The Application of Dual Fuel ($JP\text{-}LH_2$) for Hypersonic Cruise Vehicles

John P. Weidner*
NASA Langley Research Center, Hampton, Va.

The possibility of utilizing jet fuel (JP) stored primarily in the wings of hydrogen-fueled hypersonic cruise vehicles has been evaluated and compared to the performance of all-hydrogen-fueled aircraft. Parametric investigations of wing loading, thrust-to-weight ratio, payload size, and vehicle size are presented. Results indicate improvements in performance for a wide range of potential payload sizes, particularly when inflight refueling of the JP fuel is considered as a means of increasing range and mission flexibility.

Introduction

A NUMBER of studies have been conducted over the past years considering liquid hydrogen as a fuel for cruise vehicles operating at subsonic, supersonic, and hypersonic speeds. Hydrogen fuel has shown promise as an alternate fuel at lower speed, and is necessary at hypersonic speeds to serve as a heat sink to cool the engine and other parts of the vehicle. Typically, a hydrogen-fueled vehicle contains a large volume and has a low wing loading, with the hydrogen fuel contained in the body in cylindrical or bubble tanks. Standard jet fuel (JP) may be added, primarily in the wings of the basic hydrogen-fueled vehicle, to provide additional fuel for acceleration to hypersonic speeds. This paper examines the potential of containing both hydrogen and JP fuel in a cruise vehicle as a means of improving volumetric and operational efficiency in order to increase range performance.

Although a hydrogen and JP dual-fuel system can be utilized at any design speed, this paper will focus on a hypersonic cruise vehicle employing an HT-4 type configuration.[1] Three payload conditions have been considered: a large low-density payload consistent with long-range commercial transports, and large and small high-density payloads consistent with possible military missions. Relative performance is compared over a range of parameters including vehicle size, wing loading, and thrust loading. Also, aerial refueling of the JP fuel is considered for the small payload vehicles.

Vehicle and Propulsion Definition

The performance of a hypersonic cruise vehicle is very sensitive to the combined weight of the airframe and propulsion system, and an in-depth study will be needed to obtain accurate weight estimations. This exploratory study used the simplified weight estimation procedure outlined in Fig. 1. Airframe weights are based on a unit surface area and include the fuel tank, shell weight, and Mach 6 thermal protection system. These weights roughly correspond to minimum gage structures and are limited to light wing loadings consistent with a design wing load, including the maneuver load factor, of less than 150 lb/ft^2. An afterburning turbojet from studies of the advanced supersonic transport[2] was used for acceleration from takeoff to Mach 3 and for supersonic cruise with JP fuel. Hypersonic acceleration and cruise is accomplished with a dual-mode scramjet, operating as a ramjet at speeds below Mach 4 and is patterned after the scramjet concept described in Ref. 3. The low- and high-speed propulsion systems are assumed to be independent, with separate inlet systems, and with installed weights based on the inlet frontal cowl area given in Fig. 1. While weight estimation using the information given in Fig. 1 is approximate, it is felt that this method is satisfactory for the parametric analysis of this study.

Liquid hydrogen is a high-energy content fuel with a low density (4.4 lb/ft^3) and requires a large tank volume for a given mission. Thus, the volumetric efficiency of the vehicle is critical to achieving a high-performance configuration. The volume assumed for the hydrogen fuel tank that can be contained in a given size vehicle is presented in Fig. 2. The curve on the left side of the figure gives the hydrogen tank volume assumed relative to the body volume measured to the external skin over the length of the tank. The integral tank data point is from a structures study of a blended body modified HT-4 configuration,[4] and the nonintegral tank data point is from an inhouse hypersonic research airplane study.[5] The right-hand curve is a measure of the fore and aft body volume that cannot be used for payload or fuel tanks. Small hydrogen-fueled vehicles are volume constrained and, as illustrated in Fig. 2, are further penalized by a reduced volumetric efficiency brought about by minimum dimensions for tank clearance, frame depth, and thermal protection system thickness.

Utilizing wing volume for high-density JP fuel improves the overall volumetric efficiency of the hydrogen-fuel vehicle. The assumed available wing tank volume is correlated in Fig. 3 with the theoretical wing reference area for the blended wing-body vehicle given in Ref. 4. Fuel distribution in the wing results in a structural relief of the aerodynamic wing load by about 60% of the wing fuel weight.

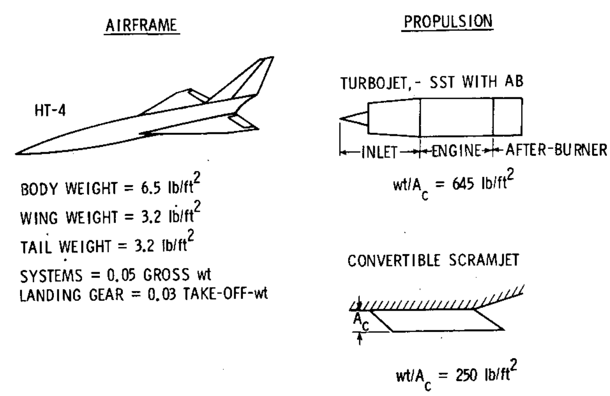

Fig. 1 Airframe and engine weight estimates.

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*Aero-Space Technologist, Hypersonic Aerodynamics Branch, High-Speed Aerodynamics Division.

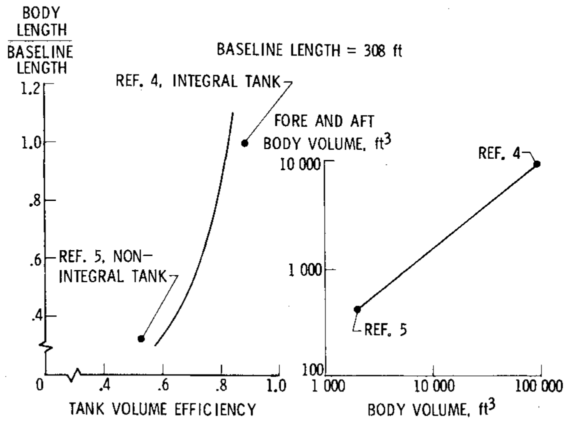

Fig. 2 Hypersonic vehicle hydrogen fuel tank volume.

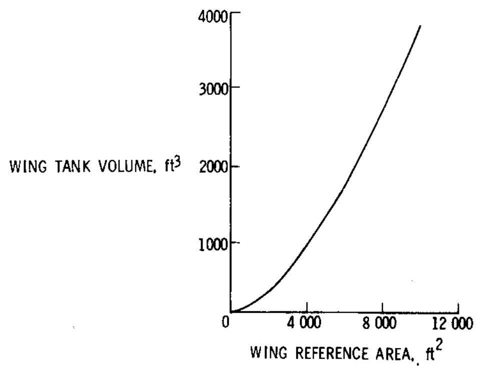

Fig. 3 Usable wing tank volume.

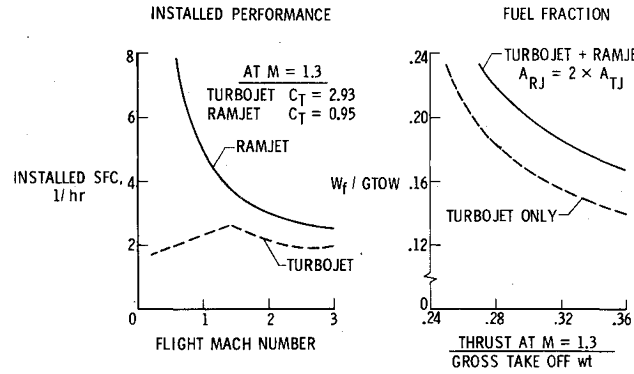

Fig. 4 Acceleration performance from takeoff to Mach 3.

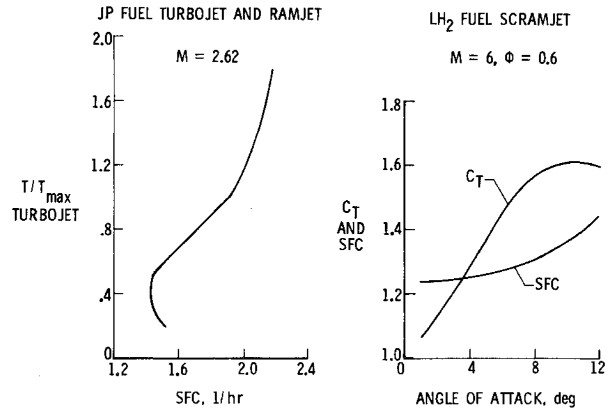

Fig. 5 Supersonic and hypersonic cruise performance, $L/D \approx 6$.

Propulsion System Performance

The airbreathing propulsion system studied consists of a turbojet and convertible scramjet with independent inlet systems. It is assumed that both engines can burn either JP or hydrogen fuel, and that JP fuel is used exclusively for acceleration to Mach 3, with hydrogen fuel used above Mach 3 and as reserves for subsonic loiter. The actual geometric integration of these propulsion systems is the subject of current investigations and is beyond the scope of this study. However, one element of this study is to define attractive propulsion options to improve vehicle performance and the integration of the engines with the airframe.

Operating a convertible scramjet to increase thrust at low speeds is one approach to decreasing the size of the turbojet required for acceleration through the transonic speed regime. Specific fuel consumption typical of an advanced afterburning turbojet and a low-speed ramjet is given by the curves on the left-hand side of Fig. 4. Thrust coefficient (C_T) at the peak of the transonic drag rise is also given and is defined as installed thrust divided by the product of flight dynamic pressure and inlet frontal area (T/qA_c). Ramjet thrust coefficient is based on a streamtube capture area equal to 30% of the inlet frontal area, consistent with the inlet geometry of the scramjet concept described in Ref. 3. The quantity of JP fuel consumed to accelerate to Mach 3 relative to gross takeoff weight, based on numerous trajectory calculations from earlier studies using various engine sizes is correlated against total thrust at Mach 1.3, as shown on the right side of Fig. 4. For the example shown, the ramjet had twice the frontal area of the turbojet inlet. The difference in the curves illustrates the effect of operating the less-efficient ramjet at lower speeds. These fuel fractions will be used later in the paper to compute performance and to assess the overall impact of operating the ramjet at low speeds.

Propulsive cruise performance assumed for the study is given in Fig. 5. Supersonic cruise performance given by the left curve was assumed to be independent of vehicle angle of attack. Maximum turbojet thrust is with the afterburner operating with an equal quantity of thrust provided for the ramjet and corresponding increase in specific fuel consumption. Integrated scramjet performance at Mach 6 makes maximum use of forebody precompression and thus is sensitive to vehicle angle of attack. For both supersonic and hypersonic cruise, the dynamic pressure is found to maximize range.

For this study the scramjet is sized for thrust equal to drag at cruise altitude at a combustor fuel to air equivalence ratio of 0.6. The turbojet is parametrically varied, primarily effecting low-speed acceleration and supersonic cruise efficiency, to maximize total range.

Range Performance Comparison

Two basic steps were used to calculate performance. The vehicle weight and fuel load were first determined based on fixed wing loading and thrust loading, and the range was then calculated based on vehicle and engine performance. The procedure used to estimate vehicle weight and fuel load is illustrated in Fig. 6. Major variables involved are listed on the left side of the figure, and consist of body size, turbojet thrust loading at takeoff, structural wing loading at takeoff, and wing loading at the beginning of hypersonic cruise.

Structural wing loading is defined as aerodynamic takeoff wing loading minus the span load effect of containing JP fuel in the wings which is assumed to be 60% of the wing JP fuel weight. Wing loading at cruise is defined as the vehicle wing loading after the JP fuel has been consumed and the vehicle has accelerated to Mach 6. JP fuel is consumed during takeoff and acceleration to supersonic speed, with any remaining JP fuel consumed by cruising at supersonic speed.

Wing size is a key parameter in defining JP fuel load and is a primary function of the hypersonic cruise wing loading. By allowing JP fuel to displace hydrogen fuel volume in the

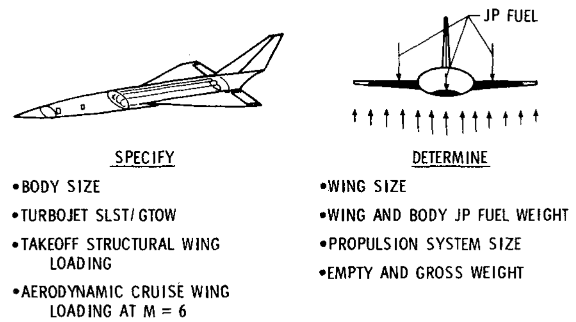

Fig. 6 Wing loading iteration for a dual-fuel cruise vehicle.

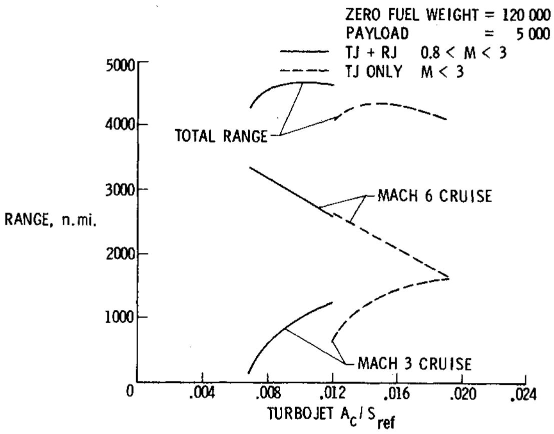

Fig. 7 Effect of low-speed engine performance on range.

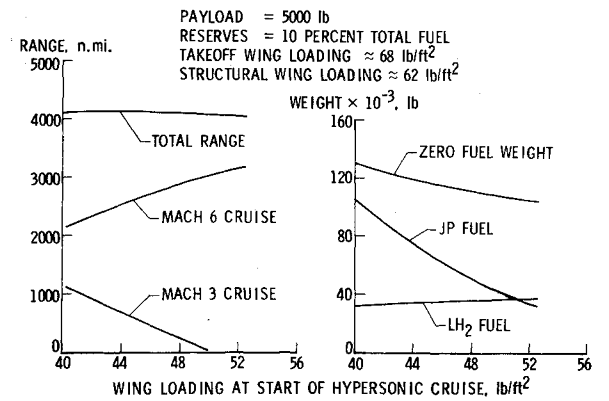

Fig. 8 Cruise performance for a 55% scale HT-4 vehicle, body length = 169.4 ft.

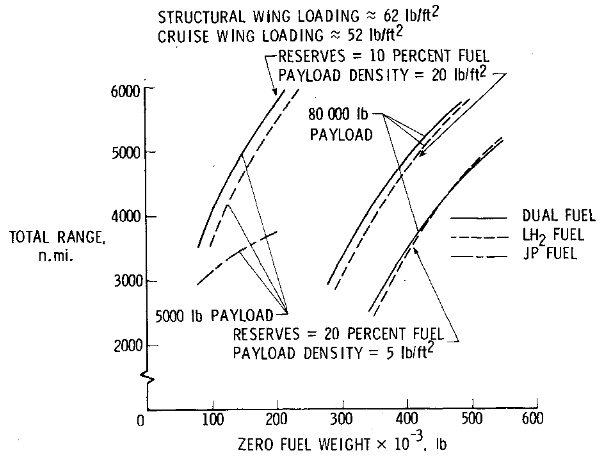

Fig. 9 Cruise performance comparison of dual-fuel, hydrogen-fuel, and JP-fuel vehicles.

body, both a specified takeoff wing loading and hypersonic cruise wing loading can be simultaneously satisfied. An iterative procedure is required to define wing size, scramjet size to satisfy cruise thrust, and systems, landing gear, and turbojet weights which are a function of takeoff weight. Once the empty and gross weight is determined, acceleration and range performance are calculated based on aerodynamics derived from Ref. 1. Cruise L/D is altered from Ref. 1 to account for changes in the wing reference area required to satisfy the specified wing loading.

Effect of Turbojet Size

In sizing the turbojet propulsion system to maximize performance, it is necessary to determine the optimum thrust load of the turbojet and the effect of operating the ramjet at low speed. Basically, the increased propulsive efficiency of a larger turbojet during acceleration and supersonic cruise must be traded against the resulting increase in weight of the vehicle during hypersonic cruise on scramjet thrust.

Results of a performance analysis of the effect of turbojet size on range performance is given in Fig. 7 for acceleration to Mach 3 both with and without the scramjet operating at its maximum potential thrust. Results are given for a constant zero fuel weight vehicle containing a small payload with range correlated against turbojet inlet frontal area relative to the vehicle reference wing area. A basic trend of increasing turbojet size is to increase the overall aircraft density and the quantity of JP fuel carried. This comes about through increased systems and landing gear weights, a larger wing to maintain a specified wing loading, and a subsequent increase in the quantity of JP fuel carried. The result is an increase in the supersonic cruise range to burn off the JP fuel and a decrease in hypersonic range caused by the higher density vehicle.

Operating the ramjet at low speed further decreases the required turbojet size and results in a small increase in total range. Low-speed ramjet thrust has the advantage of maximizing total range, increasing hypersonic range, and reducing the size of the turbojet. Only the calculations for turbojet thrust may be considered conservative since installed ramjet drag was based on an orderly flow of air through the ramjet. In Ref. 6, subsonic wind-tunnel test indicate internal nozzle airflow separation and high drag for a nonoperating integrated scramjet. Thus, a combined turbojet and ramjet was selected as the accelerator mode of operation for the remainder of this paper. Also, a turbojet (A_cS_{ref}) of 0.0085, corresponding to a thrust load at takeoff of about 0.3, was used to maximize hypersonic range.

Effect of Cruise Wing Loading

Specifying cruise wing loading sizes the wing and determines the quantity of JP fuel carried by a given size vehicle. The effect of cruise wing loading on range performance and vehicle weight is given in Fig. 8 for a constant size body which has a length that is 55% of the transport size vehicle given in Ref. 4. The specified structural wing loading is 62 lb/ft^2, and results in a takeoff wing loading of about 68 lb/ft^2.

Increasing cruise wing loading reduces wing size with a corresponding decrease in JP fuel and supersonic cruise range using that fuel. Also, the hydrogen fuel is increased as the amount of JP fuel required in the body to meet a specified wing loading is reduced. Total range is nearly independent of wing loading. Zero fuel weight decreases with increasing wing loading as a result of the reduced wing size and vehicle components that are based on gross weight. Thus, best range performance for a given vehicle zero fuel weight is achieved with a high cruise wing loading, where JP fuel is primarily confined to the wing, and the hydrogen fuel load contained in the body is maximized.

Comparison of Dual-Fuel and Hydrogen-Fuel Vehicle

So far the range performance of a dual-fuel vehicle has been examined in terms of turbojet thrust loading and cruise wing loading. In this section the turbojet thrust loading and cruise wing loading that gave best performance is used to calculate performance over a wide range of vehicle size and is compared with all hydrogen-fuel vehicles. The hydrogen-fuel vehicles are identical to the dual-fuel vehicles except that they do not contain wing fuel tanks. With no span load effect, the takeoff structural wing loading of the hydrogen vehicles is the same as the aerodynamic takeoff wing loading.

Performance is compared in Fig. 9 for three different payloads: 5000 and 80,000 lb high-density payloads consistent with potential military applications, and an 80,000 lb low-density payload with increased fuel reserves consistent with commercial transport applications. The larger payloads displace body volume that could be used for hydrogen tanks, so that payload weight and density effects the quantity of hydrogen fuel carried in a given size body. Referring to Fig. 9, the combined effect of volume displaced and increased inert weight of a larger payload substantially increases the vehicle zero fuel weight required for equal range. Reducing payload density and increasing reserves for a transport type application further increases zero fuel weight by about 25%.

Using the weight estimating procedure of this study, a small increase in range performance is obtained; in most cases through the application of dual fuel amounting to as much as 10% for a small payload. However, compared to an all JP-fuel vehicle of the same configuration, both the hydrogen and dual-fuel vehicles exhibit a large increase in range as the vehicle is made larger, illustrating the long-range cruise potential of hydrogen fuel.

Considering the high sensitivity of range performance to inert weight, the weight differences of the hydrogen and dual-fuel vehicles that result from the weight estimating procedure of this paper have a strong effect on the performance comparison of Fig. 9. The weight penalty imposed on the dual-fuel vehicles of Fig. 9 for carrying JP fuel in wing tanks is about 30% of the quantity of JP fuel contained in the vehicle. A more detailed study is needed to more accurately determine the actual weight penalty appropriate for dual-fueled aircraft.

The relative costs of dual-fuel and hydrogen fuel vehicles were not assessed in this study. Factors that would tend to reduce the costs of a dual-fuel vehicle are its reduced size and surface area for a given mission. Adding JP fuel in the wings of a basically hydrogen-fuel vehicle reduces the hydrogen volume requirements, improves volume utilization, and thus increases the vehicle density. Factors that would tend to increase the costs of a dual-fuel vehicle are the increased complexity of two different fuel systems and the development of propulsion systems to operate with both JP and hydrogen fuel.

Performance with In-Flight Refueling

So far, a range advantage has been identified for storing JP fuel in the wings of a hydrogen-fuel vehicle, particularly for a small payload that results in a smaller and more volume-constrained vehicle. The dual-fuel vehicle also exhibits the same advantages as a hydrogen-fuel vehicle in that long ranges can be achieved relative to JP-fuel vehicles. The purpose of this section is to further explore advantages of a small dual-fuel vehicle by using conventional in-flight refueling techniques. In-flight refueling of either JP or hydrogen fuel is theoretically possible. However, this study explored only JP refueling using conventional tankers.

A schematic of the flight profile of a dual-fuel vehicle using in-flight JP refueling is illustrated in Fig. 10. This vehicle could take off with partially empty JP fuel tanks and top off the tanks when airborne. This technique would reduce the landing gear size and structural loads on takeoff and thus reduce the vehicle weight penalty imposed by carrying JP fuel. The JP fuel is consumed during an initial supersonic cruise, followed by acceleration and cruise at hypersonic speed and high altitude using hydrogen fuel. Hydrogen fuel is held in reserve for a second refuel sequence, after which JP is used as the reserve fuel for a supersonic cruise back to the airport. Refuel ranges are about the same either with or without the hydrogen fuel load, since when hydrogen fuel is onboard, the hydrogen fuel can serve as reserve fuel allowing all of the JP fuel to be used for cruise. It is assumed that throughout the mission, 10% of the total gross fuel energy is held in reserve and that the hydrogen fuel reserve is lost in the refuel sequence after hypersonic cruise.

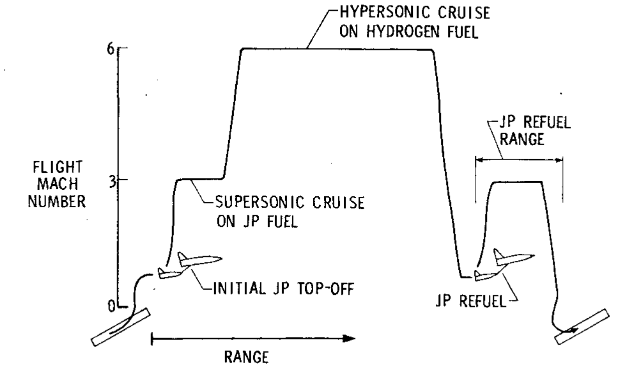

Fig. 10 Mission profile for a hypersonic dual-fuel vehicle with aerial JP refuel capability.

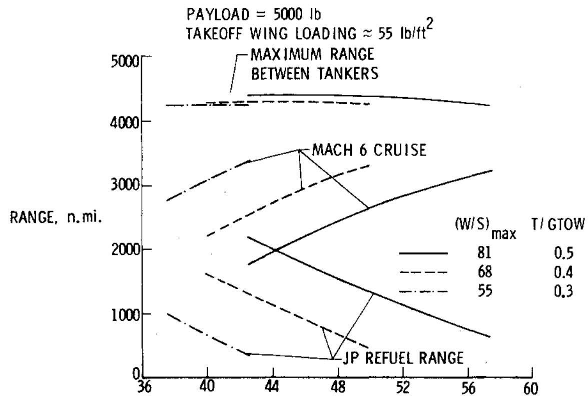

Fig. 11 Hypersonic dual-fuel cruise performance with aerial JP refuel, body length = 169.4 ft.

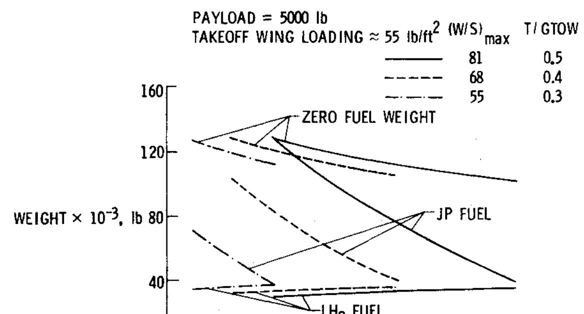

Fig. 12 Fuel weights for a dual-fuel vehicle with aerial refuel capability, body length = 169.4 ft.

Effect of Wing Loading

In defining the JP fuel load for the dual-fuel vehicle, considerable latitude is available through combinations of maximum wing loading and wing loading at the start of

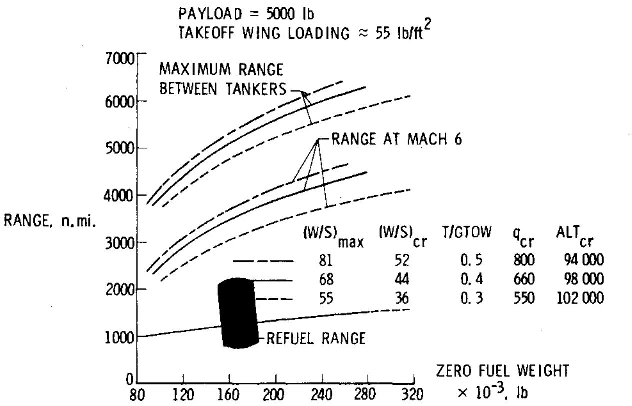

Fig. 13 Range performance with vehicle size for three wing loadings at the same refuel range.

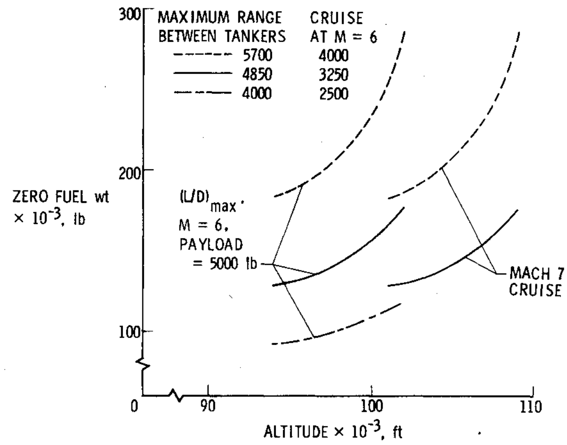

Fig. 14 Effect of increased altitude on vehicle weight.

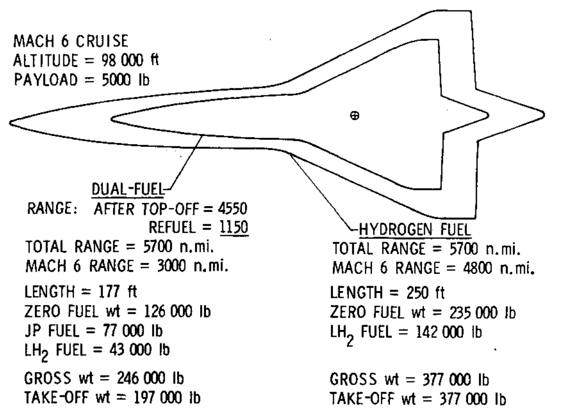

Fig. 15 Vehicle comparison: dual fuel vehicle with aerial refuel vs hydrogen fuel vehicle.

hypersonic cruise. Range performance for various combinations of wing loading is given in Fig. 11 in terms of maximum range between tankers using both JP and hydrogen fuel, Mach 6 cruise range on the hydrogen fuel, and refuel range between tankers on the JP fuel. A constant aerodynamic takeoff wing loading of 55 lb/ft^2 was assumed with higher maximum wing loadings achieved by taking off with partially empty JP fuel tanks and topping off the tanks in flight. Thus, the allowable maneuver load at maximum wing loading is altered from 3 *g* at takeoff to 2.4 and 2 *g* at the increased wing loadings. Another impact of topping off fuel tanks in flight is to increase takeoff thrust loading, since turbojet size is primarily based on transonic acceleration requirements.

As illustrated in Fig. 11, Mach 6 cruise range and JP refuel range are sensitive to both the initial wing loading after JP fuel top-off and the hypersonic cruise wing loading. Large refuel ranges can be achieved with a high initial wing loading and a low-cruise wing loading, but at the expense of hypersonic cruise range. Vehicle and fuel weights corresponding to these range performances are given in Fig. 12, illustrating the increased JP fuel load required to achieve the refuel ranges of Fig. 11. As noted in Fig. 8, zero fuel weight is reduced at higher cruise wing loadings while maximum range (Fig. 11) is nearly constant, suggesting the lowest weight vehicle for a given range would have a high cruise wing loading. Thus, the best combination of JP refuel range and hypersonic cruise range depends on particular mission requirements.

Performance calculations given in Figs. 11 and 12 are for a constant size vehicle fuselage. Calculations were also made for a combination of hypersonic cruise wing loading that would give a constant refuel range for the three maximum wing loadings considered. Figure 13 gives the results of these calculations, and also tabulates the resulting hypersonic cruise wing loading and corresponding flight dynamic pressure and altitude for maximum range. A performance advantage is obtained by operating at high wing loading in terms of both total range between tankers and Mach 6 cruise range. For some applications, high-altitude cruise may be needed. The effect of cruise altitude on zero fuel weight for constant range is given in Fig. 14. Substantial penalties are incurred by designing the vehicle for a low wing loading in order to operate at higher altitudes. These penalties may be partially offset by designing the vehicle to cruise at a higher speed, as shown by the Mach 7 curves which assume that penalties incurred by Mach 7 speeds are offset by the increase in cruise velocity.

Comparison of Dual-Fuel and Hydrogen-Fuel Vehicle

Based on results given in Figs. 9 and 13, vehicle size increases rapidly with range. Thus, a dual-fuel vehicle, using JP refueling, has a large advantage over a nonrefueled hydrogen-fuel vehicle. For example, in Fig. 15, vehicles designed for a mission that requires a total range of 5700 n. mi. and a hypersonic cruise range of 3000 n. mi. are compared. The dual-fuel vehicle is assumed to fly the trajectory illustrated in Fig. 10, utilizing an initial top-off of the JP fuel tanks over the airport and a single refuel on the return leg of the mission. Comparing the resulting vehicles, there is nearly a two-to-one difference in both the vehicle zero fuel weight and takeoff weight, suggesting a large advantage in cost and operating flexibility for the dual fuel vehicle using in-flight JP refueling. Also, the quantity of JP fuel required for refueling is well within the capabilities of current tankers. Advantages of the hydrogen-fuel vehicle are increased hypersonic range giving reduced mission time and a less complex flight trajectory without a refuel rendezvous.

Conclusions

A study has been conducted to explore the advantages of storing JP fuel in the wings and body of a basically hydrogen-fuel hypersonic cruise vehicle. In addition, the advantages of operating the hypersonic propulsion system at low speeds (Mach 0.8-3.0) was considered. Overall results indicate that:

1) Both total range and hypersonic cruise range are improved if transonic thrust can be obtained from the hypersonic propulsion system. This further results in a reduced size of the turbojet engines and a simplification of the integration of the propulsion system with the airframe.

2) For a fixed empty weight, range is increased by storing JP fuel in the wings of a hydrogen-fuel cruise vehicle.

3) Dual-fuel vehicles offer design flexibility by providing sufficient JP fuel for up to 2000 n. mi. of additional range through in-flight JP refueling, effectively combining the long-range advantages of hydrogen fuel and the versatility of JP fuel.

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