Potential of Hydrogen Fuel for Future Air Transportation Systems

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W. J. SMALL
Aero-Space Technologist, Configurations and Performance Section, HVD

D. E. FETTERMAN
Head, Advanced Aircraft Section, HVD

T. F. BONNER, JR.
Head, Aeronautical Engineering Section, SED
NASA Langley Research Center, Hampton, Va.

Recent studies have shown that hydrogen fuel can yield spectacular improvements in aircraft performance in addition to its more widely discussed environmental advantages. Its high heat of combustion permits major increases in engine performance and aircraft range. Its large heat sink capacity makes possible the development of long life engines and airframes for hypersonic aircraft through the use of active cooling. Environmentally, hydrogen is unusually clean, and unlike the fossil fuels, the supply is virtually inexhaustible (although energy must be provided for hydrogen production). This paper discusses the characteristics of subsonic, supersonic, and hypersonic transport aircraft using hydrogen fuel and compares their performance and environmental impact to that of similar aircraft using conventional fuel. The possibilities of developing hydrogen-fueled supersonic and hypersonic vehicles with sonic boom levels acceptable for overland flight are also explored.

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INTRODUCTION

One of the more serious problems facing us is the oncoming energy crisis. Projections of petroleum production and U. S. demands \(^1\) are shown in Fig. 1. The demand for oil in the United States has already outstripped domestic production and forced the importation of oil. Because of the depletion of domestic reserves, U. S. oil production is now declining. By 1985, the United States is expected to import over one-half of its petroleum needs \(^2\). The availability of Alaskan North Slope oil will not provide a long-term solution, but will merely delay this decline in U. S. production until the mid 1980's \(^2\).

Transportation now accounts for about one-half the U. S. oil consumption. Today, U. S. aviation uses a minor share of total oil consumption. However, air travel is projected to expand tenfold by 2000 \(^3\) and would then consume almost one-half of U. S. oil production. Thus, aviation will become a substantial user of this dwindling natural resource.

One possible solution to the projected fuel shortage is development of alternate fuels. For aviation, a very attractive possibility is hydrogen. In the sections that follow, results of our studies of subsonic, supersonic, and hypersonic hydrogen fueled aircraft are described. Each is foreseen to have a place in future markets, and for each, hydrogen provides substantial performance benefits.

HYDROGEN ECONOMICS

Predictions of future fuel costs are very speculative; however, they are an important consideration in aircraft economic comparisons. Projections of future relative costs (per Btu) of JP and hydrogen are shown in Fig. 2, taken from the data of reference \(^4\). According to the author, these projections include an assumed 2.5 percent per year inflation rate. Recent experience shows that the cost of JP has risen much faster than this assumed 2.5 percent rate; for example, in 1971 and 1972, the average rate of increase was over 12 percent \(^5\). Realistic projections of the price of JP fuel derived from crude oil indicate that it may increase fourfold by the year 2000 due to the increased costs of

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\(^1\) Numbers in parentheses designate References at end of paper.

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Fig. 1 Petroleum resources and consumption

Fig. 2 Estimated fuel costs
ENERGY:
1 lb H₂ = 2.77 lb Kerosene

HEAT SINK:
1 lb H₂ = 38.05 lb Kerosene
(H₂(-360°F - 1600°F), Kerosene(100°F - 400°F))

DENSITY:
1 ft³ H₂ = 0.091 ft³ Kerosene

SAFETY: COMPARABLE TO GASOLINE

Fig. 3 Properties of liquid hydrogen

domestic and imported oil. A similar trend will likely develop for natural gas, which would rapidly increase the cost of hydrogen manufactured by steam reforming of natural gas. By the year 2000, then, the costs of liquid hydrogen and JP manufactured from coal would be nearly equal and competitive with JP and hydrogen derived from traditional sources.

The cost of liquid hydrogen will be a strong function of the technology used to produce it and the quantities in which it is used. Liquid hydrogen costs based on the postulated economics of electrolysis of water using electrical energy levels than petroleum fuel, but is not explosive under unconfined conditions (9). Liquid hydrogen has several safety advantages. It vaporizes and rises when spilled, whereas gasoline or JP fuel evaporates slowly and its vapors tend to remain in the area of the spills. Also, hydrogen flames radiate little heat when compared to gasoline flames. The impressive safety record of the space program in the handling of liquid hydrogen is proof that, with proper procedures, hydrogen can be used with safety.

PERFORMANCE WITH HYDROGEN

Engine performance, structural weight fraction, aerodynamic performance, and cruise velocity are four essential items involved in aircraft cruise performance. For a given cruise velocity, liquid hydrogen has the effect of greatly favoring engine performance and somewhat degrading the structural weight fraction and aerodynamics. Large gains in specific impulse (pounds of thrust/pounds of fuel/sec) are achievable with hydrogen fuel, resulting from the increased energy content of hydrogen as compared to JP fuel. Fig. 4 shows the approximate performance levels that can be achieved by hydrogen and JP engines at their design flight velocity. Of these various engine types, turbine power plants are the usual means of propulsion for subsonic (M < 1) and supersonic speeds (1 < M < 4), while ramjets and supersonic combus-
tion ramjets (scramjets) are most efficient in the hypersonic speed regime ($M > 4$).

Because of the low density of liquid hydrogen, the volume of a hydrogen aircraft will generally be larger than that of a JP fueled vehicle. This increased size and the added weight of the cryogenic fuel tanks and insulation will result in structural weight fractions substantially above those of JP fueled aircraft (about 50 percent greater for $M = 3$ aircraft). The larger volume also contributes a drag penalty. However, the performance of hydrogen engines more than compensates for these disadvantages and results in the large range increase relative to JP fueled aircraft shown in Fig. 5.

At subsonic speeds, the use of liquid hydrogen nearly doubles aircraft range. A $750,000$-lb hydrogen-fueled subsonic aircraft of approximately the weight of today's jumbo jets could fly nonstop nearly halfway around the world with $300$ passengers. A more practical aircraft would probably be designed for a shorter range with a larger payload.

The results shown in Fig. 5 for the Mach 3 to 8 speed range (8) were obtained by optimizing wing loading, fuselage fineness ratio, wing thickness, engine size, and engine types. Supersonic hydrogen aircraft achieve maximum range at about Mach 6 as opposed to JP aircraft which optimize at slightly under Mach 3 (10). The Mach 3 transport shown is a "current technology" titanium aircraft (with modifications incident to hydrogen fuel) using hydrogen-burning versions of an SST turbojet engine. The Mach 6 aircraft of this study uses a shielded superalloy structure and turbojet/ramjet engines. Refinements in aerodynamic, structural, and propulsion concepts in all of these speed ranges will, of course, alter the details of these preliminary results; however, the basic trends can be expected to remain valid for both fuels.
Fig. 9 Mach 6 hypersonic transport

Fig. 10 Sonic boom overpressures, cruise conditions

SUBSONIC AIRCRAFT

The characteristics of subsonic "current technology" JP and hydrogen-fueled cargo aircraft are compared in Fig. 6 (11). For the specified mission, there is a reduction in takeoff weight of 39 percent and an empty weight savings of over 19 percent for the hydrogen aircraft. One obvious difference between these two configurations is in the fuel tankage arrangement, where, in contrast to the conventional practice of placing fuel in the wing, the liquid hydrogen is stored in large cryogenic fuselage tanks. Although these particular concepts were cargo aircraft, similar results could be expected for passenger configurations. The impact of advanced technology (composite materials, active flight controls, and supercritical aerodynamics) on these subsonic aircraft has also been assessed as illustrated in Fig. 7. Utilization of these concepts could reduce the gross weight of the hydrogen aircraft to approximately that of today's jumbo jets but with greatly increased payload capability.

SUPersonic AIRCRAFT

A comparison of "current technology" hydrogen and JP fueled SST's are shown in Fig. 8. The use of hydrogen fuel allows a one-third reduction in takeoff weight for an equivalent range. However, for an equivalent mission, the hydrogen aircraft's size is somewhat larger and its empty weight nearly equal to its JP counterpart, a result of the low density of liquid hydrogen. Alternately, a hydrogen SST could be built for the same gross weight (750,000 lb) as the JP fueled vehicle, but with almost one and one-half times the range. Such an aircraft would have an obvious application to many long-range transpacific routes.

Of course, these supersonic transports would also benefit from the application of advanced technology concepts (8, 10).

HYPERSONIC AIRCRAFT

Hypersonic aircraft represent the most dramatic departure from existing aircraft technology that we have so far discussed (7, 8, 12-
Among the new technology requirements for these vehicles are structures compatible with a high temperature environment, dual propulsion systems, and aerodynamic control over a wide speed range. As will be discussed later, hydrogen is the only fuel that has been seriously considered for cruise in this speed regime because of engine cooling requirements. Fig. 9 shows a typical hypersonic transport design from reference (12), which uses large nested "pillow tanks" and a blended wing body airplane design. Passengers sit above the tanks in a separate compartment, protected from the cold cryogenic tankage below and from the high temperature outside environment by insulated cabin walls. Cruise altitudes would be over 100,000 ft, well above any severe weather systems. At cruise speeds of approximately 4000 miles an hour, travel times of only a few hours would separate most portions of the globe. A 750,000-lb gross weight aircraft of this type could fly nonstop over 6000 miles with a payload of 300 passengers. The application of advanced technology concepts and postulated improved engine and aerodynamic performance could possibly reduce aircraft gross weight to approximately 500,000 lb (8).

SONIC BOOM

Commercial overland supersonic flight has recently been prohibited in the United States because of sonic booms. Existing supersonic aircraft designs were not compromised for low sonic boom requirements and produce the so-called N-wave far field signatures illustrated in Fig. 10. The intensity of such signatures depends primarily on cruise altitude and secondarily on aircraft weight. As Mach number increases, cruise altitude also increases and the far field boom levels drop significantly (Fig. 10). Thus, hypersonic aircraft tend to have the lowest sonic boom levels. However, if sonic boom requirements are brought into the design trades from the outset, the aircraft may be shaped to produce the more complex "near-field" signature (also illustrated in Fig. 10), and sonic boom levels on the ground may be substantially reduced for Mach 3 aircraft as well (17).

Research into such possibilities is currently underway. The compromises required to achieve decreased boom levels may result in performance losses. Hydrogen SST’s, however, may be able to trade some of their superior performance for lower boom levels and still provide performance comparable to JP-SST designs not configured for low boom. Should boom levels be attained that are low enough to be acceptable for overland flight, vast transcontinental markets would open up for supersonic and hypersonic aircraft. As shown in Fig. 11, a hypersonic transport coast-to-coast flight requires less than 2 hr instead of over 4 hr by conventional jet. This includes time for overwater acceleration and deceleration, since it may not be possible to tailor the aircraft for low sonic boom at all speeds.

NOISE

Hydrogen subsonic aircraft should easily meet noise standards by using high bypass turbofan engines with acoustically treated nacelles of the same type successfully developed for JP-fueled aircraft. For the Mach 3 configuration, studies have shown that dramatic engine noise reductions are possible with a hydrogen aircraft. These studies indicate that a hydrogen SST will optimize with about half the wing loading and substantially larger engines than conventional JP SST's, permitting takeoff with reduced power settings (13). The resulting reduction in sideline noise at brake release is shown in Fig. 12. The 100-dB level corresponds to a takeoff meeting current airline practice. That is, the engine power is not increased in the event of engine failure. The lowest noise level of 85 dB corresponds to a condition where the major portion of the runway is used for takeoff in a very low (20 percent) throttle mode. Should an engine failure occur, the remaining engines could be increased in power to make up for the engine loss. This latter option is available to the hydrogen aircraft because of the large engine thrust available. Achievable takeoff noise levels probably lie between these two extremes.

For hypersonic transports, the takeoff turbojets are typically sized transsonically and are completely divorced from the cruise scramjet. This will allow a greater degree of freedom in designing for both takeoff requirements and cruise efficiency with possible reduced takeoff noise.

AIR POLLUTION

The clean burning characteristics of hydrogen should contribute significantly to the alleviation of atmospheric pollution by aircraft. Hydrogen engines do not emit carbon dioxide, carbon monoxide, unburned hydrocarbons or particulate matter, the only products of combustion being water vapor and nitrous oxides (NOx). NOx emissions are reduced since hydrogen is in-
introduced into the burners of turbine engines as a gas, thus obtaining a uniform, lean-fuel-air distribution. The resulting reduction in temperature and residence time of air in the combustion zone could substantially reduce nitrous oxide emissions. Overall, hydrogen's impact on air pollution around airports and for flight within the troposphere should be less than any other known fuel. However, the effects of NOx and water vapor in the stratosphere, where supersonic and hypersonic aircraft must cruise, is not yet firmly established and are the subject of current extensive government research programs (18).

TYPICAL FUTURE HYDROGEN-FUELED AIRCRAFT

How will the various aircraft we have been discussing fit into the world airline picture toward the end of this century? Obviously, economics and speed will play an important part in the selection of these aircraft.

Speed has historically been the essential ingredient in the appeal of air transportation. Higher speeds not only increase the attractiveness of air travel, but also increase aircraft productivity. The effect of aircraft speed on trip time is shown in Fig. 13. A hypersonic transport (HST) will cut travel time by more than 50 percent compared to a Mach 3 SST at ranges greater than 5500 miles. A nonstop 6500-n.m. trip from Los Angeles to Sydney takes about 2.4 hr by HST versus 5 hr by SST, 14 hr by subsonic jet. At distances less than 3000 n.m., there is no great difference in time between a hypersonic or a supersonic transport, and the aircraft employed will be based on economic and environmental considerations, such as sonic boom limitations on overland flights.

Indications are then that we could see a mix of subsonic, supersonic (Mach 1 to 4), and hypersonic (Mach 5+) aircraft, with the subsonic aircraft flying "short haul" passenger routes and possibly long-range freight routes. Supersonic and hypersonic aircraft will probably dominate the intercontinental freight routes. Should supersonic and hypersonic aircraft with boom levels acceptable for overland flight prove feasible, then the resulting use of transcontinental routes would sharply increase the economic viability of these aircraft. The present substantial flow of traffic in short-, medium-, and long-range routes (Fig. 14) (19) will by the year 2000 be approximately increased tenfold (3). Somewhat higher growth rates are projected for the long transpacific routes than for the shorter transatlantic routes (19).

TECHNOLOGY STATUS

Propulsion

The technology required for hydrogen-fueled turbojet engine development is essentially directly transferable from JP technology. Experiments with hydrogen turbojets in the 1950's clearly showed the compatibility of hydrogen
with standard aircraft engines. In 1957, a B-57 was successfully modified to burn hydrogen in one of its two J-57 engines (Fig. 15). Liquid hydrogen was stored in the left wing tip tank and pressurizing helium in the right tip tank. The liquid hydrogen was vaporized in a ram air heat exchanger prior to being injected into the engine combustor. This test program, conducted by the Lewis Research Center, demonstrated both the practicality and the performance of hydrogen fueled turbojets (20). During this same time period, the Pratt and Whitney Aircraft Corporation developed two engines to burn hydrogen, a modified J-57 turbojet and an Expander Cycle (21) turbojet for supersonic high altitude application. Instead of a standard turbine driven by combustion products, this engine used a turbine driven by hydrogen which had been vaporized in a heat exchanger in the engine exhaust duct. After leaving this turbine, the gaseous hydrogen was injected into the combustor.

As shown in Fig. 4, ramjet or scramjet engines become more efficient than turbojets at Mach numbers greater than about 3.5. At such speeds, rotating machinery is no longer necessary to compress the air, since very high combustor pressures are available from the inlet alone. Also, the high total temperature of a hypersonic airstream precludes its use for engine cooling. The relative simplicity of ramjets or scramjets eases this problem by eliminating rotating machinery and reducing the internal wetted surface areas. The basic engine duct can be cooled by internally circulating the fuel through the internal surfaces of the engine before injection into the combustor. It is in this application that the large heat sink capacity of hydrogen fuel is so important for hypersonic flight.

The hydrogen fuel flow required for engine cooling is compared to the fuel flow required for thrust in Fig. 16. As shown, fuel in excess of that required for thrust would have to be supplied to avoid overheating of the engine structure at Mach number 11. With hydrogen fuel, excess fuel heat sink capacity would be available at Mach numbers up to 10 or 11 that could be used for cooling other aircraft components (see next section).

Several experimental hypersonic engines have been tested, the most advanced of which is the NASA-sponsored Hypersonic Research Engine (ERE) (14, 15) (Fig. 17). Originally planned for flight testing on the X-15 research aircraft at Mach numbers from 3 to 8, the ERE is capable of operating in either a subsonic or a supersonic combustion mode. When the X-15 program was terminated, an expanded ERE ground test program was initiated which is still in progress. The engine shown in Fig. 17 is the structural assembly model of the ERE (22). Hydrogen is circulated as a coolant in passages between the
inner and outer walls prior to being injected in the combustor. The structural design concept of this flight weight, regeneratively cooled engine has been successfully demonstrated at Mach 7 in tests in the Langley 8-Foot, High Temperatures Structures Tunnel. Performance tests at Mach 5, 6, and 7 of the HRE in both the subsonic and supersonic combustion modes are currently being conducted at the Lewis Research Center, Plumbrook Station.

In their basic form, neither ramjet nor the scramjet can produce low speed thrust, requiring that an auxiliary low speed acceleration system be provided. One approach to this requirement involves integrating turbojets with the hypersonic propulsion system as shown in Fig. 18. The turbojet acts as an acceleration device from takeoff through the supersonic speed range, while the scramjet provides supersonic and hypersonic thrust. As shown, airflow is provided to the turbojet engines by an adjustable inlet door during acceleration to about Mach 3. The turbojet would then be shut down, the inlet door closed, and acceleration continued on the scramjet engine alone. The scramjet shown in this figure is the Langley Fixed Geometry Scramjet, which is designed to operate efficiently through a large Mach number range with minimal engine cooling requirements (14, 23, 24).

**Structures**

Subsonic and supersonic (Mach 3) hydrogen fuel transports could use conventional aluminum and titanium (and possibly composite) construction techniques. The major technological requirement for this type of aircraft is the development of practical cryogenic tankage, insulation, and purge systems. Hypersonic aircraft, however, operate in a high temperature environment. Typical surface temperatures are shown in Fig. 19 for a Mach 8 transport under maneuver conditions. The structure of hypersonic aircraft must be able to cope with these severe temperatures and associated heating rates, reliably and without frequent or extensive refurbishment over the long service life typical of transport aircraft. Airline economics dictate that they also be easily maintained and be capable of rapid airport turnaround times. One hypersonic structural concept is the hot structure in which high temperature materials are used in a load bearing structure. Insulation and thin exterior heat shields would be provided where necessary to limit the temperature rise of the primary structure. These "hot structural" concepts demand major state-of-the-art advances over present design and fabrication techniques. As illustrated in Fig. 20, hot structures for hypersonic speeds are considerably heavier than the aluminum structure of subsonic aircraft. The use of the "advanced hot structure" (a
semi-monocoque spanwise-stiffened beaded skin) results in considerably reduced weights relative to conventional skin-stringer hot structure arrangements (25).

The long lifetime required for commercial transports makes the development of the "hot structure" a formidable task. Active cooling systems (14, 26), however, hold the promise of reducing structural weight (Fig. 20) while simultaneously obtaining long life by utilizing for airframe cooling that part of the hydrogen heat sink not required for engine cooling (Fig. 16).

A schematic of an actively cooled hypersonic transport is shown in Fig. 21. Hydrogen is not circulated through the aircraft. Rather, a secondary coolant (water glycol in this case), circulated through tubes integrally formed into the aircraft skin, is used to transport the aerodynamic heat load to a heat exchanger. This heat load is, in turn, transferred to the hydrogen fuel on its way to the engines.

The total weight of a cooled structure, including the cooling system weight (heat exchangers, coolant, pumps, manifolds, etc.) is significantly lower than uncooled structures. Weight savings resulting from active cooling have been estimated to result in a 70 percent increase in payload (14). Advantages of this system include the use of lightweight aircraft materials, such as aluminum, titanium, and perhaps advanced composites, the use of existing fabrication and subsystem technologies, and the minimization of thermal stress and warpage. Although a major development program will be required to develop active cooling to a point of flight readiness, all current indications are that this is the most promising concept for long life structures required for commercial transports.

CONCLUSIONS

Liquid hydrogen has great potential as an aviation fuel, due to its large energy content and cooling capacity, its minimal environmental impact and potentially unlimited supply. Its use as a fuel greatly improves the performance of subsonic and supersonic aircraft. Hydrogen fuel makes possible hypersonic transports which can carry travelers to any portion of the globe within a few hours.

The cost of conventional aircraft transportation is projected to rise due to raising petroleum fuel prices and the indirect, but none the less real cost of reducing noise and air pollution levels. Hydrogen fuel is expected to become cheaper as its use increases. At some time within this century, hydrogen fuel is expected to become relatively cheaper for air transportation than JP fuel, and contribute much less to noise and air pollution than any other known fuel. Given the long lead times necessary for new aircraft development, the use of hydrogen should merit immediate increased attention by both government and industry to provide a sound technological base from which the aircraft industry can draw.

REFERENCES


