where c is given by

$$c=\left[\frac{2f}{1+f}\left\{(\mu^2l^2+2)\sinh\mu l-2\mu l\cosh\mu l\right\}+(\mu^2l^2+2\mu l+2)e^{-\mu l}\right]\times\left(\frac{2f}{1+f}\sinh\mu l+e^{-\mu l}\right)^{-1} \tag{29}$$

Since the use of Eq. (3) causes some errors in the analysis involving specular reflections, the accuracy of Eq. (7) must be evaluated for practical applications. Comparison between results computed from Eq. (28) and those given in the literature[5] provide numerical justification of Eq. (3). The computation is performed for purely specular surfaces specified as $\rho_D=0.0$. Numerical results for a cylinder with $l=10.0$ are shown in Fig. 1. This figure displays dimensionless wall temperature distributions for various emittances. For two curves specified by the same emittance value, the difference is fairly small. Furthermore, they are alike in tendency although the curve based on Eq. (28) is slightly higher than the reference curve[5] drawn in dashes. From such good agreement, it is concluded that Eq. (7) can be used as a basis of thermal analyses relating to cylindrical configurations.

References

[1] Saunders, O.A., "Notes on Some Radiation Heat Transfer Formulae," *Proceedings of the Physical Society, (London)*, Vol. 41, 1928-29, pp. 569-575.

[2] Gebhart, B., "Unified Treatment for Thermal Radiation Transfer Processes-Gray, Diffuse Radiators and Absorbers," ASME Paper 57-A-34, 1957.

[3] Gebhart, B., "A New Method for Calculating Radiant Exchanges," *ASHAE Journal, Heating, Piping, Air Conditioning,* July 1958, pp. 131-135.

[4] Gebhart, B., "Surface Temperature Calculations in Radiant Surroundings of Arbitrary Complexity for Gray, Diffuse Radiation," *International Journal of Heat Mass Transfer,* Vol. 3, 1961, pp. 341-346.

[5] Perlmutter, M. and Siegel, R., "Effect of Specularly Reflecting Gray Surface on Thermal Radiation through a Tube and from its Heated Wall," *Transactions of the ASME, Journal of Heat Transfer,* Vol. 85, Feb. 1963, pp. 55-62.

[6] Graham, J.D., "Radiation Heat Transfer around the Interior of a Long Cylinder," *Journal of Spacecraft and Rockets,* Vol. 7, March 1970, p. 372-374.

[7] Sparrow, E.M. and Cess, R.D., *Radiation Heat Transfer,* Brooks Cole Pub. Co., 1967, p. 110.

Dual-Fuel Propulsion: Recent Results for Earth-to-Orbit Vehicles

James A. Martin* and Alan W. Wilhite†
NASA Langley Research Center, Hampton, Va.

Introduction

IN the first two decades of space flight, the most important goals of vehicle design were to establish the feasibility and capability for flight beyond the atmosphere. Multiple expendable stages were appropriate for these pioneering flights. The Space Shuttle,[1] which will begin orbital flights soon, will be the first step toward a more mature transportation system with low operational cost and the capability to accomplish a broad range of mission requirements.

When the Space Shuttle concept was selected, traffic projections did not justify designs that were more desirable operationally. The development cost would have been too high with the available technology.[2] The situation will be different, however, in the near future for follow-on transportation systems. The improved transportation offered by the Space Shuttle will spur traffic growth. In fact, user demand through 1982 may already be more than the Space Shuttle can accommodate.[3] Proposed space activities could potentially increase traffic greatly.[4] Improved technology will also be available for new transportation systems. Many technology improvements have already been developed by the Space Shuttle program. Others are being developed by the air transport industry, the military, and others. Still further technology improvements are now foreseen but will require development by an advanced vehicle program.[5,6]

One of the promising technologies for advanced vehicles is dual-fuel propulsion. Salkeld first showed the advantage that can be achieved by using two fuels in a single-vehicle stage if a high-density-impulse fuel is used first and a high-specific-impulse fuel is used second.[7] Martin then showed that this approach might not be attractive for Earth-to-orbit vehicles if separate engines are used in series, but that it might be attractive if a single engine could use both fuels in series.[8] Martin also showed that separate engines could be attractive if they operate in parallel initially. Figure 1 is a schematic diagram of these concepts. Beichel then proposed a dual-expander engine which uses two fuels in parallel initially to maximize benefits of dual-fuel propulsion for advanced Earth-to-orbit transportation systems.

The purpose of this note is to provide an update of dual-fuel propulsion efforts. Engine options are discussed and some Earth-to-orbit vehicle results are updated.

Engine Options

Several engine options have been studied for dual-fuel propulsion in Earth-to-orbit vehicles.[12-16] The best performance and cost results[10,11] have been achieved with the dual-expander engine[9] which utilizes a coannular nozzle. The simplest engine combination for dual-fuel vehicles, from a technology development point of view, uses the Space Shuttle main engine (SSME) in parallel with a hydrocarbon engine that has hydrogen cooling and a hydrogen-rich gas generator. This engine has been called the hydrogen gas generator (HGG) engine. The dual expander and HGG engines have in

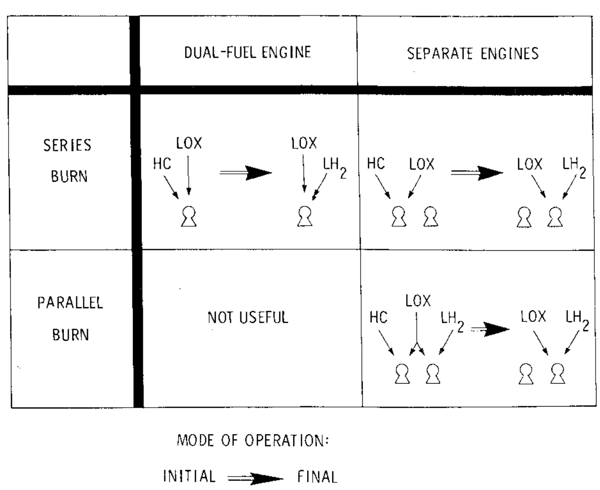

Fig. 1 Schematic diagram of engine concepts.

Presented as Paper 79-0878 at the AIAA/NASA Conference on Advanced Technology for Future Space Systems, Hampton, Va., May 8-11, 1979; submitted June 18, 1979; revision received Feb. 28, 1980.

Index categories: LV/M Propulsion and Propellant Systems; LV/M Mission Studies and Economics; Liquid Rocket Engines and Missile Systems.

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

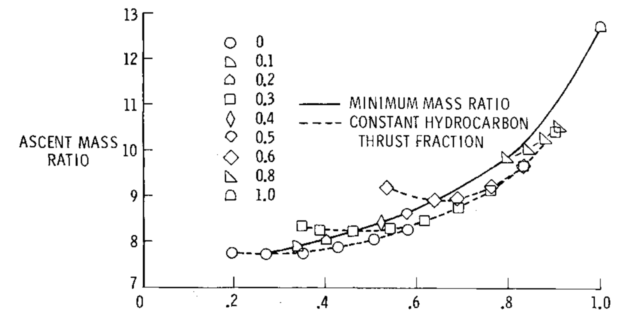

Fig. 2 Ascent gross-to-burnout mass ratio for a dual-fuel series-burn engine.

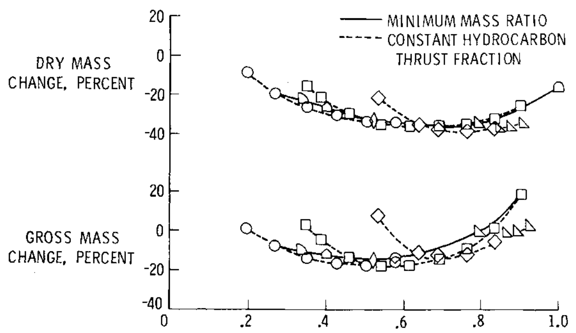

Fig. 3 Mass results for a series-burn vehicle—data points correspond to Fig. 2.

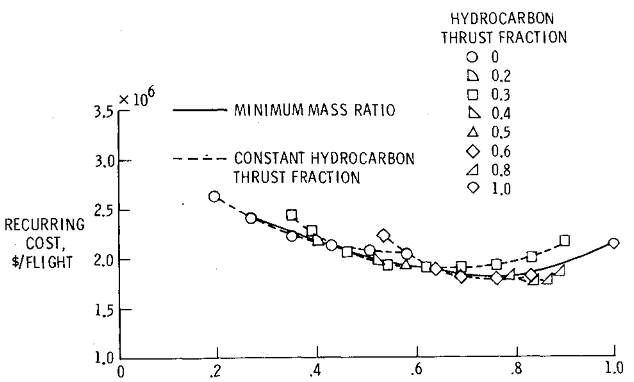

Fig. 4 Recurring cost per flight for a series-burn vehicle—data points correspond to Fig. 2.

common the use of hydrogen cooling and hydrogen/oxygen pump power supplies.

Another possibility for dual-fuel propulsion is to combine the advantages of these two engines. This recently proposed engine, the dual bell, has not been analyzed yet. Its cycle is essentially the same as the dual-expander, but it does not incorporate the advanced coannular nozzle. The expansion ratio benefit of the coannular nozzle would be lost, but its development difficulties would also be eliminated. Compared to the HGG engine, the dual-bell would be more complicated in only one aspect—it would require an oxygen-rich preburner. This should not be a difficult technology development if the preburner temperature is kept low.

Earth-to-Orbit Vehicle Results

Earth-to-orbit vehicles have been analyzed with hydrogen propulsion and with various engine concepts for dual-fuel propulsion.[10,11] The results were presented for many combinations of hydrocarbon thrust fraction and hydrocarbon propellant fraction in order to show the optimum combination for each concept. Hydrocarbon thrust fraction refers to the fraction of the vehicle thrust generated by the hydrocarbon engines; hydrocarbon propellant fraction refers to the fraction of the propellant that is hydrocarbon or oxygen burned with hydrocarbon. The results indicated that the dual-fuel series-burn engine, which is oxygen-cooled, was not attractive compared to hydrogen-cooled engines such as the dual-expander or HGG engines.

The data in Refs. 10 and 11 did not clearly define the optimum combination of hydrocarbon-thrust and hydrocarbon-propellant fractions for the dual-fuel series-burn engine. Additional analyses have been completed and are shown in Figs. 2-4, in which the additional data points have been added. These additional points, at a hydrocarbon-thrust fraction of 0.8, more adequately define the optimum combination of hydrocarbon-thrust and hydrocarbon-propellant fractions. Although these new data points show some reduction in recurring cost, the change is not large, and the conclusions of Refs. 10 and 11 are still valid. The dual-expander, dual-bell, or HGG engines seem preferable on the basis of performance and developmental difficulty.

Conclusion

The results presented in this note indicate that, even with additional optimization, the dual-fuel series-burn engine is not attractive for Earth-to-orbit vehicles. Hydrogen-cooled engines seem preferable.

References

[1] Anon., *Space Shuttle,* NASA SP-407, 1976.

[2] Layton, J.P., "Our Next Steps in Space," *Astronautics & Aeronautics,* Vol. 10, May 1972, pp. 56-65.

[3] Anon., "Industry Observer," *Aviation Week and Space Technology,* Vol. 109, No. 24, Dec. 11, 1978, p. 11.

[4] Grey, J., "How Real the Promise," *Astronautics & Aeronautics,* Vol. 16, March 1978, pp. 34-36.

[5] Haefeli, R.C., Littler, E.G., Hurley, J.B., and Winter, M.G., "Technology Requirements for Advanced Earth-Orbital Transportation Systems, Dual-Mode Propulsion," NASA CR-2868, Oct. 1977.

[6] Hepler, A.K., and Bangsund, E.L., "Technology Requirements for Advanced Earth Orbital Transportation Systems," NASA CR-2879, July 1978.

[7] Salkeld, R., "Mixed-Mode Propulsion for the Space Shuttle," *Astronautics & Aeronautics,* Vol. 9, No. 8, Aug. 1970, pp. 52-58.

[8] 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.

[9] Beichel, R., "The Dual-Expander Engine—Key to Economical Space Transportation," *Astronautics & Aeronautics,* Vol. 15, No. 11, Nov. 1977, pp. 44-51.

[10] Wilhite, A.W., "Optimization and Evaluation of Main Liquid Rocket Propulsion Systems Currently Studied for Advanced Earth-to-Orbit Shuttles," AIAA Paper 78-972, AIAA/SAE 14th Joint Propulsion Conference, Las Vegas, Nev., July 1978.

[11] Martin, J.A., "Econometric Comparisons of Liquid Rocket Engines for Dual-Fuel Advanced Earth-to-Orbit Shuttles," AIAA Paper 78-971, AIAA/SAE 14th Joint Propulsion Conference, Las Vegas, Nev., July 1978.

[12] Johnson, J.R., "Update on Development of the Space Shuttle Main Engine (SSME)," AIAA Paper 77-808, AIAA/SAE 13th Propulsion Conference, Orlando, Fla., July 1977.

[13] Spencer, R.G., Rousar, D.C., and Price, H.G., "LOX Cooled Thrust Chamber Technology Developments," AIAA Paper 78-1035, AIAA/SAE 14th Propulsion Conference, Las Vegas, Nev., July 1978.

[14] Martin, J.A., "Parallel-Burn Options for Dual-Fuel Single-Stage Orbital Transports," *Journal of Spacecraft and Rockets,* Vol. 15, Jan.-Feb. 1978, pp. 4-6.

[15] Luscher, W.P., and Mellish, J.A., "Advanced High-Pressure Engine Study for Mixed-Mode Vehicle Applications," NASA CR-136141, Jan. 1977.

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