Parallel-Burn Options for Dual-Fuel Single-Stage Orbital Transports

James A. Martin*
NASA Langley Research Center, Hampton, Va.

A parallel-burn version of a single-stage vehicle for transport from the Earth to low-Earth orbit using two fuels and rocket propulsion is considered. New engine results were incorporated in vehicle performance and design studies. The results indicate that a hydrogen-cooled gas generator cycle engine provides attractive vehicle performance and that there is little incentive for increasing the chamber pressure beyond 27 MPa.

Nomenclature

f = hydrocarbon fuel fraction
HGG = hydrogen-cooled gas generator engine
I_{sp} = vacuum specific impulse of the hydrocarbon engine
m_D = dry mass of the vehicle
m_H = mass of hydrogen fuel
m_p = mass of propellants
m_0 = gross vehicle mass
MSC = methane-cooled staged combustion engine
P_c = chamber pressure
r = ratio of m_0 to $(m_0 - m_p)$
RPGG = oxygen-cooled gas generator engine
RPSC = oxygen-cooled RP-1 staged combustion engine
t = time at which the hydrocarbon engines were shut down
ϵ = nozzle expansion ratio

Introduction

THE concept of a single-stage vehicle for transport from the Earth to low-Earth orbit using two fuels and rocket propulsion was first suggested by Salkeld.[1] Separate hydrocarbon and hydrogen engines operated in series were proposed. The dual-fuel engine concept was introduced later[2,3] to reduce the mass of the hydrogen engines which must be carried during the hydrocarbon burn. The parallel-burn concept was proposed[4,5] as an alternative that does not require a dual-fuel engine in order to achieve good performance. In the parallel-burn concept, the hydrogen engines are used with the hydrocarbon engines during the first phase of the flight. The hydrogen engines may be throttled partly or completely during the hydrocarbon burn, depending on the acceleration history.

Because preliminary analysis[5] indicated that dual-fuel, single-stage vehicles were attractive for transport from the Earth to low-Earth orbit, a more detailed engine study was conducted.[6] The resulting engine data have been used in several vehicle designs.[7] This paper describes some results of parallel-burn vehicle designs using the resulting engine data. Parameters varied were the engine cycle, the fuel, the hydrocarbon fuel fraction, the chamber pressure, and the nozzle expansion ratio. The initial thrust-to-weight ratio was 1.3, and half of the initial thrust was provided by the hydrocarbon engines.

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*Aerospace Engineer, Space Systems Division. Associate Member AIAA.

Engine Cycles, Fuels, and Hydrocarbon Fuel Fraction

Two engine cycles were considered in the engine study which might be used for the hydrocarbon engines of a parallel-burn vehicle. One of these was a staged combustion cycle with either RP-1 fuel and oxygen cooling (RPSC) or methane fuel and cooling (MSC). The other was a gas generator cycle (HGG) in which a relatively small hydrogen flow was used for cooling before entering a gas generator, which provided the power for all turbopumps. Another gas generator engine was suggested by Beichel[8] which would use oxygen cooling and RP-1 fuel for both the main combustion chamber and the gas generator (RPGG).

These four engine concepts were used in analyses of parallel-burn dual-fuel vehicles which included trajectory optimization using the Program to Optimize Simulated Trajectories (POST).[9] The results of the trajectory analyses then were used in a vehicle-sizing program. This program iteratively varied the vehicle length while maintaining the geometric shape until the following criteria were satisfied: the fuel volume matched the requirement; the calculated mass of the inert elements and the mass of the propellants added up to the gross mass while meeting the mass ratio requirement from the trajectory results; and the payload equaled 29.5 Mg.

Figures 1 and 2 show the trajectory mass ratio (r) results. Figure 1 shows the results plotted against the vacuum specific impulse of the hydrocarbon engine (I_{sp}) for various values of the time at which the hydrocarbon engines were shut down (t). Figure 2 shows the same data except that the ordinate is the hydrocarbon fuel fraction (f), given by $f = 1 - 8(m_H/m_p)$, where m_H is the mass of hydrogen, m_p is the total propellant mass, and 8 is the oxidizer-to-fuel ratio of the hydrogen engines plus one. This definition of f puts the effect of the hydrogen flow in the HGG engine into the hydrogen fuel fraction $(1 - f)$ so that f reflects the fraction of high-density propellants.

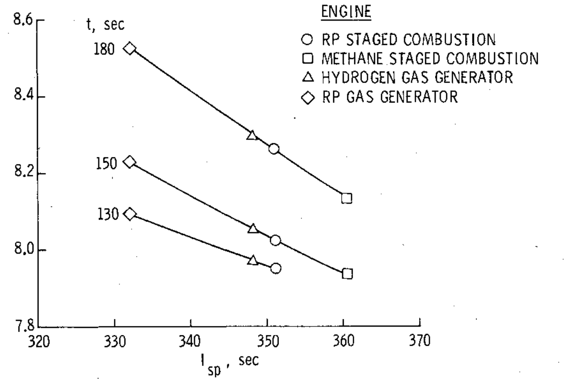

Fig. 1 Effect of specific impulse of the hydrocarbon engine on mass ratio.

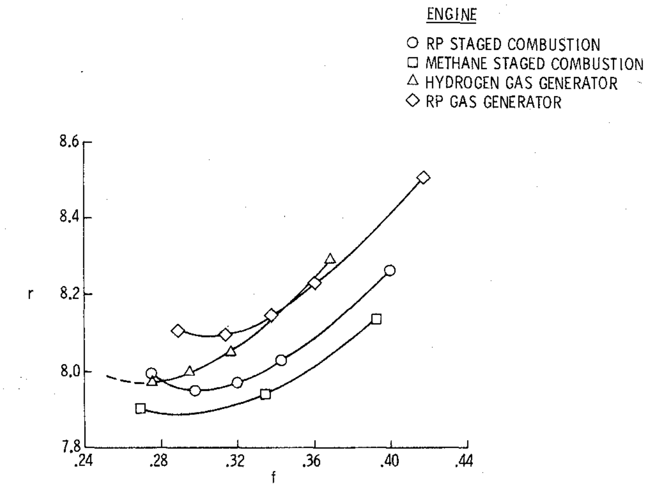

Fig. 2 Effect of engine type on mass ratio variation with hydrocarbon fuel fraction.

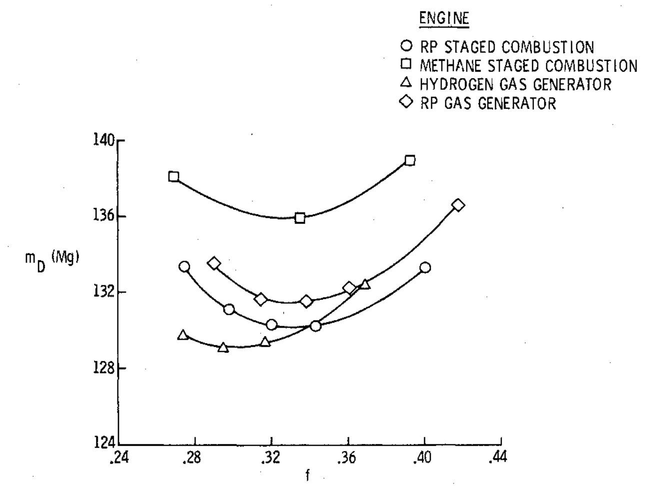

Fig. 3 Effect of engine type on dry mass variation with hydrocarbon fuel fraction.

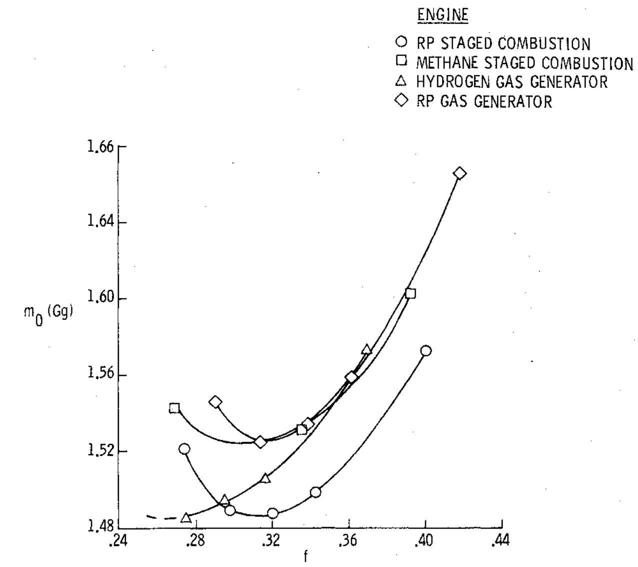

Fig. 4 Effect of engine type on gross mass variation with hydrocarbon fuel fraction.

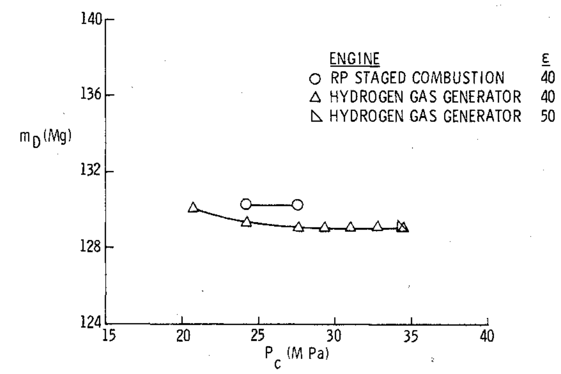

Fig. 5 Effect of chamber pressure and expansion ratio on dry mass.

Figure 1 shows that r decreases with increased I_{sp} and with decreased t, which is expected from ideal velocity considerations, since decreasing t decreases the fraction of the total impulse provided by the hydrocarbon engines. The trend does not continue for further decreases in t, however, as shown in Fig. 2. Decreases in t correspond to decreases in f, and Fig. 2 shows that there is a minimum r for each engine. The reversal of the ideal velocity trend at low values of f is due to the low acceleration after shutdown of the hydrocarbon engines, which increases the trajectory velocity losses.

The reason for plotting r vs f in Fig. 2 instead of vs t is to show the shift of the HGG curve due to the use of hydrogen for cooling. The small specific impulse decrease of the HGG engine relative to the RPSC engine would shift the curve upward and to the right, such that it would be between and parallel to the RPSC and RPGG curves. The hydrogen flow shifts the curve to the left considerably, which is undesirable because decreasing f increases the tankage volume requirement.

From a propellant mass and volume standpoint, points lower and further to the right are more desirable. In this sense, the methane engine appears attractive, but, because of the lower hydrocarbon fuel density, the methane cannot be compared directly with the other engines, which use RP-1.

Figures 3 and 4 show the results of the vehicle-sizing analysis for each of the trajectory points shown on Fig. 2. Since methane had the lowest fuel density and the MSC engine had the greatest mass, the dry mass and gross mass results were relatively high despite the low mass ratio. Comparing the RPSC and HGG data shows that the minimum mass ratio and gross mass are comparable, but the HGG engine results in a lower dry mass. The RPGG dry mass and gross mass are higher than those of the HGG.

One conclusion that can be drawn from these results is that the HGG engine has attractive performance despite the required hydrogen flow. When the reduced technology requirements for this engine are considered, the HGG appears to be a good engine to include in further work. A problem with the HGG engine is that three propellants are required, which may reduce the applicability of the engine to vehicles that otherwise might need only two propellants.

The RPGG engine avoids the requirement for three propellants, but the RPGG and the RPSC engines both require oxygen cooling, which is not a fully developed technology. The MSC engine requires neither three propellants nor oxygen cooling. A gas generator cycle with methane fuel and cooling would require neither three propellants nor oxygen cooling and would have the reduced development difficulty of the gas generator cycle. The vehicle results with such an engine probably would be within the ranges shown in Fig. 3 and 4.

Chamber Presssure and Nozzle Extension Ratio

The chamber pressure P_c was varied for the HGG and RPSC engines from the maximum allowable P_c determined in the engine study downward until a minimum dry mass was determined. For the RPSC engine, minimum dry and gross

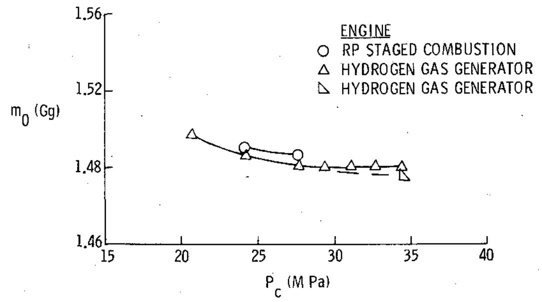

Fig. 6 Effect of chamber pressure and expansion ratio on gross mass.

mass occurred at the maximum chamber pressure as shown in Fig. 5 and 6. For the HGG engine, minimum dry mass occurred at about 30 MPa, but the change from 27 to 34 MPa was insignificant. The expansion ratio was increased to 50 at the maximum chamber pressure for the HGG engine, but the effect on dry mass was insignificant. The gross mass decreased slightly with increased chamber pressure, particularly with increased expansion ratio. There appears to be little incentive to increasing chamber pressure beyond 27 MPa for the staged combustion and gas generator cycles.

Conclusions

The results of this investigation indicate that hydrogen-cooled gas generator cycle engine provides attractive vehicle performance for single-stage, parallel-burn, dual-fuel vehicles for transportation from the Earth to low-Earth orbit. The results also show that there is little incentive for increasing the chamber pressure beyond 27 MPa.

References

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

[2]Salkeld, R., "Contribution to the Discussion of Mixed-Mode Propulsion and Reusable One-Stage-to-Orbit Vehicles," *23rd International Astronautical Congress*, Vienna, Austria, Oct. 8–15, 1972.

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

[4]Martin, J.A., "A Method for Determining Optimum Phasing of a Multi-Phase Propulsion System for a Single-Stage Vehicle with Linearized Inert Weight," NASA TN-D 7792, Nov. 1974.

[5]Henry, B.Z. and Decker, J.P., "Future Earth Orbit Transportation Systems/Technology Implications," *Astronautics and Aeronautics*, Vol. 14, Sept. 1976, pp. 18–29.

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

[7]Henry, B.Z. and Eldred, C.H., "Advanced Technology and Future Earth-Orbit Transportation Systems," *Third Princeton/AIAA Conference on Space Manufacturing Facilities*, Princeton, N.J., May 10–13, 1977.

[8]Beichel, R., "Liquid Propulsion System Effects on Design of Large Vehicles", *AIAA/MSFC Symposium on Space Industrialization Proceedings,* Marshall Space Flight Center, Huntsville, Ala., May 26–27, 1976, pp. 225–251.

[9]Brauer, G.L., Cornick, D.E., and Stevenson, R., "Capabilities and Applications of the Program to Optimize Simulated Trajectories (POST) Program Summary Document", NASA CR-2770, Nov. 1976.