takeoff concept is shown in Fig. 6. The gross weight is significantly greater than that of any current aircraft, but there seems to be no reason that such a large system could not be developed using known techniques. The wing loading and thrust-to-weight ratio are within the current state of the art. As long as enough wheels are used to distribute the weight across the runway, existing runway strengths should be satisfactory. The span of the booster is about 300 ft, which might limit the runways that could be used, but most large airports have sufficient cleared width along the runways. The tread width could be kept to 100 ft if needed to fit a large number of runways.

Figure 7 shows a comparison of the Phase II designs to the Space Shuttle. The mission requirements are different, but the comparison is close enough to indicate relative size and weight differences.

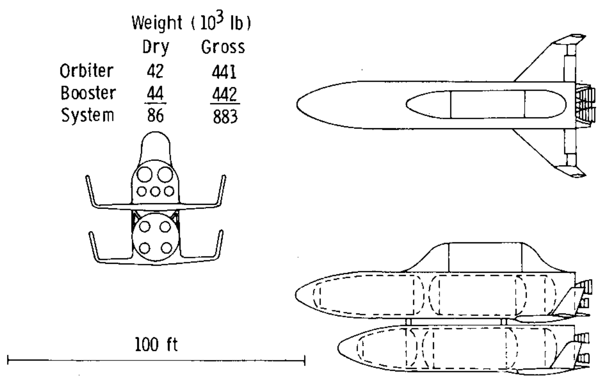

Fig. 5 Phase II vertical-takeoff design.

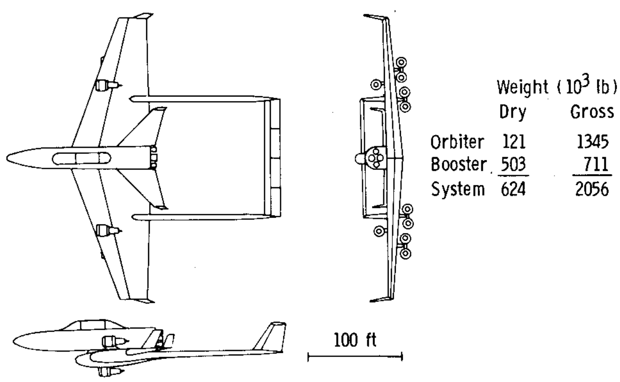

Fig. 6 Phase II horizontal-takeoff design.

Phase II Propulsion

Information about the engines used for the Phase II designs is provided in Table 2. The vertical-takeoff, two-stage concept uses two types of rocket engines. The orbiter has two hydrogen engines with two-position nozzles. These engines are smaller in thrust than the SSME, but the performance is the

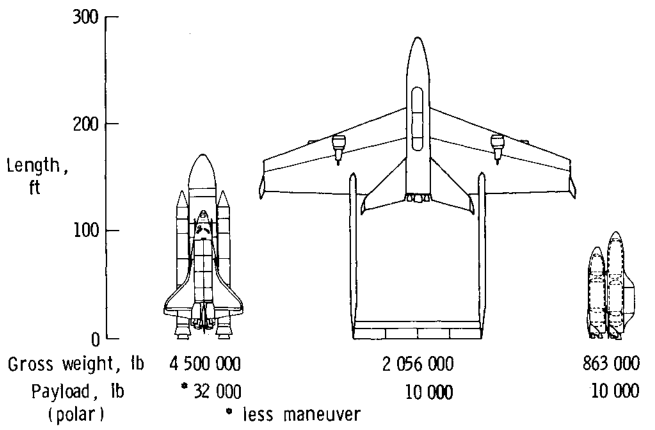

Fig. 7 Comparison of Phase II design and the Space Shuttle.

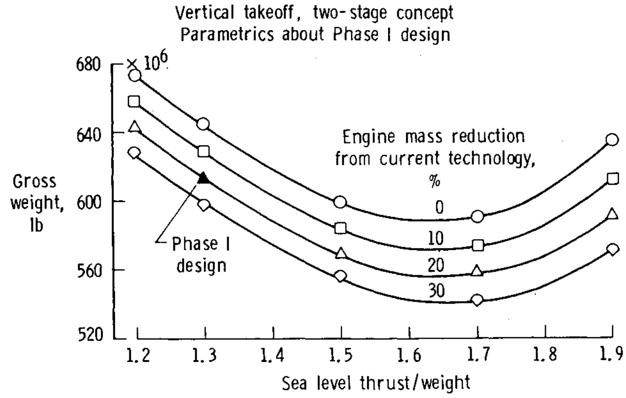

Fig. 8 Engine mass and thrust-to-weight sensitivity.

same as the SSME with full power level (109%), modified to account for the nozzle changes.

Three hydrocarbon engines are also used on the orbiter. They are hydrogen-gas-generator engines, described in Ref. 3. Although this engine is somewhat advanced over any engine yet developed, it should not be difficult to construct because each part is similar to parts of an existing engine. The pump Power is provided by a hydrogen-rich gas generator, which has been used in the J-2 engine. Because the gas is hydrogen rich, there should be no problem with deposit formation on the turbomachinery. Hydrogen is used to cool the engine, as with the SSME, and the heating rates are similar. Design of the cooling system should therefore present no serious problems. The main combustion chamber burns RP-1 and oxygen, both liquids, as in the F-1 engine. The pressure is higher, at 4200 psi, but achieving stable combustion should not be significantly more difficult. To minimize development and operating costs, the four engines on the booster are identical to the hydrocarbon engines on the orbiter.

The V-2 concept uses parallel burn. All engines on the booster and orbiter are ignited at liftoff and the booster provides all propellant until staging. The propellant for the orbiter engines during the boost phase is crossfed through lines that must be sealed quickly at staging. Developing this crossfeed capability for safe, reliable, and rapid turn-around operations may require a technology verification program. After staging, the two types of orbiter engines continue to operate in parallel until the hydrocarbon propellant is expended. When the hydrocarbon engines are turned off, the nozzle extensions for the hydrogen engines are applied to increase the vacuum thrust and specific impulse for the final portion of the ascent.

The propulsion system for the orbiter of the horizontal-takeoff, subsonic-staging concept is similar to that of the V-2 concept in that it uses parallel burn of the hydrogen and hydrocarbon engines. Two large hydrocarbon engines were selected for this vehicle, but three or four engines with the same total thrust would have provided the same capability. The hydrogen engine does not have a two-position nozzle; the staging altitude is high enough that a single expansion ratio is sufficient. The weight of the extension mechanism outweighs a small gain possible from increased effective specific impulse.

The turbofan engines on the booster are representative of projected transport engines that will be available in the early 1990s. The thrust level of 80,000 lb at sea level static conditions may not be available from commercial engines but would require only a small size increase. A larger number of smaller engines could be used at a small performance penalty.

Liftoff Thrust-to-Weight Optimization

Figure 8 shows the results of a trade study of the liftoff thrust-to-weight ratio of the V-2 Phase I design. The V-1, V-2, and V-2DT concepts were all initially designed for a thrust-to-weight ratio of 1:3. To select the best ratio for the Phase II design, the parametrics shown were computed. The minimum gross weight appears to be at a thrust-to-weight ratio of 1:6 or greater, but the analysis did not account for the aft movement of the orbiter center of gravity that would occur as more engines were added. The selected thrust-to-weight ratio for the Phase II design is 1:5, which appears to be a reasonable compromise between minimizing gross weight and avoiding a center of gravity that is too far aft for good aerodynamic trim capability.

The Phase II design for the H-2-SUB orbiter has a thrust-to-weight ratio of 1:2. Based on the results shown in Fig. 8, this value was selected over the Phase I value of 1:0. The thrust-to-weight ratio was selected beneath that of the V-2 for several reasons. First, the orbiter was already at a Mach number of 0.7 and an altitude of 30,000 ft at staging. Next, the flight path was nearly horizontal. Both of these factors reduce gravity losses, and increasing thrust-to-weight primarily benefits the system by reducing gravity losses. Finally, the center of gravity of the H-2-SUB orbiter was already so far aft that the wing design was heavier than that of the vertical-takeoff concepts.

Engine Mass Sensitivity

Figure 8 also shows the effect of changing the engine mass on the gross weight for the Phase I V-2 design. The engine mass estimates were based on the SSME and a preliminary design of the hydrogen-gas-generator engine. Neither of the estimates account for some weight growth that occurred during the SSME development program. These engine mass estimates are considered optimistic but possible for engines built with current knowledge and materials used in the SSME. With advanced technology, particularly in the use of composite materials in engines, some reduction from these mass estimates seems likely for future engines. Based on the results of Refs. 4 and 5, a reduction of 20% was selected for the OODV designs. The effect of engine mass is significant, as shown in Fig. 8. For other concepts, particularly single-stage concepts, the effects are much greater.

Dual-Fuel Propulsion with Horizontal Takeoff

The Phase II design of the H-2-SUB concept uses dual-fuel propulsion, as discussed above. Previous studies have shown that dual-fuel propulsion has a significant advantage for vertical-takeoff systems, but the advantages for horizontal-takeoff systems are less obvious. The results in Fig. 9 show that the orbiter gross weight for a horizontal-takeoff concept can be reduced slightly by using dual-fuel propulsion. Several additional advantages also occur. The orbiter is smaller and has a lower dry weight, which reduces the sensitivity to orbit maneuver increases and to vehicle development and production costs. The orbiter size reduction reduces the drag of the mated system, so that the booster can be smaller. The quantity of hydrogen can be reduced significantly. Hydrogen is more difficult to handle in keeping a vehicle in a ready status for an

Table 2 Phase II engine data

Vehicle	Fuel	Number used	Vacuum thrust, lb	Nozzle expansion ratio	Specific impulse, s
V-2 orbiter	H_2	2	72,800[a]	40.0	446.6
			75,700[a]	150.0	464.0
	RP-1	3	191,000	42.7	350.7
V-2 booster	RP-1	4	191,000	42.7	350.7
H-2-SUB orbiter	H_2	2	240,000	150.0	464.0
	RP-1	2	547,000	42.7	350.7
H-2-SUB booster	JP	10	80,000(SLS)	—	6400.0

[a]Two-position nozzle.

on-demand launch, and it is more expensive than RP-1. Advanced engines, such as the dual-expander engine discussed below, can further increase the advantages of dual-fuel propulsion. The disadvantage of dual-fuel propulsion is that the hydrocarbon engine needs to be developed. For the purposes of Phase II of the OODV study, the advantages were sufficient to justify this development.

Eliminating Hydrogen

Hydrogen has a high boil-off rate when an OODV is held in a fueled alert status. It is expensive, difficult to store, and not readily available at most locations. For these reasons, some vehicle systems were designed to use no hydrogen. The Phase I V-2 design was used as a baseline, and systems that used only a hydrocarbon fuel and liquid oxygen as an oxidizer were analyzed. The results, shown in Fig. 10, indicate that hydrogen could be eliminated with a small increase in gross weight, and the dry weight might even decrease slightly. The engine that yields the lowest vehicle weight has a propane staged combustion cycle. The propane results assume propane subcooled to the liquid oxygen boiling point. Results are shown for engine characteristics and were supplied by two engine companies.[8-9] The differences indicate the uncertainties in estimates of engine characteristics.

The problem with eliminating hydrogen is that the engines are more difficult to develop. The baseline hydrocarbon engine, as described above, has hydrogen for cooling and pump power generation. The pure hydrocarbon engines needed to eliminate hydrogen would have to use either hydrocarbon fuel or oxygen for cooling. Neither of these options are as well developed as hydrogen cooling. Also, the pure hydrocarbon engines would need either a hydrocarbon-rich or oxygen-rich drive gas for the turbopumps. Hydrocarbon-rich drive gas could leave the turbines and passages contaminated with buildups of partly-burned hydrocarbons. Hot oxygen-rich gas could lead to unstable failure modes because rubbing parts create hot spots which, in turn, cause oxidation of the parts. If pure hydrocarbon engines are desired, additional research should be initiated to examine such possible problem areas.

Dual-Expander Engines

Instead of using a hydrogen engine with a two-position nozzle and a separate hydrocarbon engine, as in the baseline designs, an engine that has both hydrocarbon and hydrogen fuels and two operating modes could be developed. The dual-expander engine[10] is one design in this category. Both fuels are used in parallel at liftoff. Later, the hydrocarbon portion of the engine is shut down while the hydrogen portion continues to operate. When the hydrocarbon portion is shut down, the exhaust of the hydrogen portion can expand into the entire nozzle, resulting in an increased expansion ratio without a two-position nozzle.

Figure 11 shows the possible benefit from applying the dual-expander engine to the single-stage, vertical-takeoff concept. Both the gross weight and dry weight are reduced significantly. Although these results indicate the importance of further consideration of the dual-expander engine and others in this category, there is some question about the magnitude of the improvements shown. The characteristics of the engines used were not estimated at the same time and the weight of the dual-expander engine may be based on a more advanced level of technology than the separate engines.

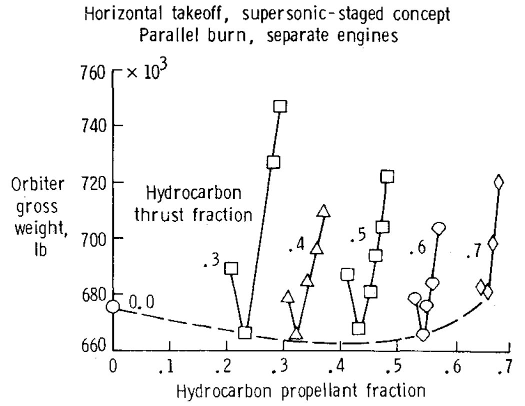

Fig. 9 Effect of dual-fuel propulsion with horizontal takeoff.

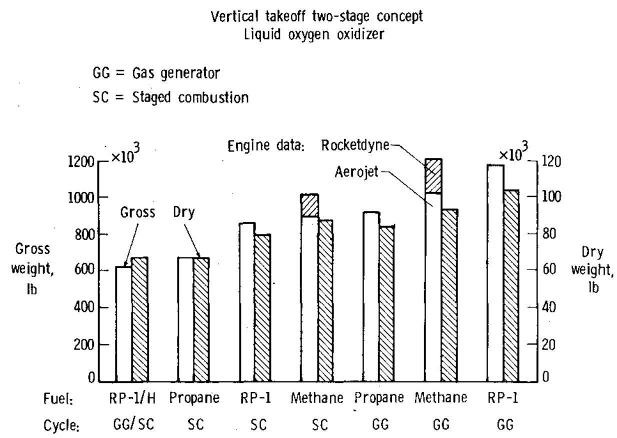

Fig. 10 Effect of eliminating hydrogen on gross weight.

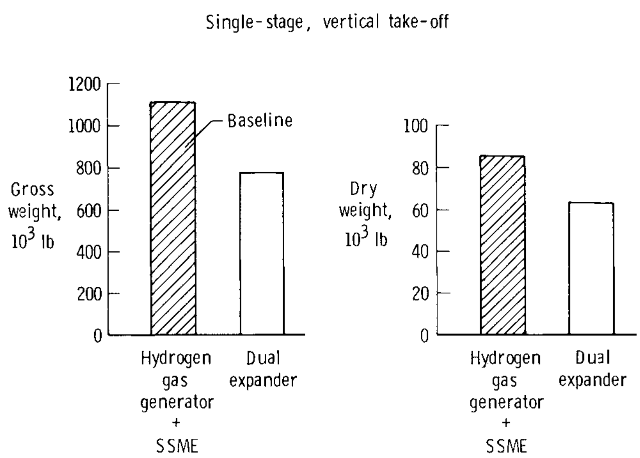

Fig. 11 Effect of the dual-expander engine on gross and dry weight.

Sled Power Sensitivity

The H-1 concept would need a sled for takeoff, and a baseline design was sized with the assumption that the sled provides the propulsion during the takeoff. If the orbiter engines and propellants are used during takeoff, the orbiter tanks would not be full. The sled could then be just an unpowered dolly, but the orbiter gross and dry weight would increase as shown in Fig. 12.

Use of Fluorine

The use of fluorine to improve Earth-to-orbit vehicles has been suggested in Ref. 11 and by others. Fluorine and hydrogen provide a higher specific impulse than oxygen and hydrogen, and the bulk density is greater with fluorine. The mixture ratio is greater, so much less hydrogen is needed. If fluorine/hydrogen engines are used instead of oxygen/hydrogen engines for the vertical-takeoff, two-stage concept, the orbiter gross weight can be reduced as shown in Fig. 13. The Phase I design with a thrust-to-weight ratio of 1:5 at liftoff was used as a starting point and is shown at an orbiter gross weight of 309,000 lb. The data points shown represent various combinations of hydrocarbon engines and fluorine/hydrogen engines on the orbiter and various propellant splits. The lowest orbiter gross weight occurs with the greatest use of fluorine at a hydrocarbon thrust fraction of 0, with no hydrocarbon engines or fuel on the orbiter. The total fluorine weight used is 132,000 lb and the orbiter gross weight is reduced by more than 130,000 lb, or more than 40%.

The problem with using fluorine in a parallel-burn system is that the exhaust products are left near the ground and can be dangerous. A more acceptable use of fluorine is to burn it only at high altitudes. Figure 16 shows the results of an investigation of using fluorine with series burn. The vertical-takeoff, two-stage vehicle system is used with the hydrocarbon engines on both the booster and the orbiter operated at liftoff. After staging the booster, the hydrocarbon engines on the orbiter continue to operate. After the hydrocarbon fuel is burned, the hydrocarbon engines are turned off, and the fluorine/hydrogen engines are ignited. Figure 14 shows the envelope curve from Fig. 13 for the parallel-burn results in addition to the new data points. The thrust level of the flurine/hydrogen engines was varied, giving various hydrocarbon thrust fractions, and the propellant split was varied. The results indicate that low values of hydrocarbon thrust fraction, or more fluorine thrust, are desired. There is a limit to how much fluorine thrust can be used on these vehicles. Because the hydrocarbon engines are still needed for the earlier part of the flight, increasing the fluorine thrust level increases the total engine weight. Increasing engine weight moves the center of gravity aft, causing trim problems that are not accounted for in the results shown. The results indicate a reduction in the orbiter gross weight of almost 60,000 lb, or about 19%, with about 60,000 lb of fluorine.

Because the results with fluorine on the two-stage concept were so promising, using fluorine on a single-stage vehicle was also examined. The results are shown on Figs. 15 and 16. As with the two-stage system, the results indicate that the maximum-fluorine vehicle has the lowest gross weight. Limiting the use of fluorine to high altitudes by operating the fluorine engines in a series-burn manner reduces the benefit somewhat. With only fluorine engines, the gross weight can be reduced by over 580,000 lb, or about 52%. With series burn, the reduction is over 420,000 lb, or about 38%. With the series-burn vehicle, the fluorine engines are used at 155,000 ft or higher, which should be high enough to insure that no exhaust products cause environmental problems on the ground.

In addition to the reduction in gross weight that fluorine provides for the single-stage vehicle, there is a reduction in sensitivity that may be equally important. Figure 17 shows the effect of fluorine on the sensitivity to orbit maneuver velocity. With fluorine, the single-stage vehicle is nearly as insensitive as is the two-stage system without fluorine.

The safety of using fluorine needs to be shown. No current systems use fluorine, although some successful tests have been completed. The small quantities needed for the series-burn system and the use only at high altitudes would seem to be more likely to be acceptable than vehicle sysems using larger quantities or at lower altitudes. If using fluorine is shown to be acceptable for an OODV, it should also be acceptable for orbit-transfer vehicles. If so, further transportation improvements would result.

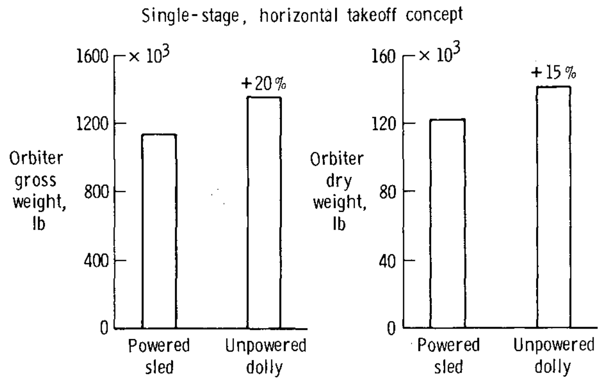

Fig. 12 Sled power sensitivity.

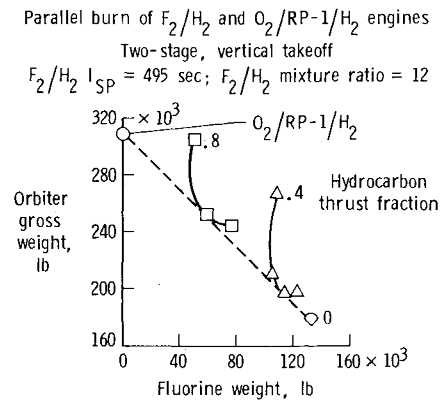

Fig. 13 Effect of using fluorine on orbit gross weight with parallel burn on a vertical-takeoff, two-stage system.

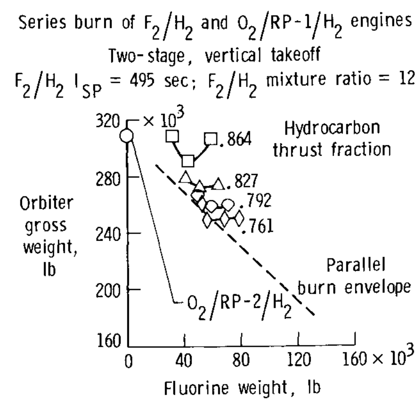

Fig. 14 Effect of using fluorine on orbiter gross weight with series burn on a vertical-takeoff, two-stage system.

Effect of Duct Burning

The subsonic boosters of the Phase I designs (H-2-SUB, H-2DT, and H-3) and the horizontal-takeoff design of Phase II were designed for a staging Mach number of 0.7 and a staging altitude of 30,000 ft. A trade study was conducted to determine the optimum staging altitude for the Phase II design. The results, shown in Fig. 18, indicate that a staging altitude of 30,000 ft is nearly optimum. At lower staging altitudes, the or-

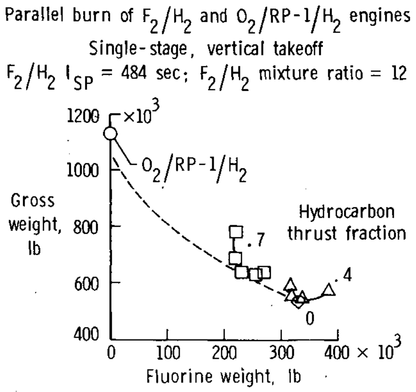

Fig. 15 Effect of using fluorine on gross weight with parallel burn on a vertical-takeoff, single-stage vehicle.

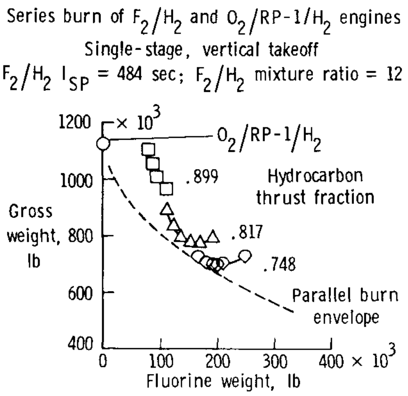

Fig. 16 Effect of using fluorine on gross weight with series burn on a vertical-takeoff, single-stage vehicle.

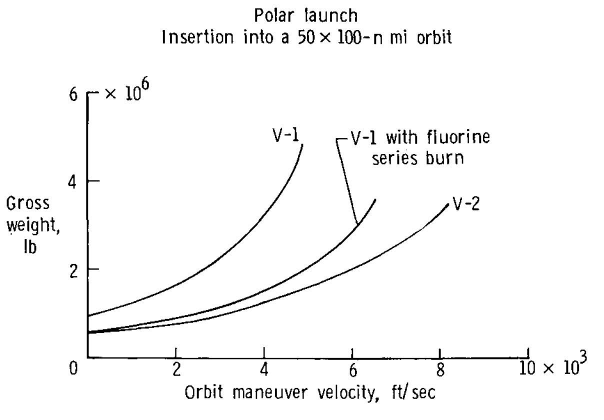

Fig. 17 Orbit maneuver parametrics with fluorine.

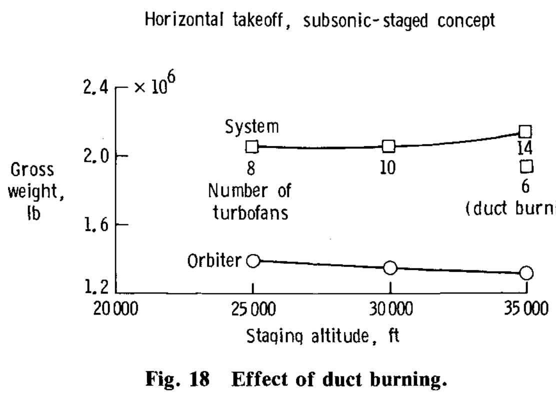

Fig. 18 Effect of duct burning.

biter is heavier, and the system gross weight is not significantly different. At higher staging altitudes, the orbiter is lighter, but the system gross weight increases.

The booster is largely designed by the short climb and acceleration period just prior to staging. Fuel comsumption during this short period is only a small part of the total booster fuel because the booster must cruise 545 n.mi. for launch offset and cruise back to the launch site. Although the turbofan engines provide adequate takeoff thrust and low fuel consumption, they are limited in thrust when thrust is most important—at the high altitude and Mach number just prior to staging. Adding a burner in the fan duct can provide a significant thrust increase in these conditions.[12] The fuel consumption increases when the duct burner is used, but the short time of use minimizes the penalty.

The effects of duct burning are significant. As shown in Fig. 18, a design with duct burning has a lower system gross weight than designs with standard turbofans. Because the staging altitude is 35,000 ft, the orbiter is lighter than the orbiter for the 30,000-ft staging altitude selected without duct burning. Perhaps the most significant benefit of duct burning is that the number of booster turbofan engines is reduced to six. Also significant is the reduction in the booster wing span and area. The design with a staging altitude of 30,000 ft had a wing span of 292 ft and a wing area of 17,000 ft^2. The design with duct burning required a wing span of 270 ft and a wing area of 14,500 ft^2. These reductions should improve the operational utility of the system.

Concluding Remarks

The results of the Orbit-on-Demand-Vehicle Study have provided insight into the characteristics of vehicle systems designed for rapid-response Earth-to-orbit missions. Several vehicle concepts are examined for a baseline Phase I mission, and parametric analyses have shown the effect of varying several requirements on the vehicle results. The results indicated that vertical-takeoff concepts have several advantages over horizontal-takeoff concepts. These advantages include lower weights, lower development risk, lower costs, and less sensitivity to increases in the difficulty of the mission requirements. On the other hand, horizontal-takeoff concepts with airbreathing boosters have certain advantages over vertical-takeoff concepts. These advantages are related to mission operations and include such capabilities as offset launch and takeoff from sites with minimal prepared facilities. the conclusion drawn during the study was that it is not yet reasonable to choose either vertical or horizontal takeoff to the exclusion of the other. As a result, both a vertical-takeoff concept and a horizontal-takeoff concept were selected for Phase II designs.

The vertical-takeoff concept selected for Phase II was the two-stage, fully-reusable concept. This concept offers a good combination of low costs and low sensitivity to increases in mission requirements. Within the class of horizontal-takeoff concepts with airbreathing boosters, the concept with subsonic-staging and a single, fully-reusable orbiter was selected. The results of the Phase II designs indicate that either concept would be a reasonable selection and could be developed with foreseeable technology.

The effect of liftoff thrust-to-weight of the vertical-takeoff, two-stage concept was analyzed and the results indicate that a value of 1:5 is a good choice. At lower values, the gross weight increases; at higher values, the additional engine weight drives the center of gravity too far aft. The sensitivity to engine mass was shown to be significant. Efforts to incorporate new materials such as composites into engine designs appear to be worthwhile.

Dual-fuel propulsion for the orbiter of a horizontal-takeoff concept was examined. Based on the improvements found, the Phase II design for the horizontal-takeoff concept included dual-fuel propulsion on the orbiter. The possibility of eliminating hydrogen from the system was shown to exist for the vertical-takeoff concept. Eliminating hydrogen would have significant operational advantages, particularly when the system is held in an alert status with propellants on board. The problem with this option is that the pure hydrocarbon engines that would have to be used are more of a challenge to develop than the baseline engines used for the rest of the study. An option was examined in which a single engine provides thrust during the early part of the flight, using both hydrocarbon and hydrogen fuels, and later in the flight, using only hydrogen. The results indicate that such engine concepts deserve additional study. Comparisons with separate engines should be made using improved engine design data.

The use of fluorine was considered. A series-burn option in which the fluorine is burned only at high altitudes was shown to provide a significant reduction in gross weight with only a small quantity of fluorine. The safety aspects of using fluorine should be examined further.

A duct burning turbofan can improve the subsonic-staging horizontal-takeoff concept. The system gross weight and orbiter weight can both be minimized. The number of engines, wing span, and wing area of the booster can be reduced.

Overall, the Orbit-on-Demand-Vehicle Study has indicated that vehicles with considerable utility and affordable costs can be developed for operations before the end of this century. Before such vehicle programs can proceed, however, many technology programs should be pursued. These could have a great impact on the options available when a vehicle program is initiated.

Acknowledgments

The Orbit-on-Demand Vehicle Study was a team effort and the results presented represent the efforts of many team members. Particularly significant to the results presented herein were the contributions of J. A. Cerro and W. D. Morris.

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