Hydrogen: Make-Sense Fuel for an American Supersonic Transport

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Liquid hydrogen, as a prospective aviation fuel, can harness the United State's relatively abundant domestic coal resources and, subsequently, nuclear and solar energy to supply air transportation's mounting energy needs. This poses an important strategy leading away from dependency upon petroleum. Hydrogen is applicable to both subsonic and supersonic aircraft with major performance benefits deriving from its gravimetric heating value which is 2.8 times that of conventional jet-fuel. Hydrogen's notorious bulkiness and the innate problems posed by a cryogenic fluid are inherent characteristics which—as demonstrated by our Space Program—can be practicably handled in all their aspects. An American second-generation supersonic transport would especially benefit from hydrogen fueling in performance, environmental effect, and in direct operating cost (considering escalation trends for petroleum-based fuels). Striking gross takeoff weight reductions and over-all energy savings of from 20 to 40 % appear certain. Engine pollutants are virtually eliminated. Stratospheric effects of nominally increased water vapor in the exhaust may not be significant; this has not been fully assessed. Marked takeoff noise reductions and sonic boom amelioration are predictable. Coupled with other airplane improvements now being evaluated in the Nation's supersonic technology program, hydrogen may be the needed step-function advancement permitting America to field an unquestionably "better airplane" in the ongoing international supersonic competition initiated by Concorde and the TU-144.

I. Introduction (Opening Scenario)

"THE check-in procedure at the Air France ticket counter at Dulles International Airport was routine. . . . The lounge departed on schedule and proceeded toward the white angular-looking aircraft on the airline ramp bearing Air France and British Airways markings. As the lounge got closer, airline mechanics could be seen performing preflight inspection on the afterburning turbojet engines while other personnel changed a tire. All familiar sights at Dulles, save for the fact the aircraft was Concorde 02." [1]

The Concorde is scheduled to commence fare-paying passenger service next year. One can expect the Soviet Union's TU-144 to enter service with Aeroflot at about the same time, if not significantly earlier; the Russians have a notable penchant for beating announced schedules. As Loftin stated in his year-ago paper, "Toward a Second-Generation Supersonic Transport":[2] "Clearly, the United States has lost the first round of international supersonic transport competition."

America is in an interesting position relative to these first-generation supersonic transports. The U.S. aviation industry will watch closely their degree of acceptance by the traveling public. Most of the aviation press who recently flew Concorde seemed most impressed. Since we have no SST program at all, we have nothing to lose, save our national pride over being displaced as world leaders in transport aviation if the Concorde and TU-144 aircraft are resounding successes. On the other hand, we stand to profit from lessons learned about shortcomings in either of these aircraft if the option is opened by the Congress to commence development of a second generation SST. Had not the marginal performance and well-voiced environmental factors (real and imagined) caused cancellation of the American candidate SST in 1971, one can speculate that the "energy crisis" which has in the meanwhile thrust itself upon us visibly would have signaled the demise of the project anyway. After all, SST's are voracious consumers of now-precious jet-fuel.

Going back a full 10 years for another quotation in support of the thesis of the paper, the day following the Presidential announcement of the American SST program in June 1963, the following appeared in the *Wall Street Journal*:[3] "It isn't necessarily disastrous if our allies have an SST lead; no law compels us to be first in everything. In fact, a calm approach could pay bigger dividends later, assuming that the studies indicate the United States can eventually develop a faster and generally better plane. That is essentially the history of the subsonic jets, in which the United States lagged at first but came out on top later . . . ." Though relatively ancient new-copy, there could be an important message here for those of us who view the supersonic transport scene today. The pivotal issue relevant to this paper is contained in the phrase: ". . . a faster and generally *better* plane" (italics added). Similarly, Loftin has pointed out a number of approaches, including hydrogen fuel, toward ". . . a truly advanced second-generation supersonic transport."

This paper makes no attempt to press for a decision to enter, or not enter, the "international supersonic transport competition." It attempts only to lay before any such decision-making process what the authors believe to be a well-founded potential for creating an optimal airplane for the times. This potential is predicated on a shift to non-petroleum based liquid hydrogen fuel as a basis for a step-function advance in aviation. For hydrogen, along with other identified technological advancements over the past decade,[2] could well provide for the quested-for "generally better plane," . . . "the truly advanced second-generation supersonic transport."

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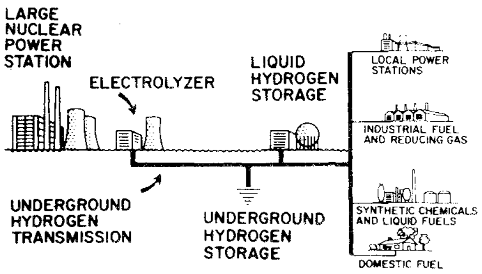

Fig. 1 The "hydrogen economy."

II. Hydrogen: A Means of Operating Aircraft on Coal and Nuclear or Solar Energy

As a basic strategy for getting aircraft "off petroleum," a case for shifting to liquid hydrogen fuel is being made by an increasing number of workers in the aviation and energy fields, particularly over the past year.[4-7] Reference 8 points out that hydrogen derived from our relatively abundant coal resources within the contiguous states (and water) could readily supply aviation's energy needs in the decades just ahead. Eventually, hydrogen can be produced from water using nonfossil nuclear, solar, or geothermal energy sources. Indeed the U.S. natural gas industry is examining "hydrogen-energy" as a long-range possibility.[9] Figure 1 schematizes the concept.

It is further pointed out that, because of hydrogen's unmatched gravimetric heating value, 2.8 times that of conventional hydrocarbon fuels, a significantly superior airplane will result if it is optimized for hydrogen fuel. This will require, of course, the development and demonstration of practical engineering methods for handling 1) hydrogen's inherent bulkiness (3 to 4 times jet fuel on an equivalent capability basis) and 2) its cryogenic nature (21 K, or −423°F). The successes of the Nation's Space Program, specifically Centaur and the Saturn vehicles' upper stages, are evidence that these particular challenges are amenable to in-hand research and development know-how.

Aircraft Impact on Petroleum Demand

Phasing commercial transport aircraft over to a nonpetroleum based fuel would make a significant contribution to easing the Nation's critical petroleum shortage. This is reflected in Fig. 2, which is based on data from the National Petroleum Council's "U.S. Energy Outlook—An Initial Appraisal, 1975–1985." The figure shows the past record (up to 1970) and immediate-future projections of U.S. petroleum demand and supply. Demand from each of the principal using sectors of the U.S. economy for the time span 1950–1985 is indicated by the bracketed areas as labeled on the right. Supply is depicted as either domestic or imported, where the hatched area represents the amount of petroleum required to be imported to meet the projected demand. The dashed line separating the "Domestic" (nonhatched, lower section) and the "Imported" (hatched upper section) areas of the diagram is an estimated trend-line reflecting domestic petroleum production from 1970 to 1985. It is shown as a nominal intermediate among the four NPC Projection Cases labeled I, II, III, and IV. These four projections are those of the National Petroleum Council as presented in late 1972 in the Council's "Report on United States Energy Outlook." In Ref. 10 a guide to this comprehensive assessment, Case I represents, ". . . the most optimistic supply condition." In contrast, Case IV is a ". . . if present trends continue . . ." projection. Cases II and III are intermediates between these extremes.

It is quite apparent that petroleum importation in increasing amounts will be mandatory at least through 1985, if all present oil-using sectors continue their traditional dependence on this energy source. The shortfall of domestic production of oil relative to anticipated demand, as seen in Fig. 2, gives rise to the now familiar statement, "over half our oil to be imported by 1985." As a result of the Mideast Oil Embargo and Administration policy goals associated with the objectives of "Project Independence," this trend may perhaps be modified. Although it is unlikely sufficient production of any alternate fuel can be realized in time to significantly change the projected supply picture shown in Fig. 2, i.e., through 1985, conservation measures could hold the line on demand to the point that the ratio of imports to total need would be favorably affected. Subsequent to 1985, and dependent on the priorities established, alternate fuels and energy sources can be expected to change the U.S. petroleum demand and supply picture.

If petroleum is not available in sufficient amounts (from all sources), or is priced out of reach of ultimate consumers, there must necessarily be a curtailment of available services. Transportation will be (and is being) particularly affected since it is essentially totally dependent on petroleum, aviation being a case-in-point. We are seeing presently the impact of fuel curtailment on the commercial and general aviation industries.

Projected aircraft demand is shown in Fig. 2 based on precurtailment estimates. Aviation is the most rapidly growing user of energy within the transportation sector by far, although at present the largest user is automotive.[11] Viewing Fig. 2, it is quite apparent that the phasing of aircraft usage of energy over to a non-petroleum base carries with it the definite potential of being an effective measure for easing the U.S. energy situation.

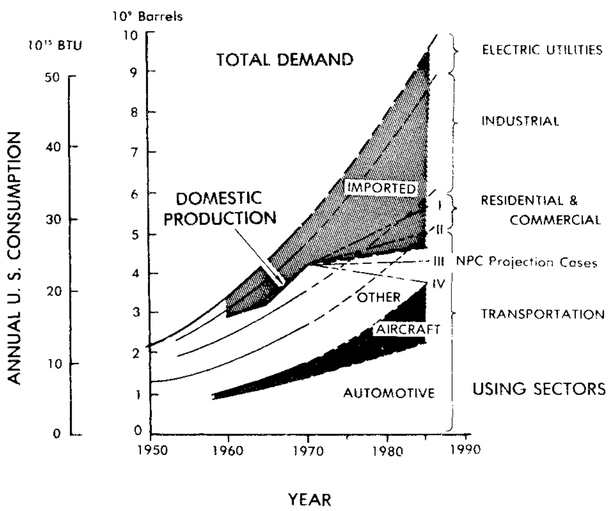

Fig. 2 U.S. petroleum demand and supply.

The Hydrogen Alternative

An alternative strategy has been succinctly stated by J. E. Johnson of Linde[5] and reiterated by one of the present authors.[8] Seeking to shift applicable sectors of transportation, and specifically aircraft, to nonpetroleum based fuel producible from domestic sources, it is proposed that liquid hydrogen derived from coal is a uniquely advantageous avenue for mechanizing this strategy. Quoting from the Johnson reference: "Liquid hydrogen is a superior alternative to continued overdependence on increasingly expensive imported hydrocarbon liquid fractions. The prospects for developing this alternative fuel strategy for air transportation offers a significant opportunity to economically contribute toward easing our energy crisis through utilization of our lowest cost domestic energy resources in an environmentally acceptable manner."

It is significant to note here that coal-to-hydrogen industrial processes are commonplace over the world. A large end-use product is ammonia fertilizer which is produced from a wide range of coals, coal dust, and lignites, along with necessary feedstock water.[8] From his assessment of the economics, Johnson[5] indicates a nominal cost of \$2.50/million Btu or 13¢/lb for liquid hydrogen "at the airport" based on production from coal, broken down in Table 1. The ramifications of this estimated fuel cost for a representative supersonic transport, the specific subject of this paper, will be subsequently shown (Fig. 7).

Summarizing general energy-aspects of hydrogen as a prospective aircraft fuel, it can be stated that a definite potential for shifting future aviation energy demand from petroleum to coal, and eventually nuclear or solar sources (via water-splitting process) exists. Such a transition would be an effective measure in easing the U.S. energy situation since aircraft are the most rapidly expanding users of energy in the transportation sector, the major consumer of petroleum products. Shifting aircraft to liquid hydrogen fuel will have favorable environmental payoffs as well as making for technically superior airplane design opportunities.

Hydrogen: The Cleanest Possible Fuel

Hydrogen-fueled aircraft offer extremely worthwhile environmental gains. Intrinsically, emissions of carbon monoxide (and carbon dioxide) hydrocarbons, soot, smoke, and offensive odors are virtually eliminated. The resulting benefits range from lower aircraft and airport cleanup costs to the probable avoidance of proposed operational constraints on idling time, taxiing procedures, etc. As discussed in the U.S. Environmental Protection Agency's "An Air Pollution Impact Methodology for Airports—Phase I": "A large fraction (approximately 90%) of aircraft carbon monoxide and hydrocarbon emissions occurs during the taxi and idle modes. . . . Operational controls, therefore, promise to be a relatively effective means of reducing airport-related emissions."[12]

Oxides of Carbon and Unburned Hydrocarbons

Among the controls being considered are partial engine-off taxiing, for which the remaining operating engines are kept at higher power-levels where CO/HC emissions are lower. Even the towing of aircraft to takeoff position has been suggested. Such proposals have a serious implication to airline operating efficiency and even to ultimate flight safety. All of this would seem to be completely avoided were hydrogen to be the fuel in use.

Some concern has also been expressed with carbon dioxide, although it is not considered a pollutant, relative to the case of high flying supersonic aircraft. Although largely disclaimed by authorities, this has to do with the theory that long-term effects of CO_2 exhaust discharge in the stratosphere may affect earth's climate through the mechanism of the "greenhouse effect." Again, any potential problem is completely bypassed in the case of hydrogen-fueled aircraft.

Potential for Low NO_x Emissions

In a recent NASA technical memorandum by Lewis Research Center personnel[13] the issue of nitrogen oxide emissions from hydrogen gas turbine engines is examined vis-a-vis hydrocarbon systems. The authors point out that, advantageously, hydrogen provides for a much wider fuel/air ratio operating range than conventional jet-fuel. Because of this, hydrogen fuel brings with it the potential for theoretical reductions in nitric oxide formation of about 2 orders of magnitude for the same primary zone dwell time. Dwell time is a measure of the time the combustion products remain at full temperature prior to air dilution and/or expansion in the turbine, usually the order of millisecond or so.

Table 1 Dollar-per-million-Btu cost

Hydrogen generating cost (from coal & water)	\$0.90
Hydrogen transportation cost (gas pipelining)	0.15
Hydrogen liquefaction cost (at the airport)	1.20
Hydrogen storage and distribution cost (liquid)	0.25
Total cost	\$2.50

Further, hydrogen provides for much higher "space heating rates" which suggests the opportunity to considerably shorten engine combustor lengths and associated dwell times, a second significant route to lower oxides of nitrogen production. Hence, new low-NO_x combustor designs can be anticipated with appropriate development efforts. R. F. Sawyer, University of California, a recognized authority on oxide of nitrogen formation in combustors, agrees with this point: "The potential for minimizing oxides of nitrogen production with hydrogen, however, is great."[14]

Effect of Water Vapor and Nitrogen Oxides on the Stratosphere

Again, as in the case of carbon dioxide effects, the question of stratospheric ramifications of water vapor and oxides of nitrogen uniquely impinges on proposed supersonic high-flying aircraft (subsonic aircraft are limited to the upper troposphere with its much more active circulation and "turnover times"). In a recent review of this aspect of environmental impact of supersonic transports in the aviation press,[15] a National Academy of Science report on technical and scientific advances in weather and climate modifications was cited: "The academy said the area of particular concern is 'the possible reduction of the naturally occuring ozone in the lower stratosphere as a result of injection of water and nitric oxide.' The resulting effect, the academy said, is that atmospheric ozone in the lower atmosphere is turned to oxygen, thus reducing the shielding capability of the ozone layer and increasing the amount of ultraviolet radiation reaching the earth's surface. This phenomenon has fostered fears in some quarters of increased skin cancer occurrence."

The Academy report assessed the situation of 800 supersonic aircraft in operation on climatic effects due to water vapor and/or contrails. A mix of aircraft types was included: 500 of the Boeing 2707 design, and 300 of the Anglo-French Concorde/Soviet Tu-144 type. Outside of the ozone interaction phenomenon cited above, the report concluded that the water exhaust "would cause no serious climatic effects."

Comparatively, the hydrogen airplane will exceed the water vapor output of the equivalent hydrocarbon-fueled aircraft by a factor of approximately two, depending on exact tanked energy requirements for optimized hydrogen aircraft designs (which do not exist today). But as already discussed, its nitrogen oxide may well be a very small fraction of its hydrocarbon counterpart. The above statements are based on consideration of aircraft designed for and performing identical missions, i.e., equal payload, range, and cruise speed.

Summarizing environmental aspects of the hydrogen-fueled aircraft, and specifically the supersonic transport category, the benefits are fairly obvious. Hydrogen is the cleanest possible chemical fuel. Only oxides of nitrogen and water vapor remain; all carbon-derivitives are eliminated. However, the relative impact on the stratosphere

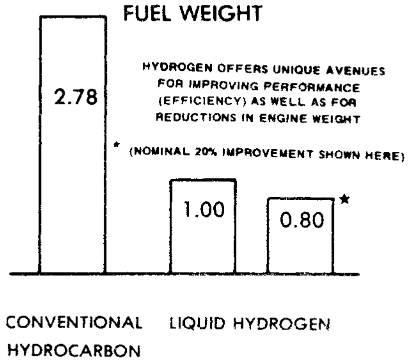

Fig. 3a Relative mass requirements.

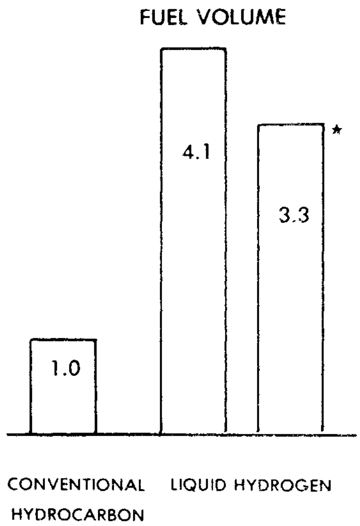

Fig. 3b Relative volume requirements.

by a hydrogen airplane is not yet known. The potential for greatly reduced oxides of nitrogen is clearly in the right direction. The effect of nominal increases in water vapor exhausted at high altitude by the hydrogen aircraft must await the findings of CIAP (for Climatic Impact Assessment Program) and related assessments.[16]

Environmental Impact of Aircraft Fuels Production

An environmental impact assessment of aircraft fueling options would be incomplete without including the effects of the environment of production and delivery of the fuels to the airplane. Currently, jet fuel is a special distillate product of oil refineries which produce the range of fuels from gasolines to residual oils. In the main, such refineries have demonstrated reasonably moderate pollution effects. Perhaps oil spills on the oceans from tankers and from offshore drilling constitute the most visible threat to the environment associated with jet fuel production.

In time, however, petroleum stocks—particularly as limited by domestic production—will force the development of alternative fossil fuel resources such as oil shale, tar sands, and coal for jet fuel production. This will open entirely new issues regarding environmental impact. For example, the impact of strip mining western U.S. coal for the production of Syncrude is largely unknown, particularly with regard to land reclaimation ultimate costs. As noted in Refs. 5 and 8, hydrogen can be produced from coal at what appears to be competitive costs as an alternative to Syncrude. But environmental questions remain.

At a significant increase in costs, hydrogen can be produced from nuclear-electrolysis facilities, again with environmental consequences which have yet to be quantified. Perhaps the most benign process for producing hydrogen proposed so far is the harnessing of solar energy in ocean based production facilities as discussed by such researchers as Heronemus and Zener, and others.[8] Clearly, such concepts are distant in time, but perhaps no more so than the need for hydrogen fuel to be created by its widespread use in aviation. The nuclear and solar production options are discussed in Sec. V.

Hydrogen: Technically, a Superior Aircraft Fuel

The basic Breguet range equation denotes the fact that aircraft specific fuel consumption (*SFC*) or, alternatively specific impulse (I_s), is a primary controlling factor on over-all aircraft performance. *SFC* is directly established by fuel gravimetric heating value, *J*/kg (Btu/lb), for the same engine efficiency. Hydrogen's heating value of 51,600 Btu/lb (vs jet-fuel's 18,400) is the salient technical advantage it offers, one which completely overshadows the disadvantages of its bulkiness and cryogenic nature. The former results in some increased drag due to the larger tankage required (reduction in L/D), while the latter adds structural weight due to the need for tank insulation, special construction, etc. Numerous studies have demonstrated this (e.g., Refs. 2, 6, 7).

Relative Mass and Volume Characteristics

Figure 3 compares conventional hydrocarbon fuel with liquid hydrogen graphically in terms of relative mass (Fig. 3a) and volume (Fig. 3b) for equivalent aircraft missions. Mission performance as considered for this elementary comparison is associated with a given flight regime (speed, altitude) and aircraft type (aeronautical and structural characteristics). "Equivalent Missions" signifies that the aircraft provides the same payload and range capability for a given class of aircraft. Two bars are presented for the hydrogen fuel case, the left-hand one being the case of "equal stored energy." In view of the demonstrated fact that the savings in fuel energy in converting to hydrogen on an equivalent mission basis is typically better than the equal-energy situation, the second (right-hand) bar reflects the case of nominal (and conservative) 20% further reduction in hydrogen fuel requirement.

Hydrogen's Improved Efficiency Factor

From the rather limited studies conducted to date on hydrogen aircraft of all kinds, estimates of this efficiency improvement factor range upward from 20 to as much as 40% over the equal-energy case. This is highly significant, since the case for the hydrogen fueled aircraft may ultimately rest to a rather major extent on the issue of efficient energy utilization. If the higher of the two estimates is shown to be valid, then the use of hydrogen will permit almost a halving of tanked fuel energy required for a given mission (payload, range).‡ The source of this gain in the aircraft energy conversion efficiency via hydrogen is attributed to two areas: 1) Compounded effects of hydrogen's providing for lower gross weight of the aircraft and 2) Improvement of propulsion cycle efficiency due to hydrogen's unique fuel properties.

It should be emphasized here that much more work is required over the entire range of aircraft types and mission requirements in order to quantify the improved efficiency factor resulting from the transition to hydrogen. In

‡The actual over-all energy savings will be less than this due to: 1) energy requirements for liquefaction of hydrogen (about 25% of the higher heating valve of the fuel) and 2) any boil-off losses experienced in the entire logistical supply system. These penalties are not experienced with conventional hydrocarbon fuels.

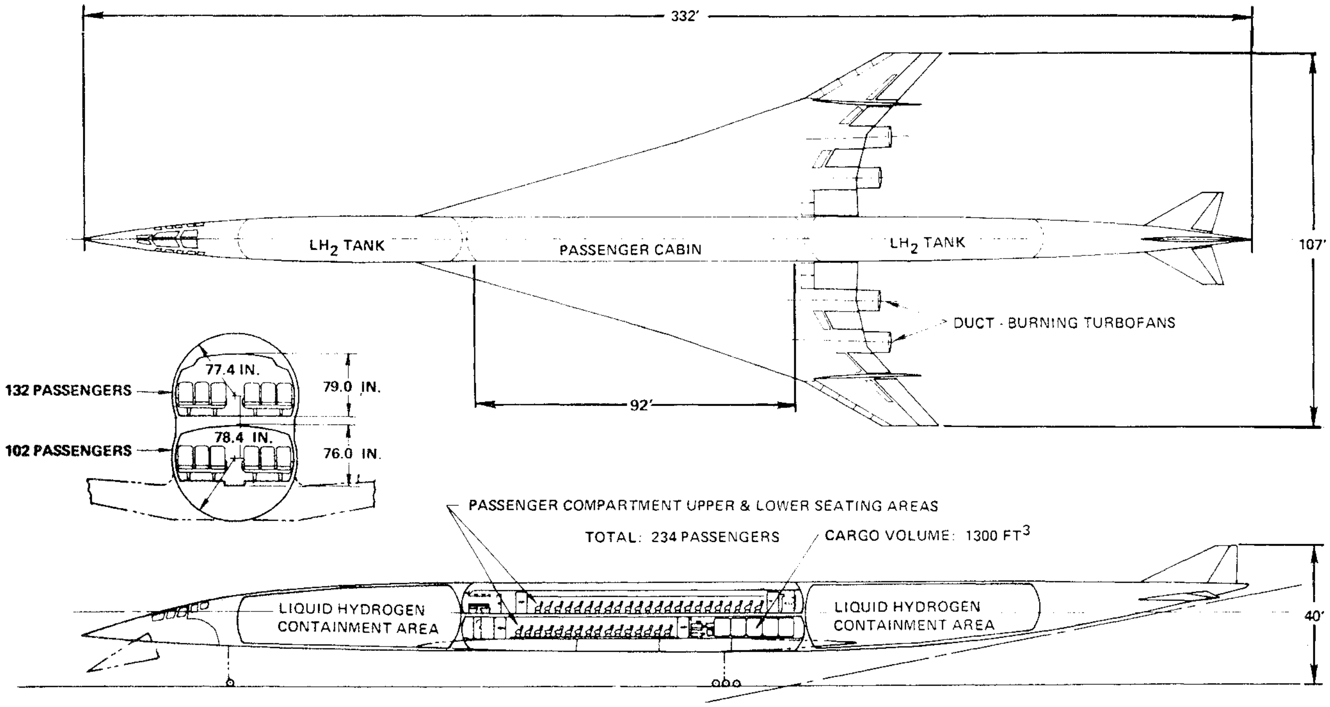

Fig. 4 Hydrogen-fueled supersonic transport design (NAS2-7732).

addition, analyses are needed to compare the energy balance of various candidate aircraft fuels, including consideration of the expenditure of energy involved in production and delivery of basic raw materials required to manufacture the fuels.

III. Envisioning the Hydrogen-Fueled Supersonic Transport

Serious consideration of a hydrogen-fueled supersonic transport seems to be a fairly recent activity. This is somewhat surprising since liquid hydrogen has been under evaluation for hypersonic aircraft and reusable launch vehicles for well over a decade. Apparently the up-to-Mach 3 regime has been assumed to be "hydrocarbon country" exclusively. The feasibility of hydrocarbons to power Mach 3+ airplanes was demonstrated some time ago by the F-12/SR-71 family of Lockheed airplanes and the North American B-70. And of course Concorde and the TU-144, which are Mach 2.0–2.2 aircraft, are predicated on conventional fuels.

Short of a few scattered and unpublished references, the report "The Case for a Hydrogen-Fueled Supersonic Transport" dated October 1972 by one of the authors (Brewer) is one of the earliest proposals noted.[17] The Loftin paper[2] made note of the hydrogen potential, but suggested that this was significantly "further out" than the technology improvements embraced in "the advanced SST." The author stated: "Hydrogen fuel offers great promise for future supersonic aircraft, however, the formidable problems associated with the use of such fuel probably precludes its use on any near term second-generation supersonic transport."

Undoubtedly, this statement remains valid depending on what one defines as a "near term" airplane. Since the publication of Refs. 2 and 17, the energy problem's impact on aviation has become distressingly clear. Stimulated by the energy and environmental attractiveness of hydrogen fuel for aviation, a special "working symposium" on liquid hydrogen fueled aircraft was held at the NASA Langley Research Center on May 15–16, 1973.[18] At this time representatives of the aviation and energy industries and representatives of the Government discussed technical and economic aspects of both subsonic and supersonic aircraft based on hydrogen fuel. Energy and environmental focus was the keynote of the symposium. Since that time, it appears that serious-minded attention to the potential of hydrogen fuel for aircraft has now gotten underway. A number of study contracts have been let or are pending on this subject from NASA for instance.

Figure 4 is a conceptual design of a hydrogen-fueled SST resulting from an ongoing Lockheed-California Company Contract supported by the NASA Ames Research Center: "Advanced Supersonic Technology Concept Study—Hydrogen Fueled Configuration." The contract number is NAS2-7732 and the Ames Center contract monitor is C. Castellano. The Lockheed study manager is G. D. Brewer, a co-author of the present paper. The study is concerned with assessment of hydrogen-fueled supersonic transport designs for comparison with a baseline hydrocarbon jet-fuel airplane also designed by Lockheed but under NASA Langley cognizance.

The cryogenic hydrogen experience of Lockheed's Advanced Development Projects (ADP, perhaps better known as the "Skunk Works") is being utilized. As reported at the previously mentioned Langley working symposium on hydrogen aircraft, the ADP carried out the design and systems testing on a liquid hydrogen fueled supersonic airplane, the CL-400, as early as 1956—some 17 years ago. Details are reported in Refs. 18 and 19. The hydrogen-fueled supersonic transport configuration shown in Fig. 4 illustrates the basis for a "point-design" study in the final phase of the work for NASA-Ames. This effort will provide conceptual designs for the hydrogen tanks, the thermal protection system, and the basic structural framework for the vehicle. The vehicle is a Mach 2.7 design, able to carry 234 passengers over a range of 4200 naut. miles. Table 2 lists some of the characteristics of the aircraft, based on an assumption of 1981 technology. The weights are good approximations but must be considered preliminary because the final report has not been released as this is written. Reference 20 will provide final information when it is issued at the conclusion of the study.

Table 2 Aircraft characteristics[a]

Aerodynamic configuration: Arrow wing	
Mach no. (cruise): 2.7	
Payload: 234 passengers and baggage	
Range: 4200 naut. mile	
Engines: turbofan, duct-burning	
Fuel: liquid hydrogen	
Wing-loading (takeoff): 50 lb/ft^2	
Thrust/weight (sea level, static): 0.5	
Gross takeoff weight	379,000 lb
Fuel weight (total)	98,000
Aircraft zero-fuel weight	280,000
Operator's empty weight	232,000
Payload weight	49,000

[a] Preliminary data, basis: 1981 technology.

Aircraft Design Approach

The design (Fig. 4) departs from most previously shown configurations by electing all-fuselage storage of the liquid hydrogen fuel. Some fuselage volume for the bulky cryogenic fuel has typically been called out (e.g., Refs. 2 and 6) but wing tanks were included in earlier supersonic aircraft concepts. The double-deck arrangement shown in the figure was adopted for the passenger cabin, in conjunction with full cross-section fuel tanks fore and aft, in order to provide: 1) fuel tanks with high structural and volumetric efficiency; 2) minimum c.g. travel as fuel is consumed; and 3) maximum separation of passengers from fuel. Basic material of construction for the airplane, with the exception of the tankage and structure which might be directly exposed to hydrogen, is titanium alloy reinforced by advanced composites. The latter is bonded to the titanium following forming operations.

After careful consideration of several applicable approaches for the cryogenic hydrogen tankage design, an integral load-carrying tank concept was selected. The details of tank construction and thermal protection systems vary with the technology state-of-the-art assumed. For example, the 1981-technology thermal protection system used in the point-design vehicle for the Ames study consists of a closed-cell polyvinylchloride (PVC) foam cryogenic insulation applied to the exterior of the aluminum tanks. This foam insulation is in turn wrapped with a polyimid/glass fiber insulation system which is capable of withstanding exposure to the high temperature and dynamic pressure experienced by the skin of the Mach 2.7 aircraft. By contrast, the thermal protection system of a later, more advanced technology, might involve use of a cryogenic insulation which is, or can be rendered, impervious to gaseous hydrogen and could therefore be applied to the inside of the tank structure. This would permit use of an advanced composite material for the tank structure and minimize the requirement for high temperature insulation. In addition, heat leaks through attachments to the tank structure would be minimized so significant weight savings could be realized in both inert materials and in the quantity of fuel which would be lost through boil-off.

A final comment relates to the unusually high thrust-to-weight ratio (0.5) and low wing loading (50 lb/ft^2). This combination may provide for significant noise relief at the airport as well as reduction in sonic boom overpressures en route. The noise reduction potential stems from the capability to takeoff with engines throttled. Sonic boom relief results from the combination of the lower gross weight and higher cruise altitude made possible by the lower wing loading and the high trust/weight. It has been speculated that hydrogen may provide new degrees of freedom for configuring the airplane to provide further reduction in overpressure levels, but work in this area remains to be carried out.

Table 3 Data for a jet A-1 fueled SST

Gross takeoff weight	750,000
Fuel weight	391,200
Aircraft zero-fuel weight	358,800
Operator's empty weight	309,700

Comparison with Hydrocarbon Fueled SST

To provide a basis for evaluating the potential benefits of using LH_2 as the fuel in a supersonic transport, data are presented in Table 3 relative to a hydrocarbon (Jet A-1) fueled aircraft of equivalent capability, i.e., same payload, range, and cruise speed.

The Jet A-1 fueled aircraft design is based on the same technology as that of the LH_2 airplane of Table 2, viz., that assumed to represent 1981 state-of-the-art for start of airframe construction. As in the case of the LH_2 design data, the weights listed for the JP fueled airplane must be considered preliminary since the study is incomplete. The work is being done by Lockheed for NASA-Langley Research Center under Contract NAS1-12288. Figure 5 illustrates the basic weight trends characteristic of hydrogen vis-a-vis hydrocarbon fueled airplane designs, using the above SST data for the example.

Three basic components of aircraft gross takeoff weight (GTOW) are reflected in the bar chart: basic aircraft inert weight, fuel weight (hydrocarbon or hydrogen), and payload weight. Payload is held constant in the comparison at 49,000 lb (equivalent to 234 passengers plus baggage or cargo). The striking nearly 50% reduction in GTOW is clearly a measure of the greatly reduced fuel loading (98,000 vs 391,200 lb). This illustrates rather graphically the heating value superiority of hydrogen (see Fig. 3a), compounded by the "efficiency factor" improvement just discussed. The difference in basic aircraft weight is the result of a strong tradeoff between the increased weight of the liquid hydrogen tankage (bulkiness and insulation aspects of hydrogen) and the decreased aircraft component weight associated with the major GTOW reduction. The items affected by this reduction encompass wing area, wing structure, undercarriage components, etc.

IV. Development Timing

Figure 6 is a nominal development schedule for an advanced second-generation supersonic transport, but one based on conventional hydrocarbon fuel—not hydrogen. Nevertheless, the progression of events and the lead-times indicated provide insight in considering the hydrogen fueled version. If anything, hydrogen selection would tend to intensify and probably stretch out the pre-go-ahead technology program. Obviously the engine activity would be basically affected, as would airplane tankage and fuel system efforts.

Assuming a 4 or 5 year intensive preliminary technological development effort for a hydrogen supersonic transport will be sufficient for the go-ahead decision and the major national commitment involved, it appears that it will require about 10 years before the first airline delivery of an airplane can take place. Assuming we start now—in 1974—it is 1988 when farepaying passenger service will be instituted by this schedule (Fig. 6). This is 13 years later than Concorde and the Russian counterpart (are planned to) enter service. Referring back to Fig. 2, the U.S. petroleum demand and supply projection, we are off the chart to the right!

Clearly, hydrogen for aircraft is a strategic and not a tactical or near-term payoff enterprise, at least for an SST. On the other hand, this impressive stretchout in time may work to the advantage of the hydrogen alternative. For one thing, petroleum products will be in increas-

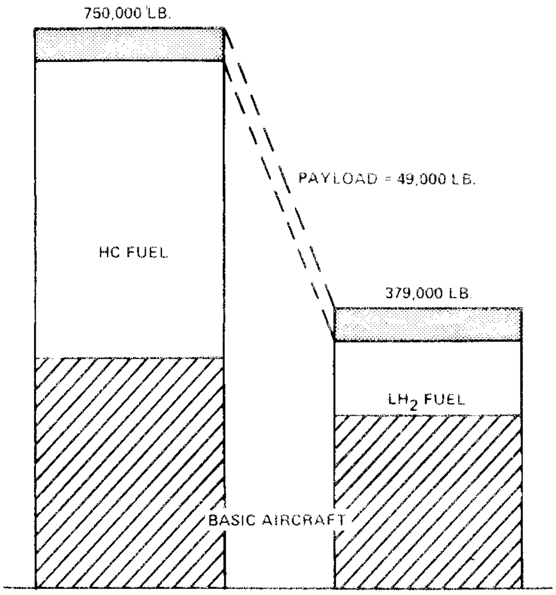

Fig. 5 Hydrocarbon/hydrogen comparison. Mach 2.7 supersonic transport designs.

ingly short supply, and a substitute for conventional jet fuel may be essential in the 1990s. (In addition to hydrogen from coal, emphasized in this paper, other alternatives are kerosene-like fuel from coal or oilshale, and liquid methane from coal.) If hydrogen remains the "front-running" candidate to be this substitute for petroleum-base fuel, there will be sufficient lead-time to develop necessary production, logistical and airport servicing facilities and equipment. Comments regarding these requirements are offered in following paragraphs. A commensurate "spreading-time" for the very major investments which will be necessary following such a go-ahead is also provided for by the timing indicated in Fig. 6.

V. Operating Economics

Although economics and development timing were a consideration in the Ames/Lockheed study effort (NAS2-7732), the effort concentrated on engineering design aspects of the hydrogen supersonic transport. Outside of this program (see Ref. 20 when published), relatively little appears to have been done on determining the operating economics for such an airplane. For one thing, liquid hydrogen price expectations for large-scale airport servicing have not been available. The recent Linde paper is a start in this direction, but more extensive studies are badly needed. These should have an entire "coal field to airport liquid storage" purview.

Based on a NASA Lewis Research Center report[21] which compared hydrogen and methane with conventional

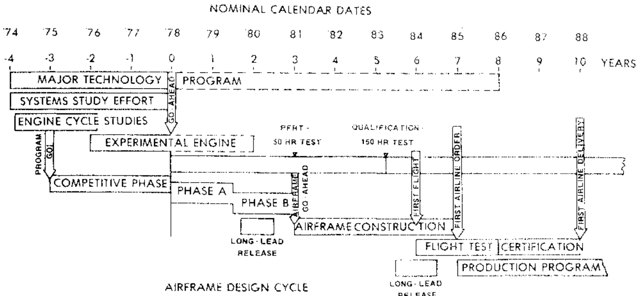

Fig. 6 Nominal development schedule for an advanced supersonic transport.

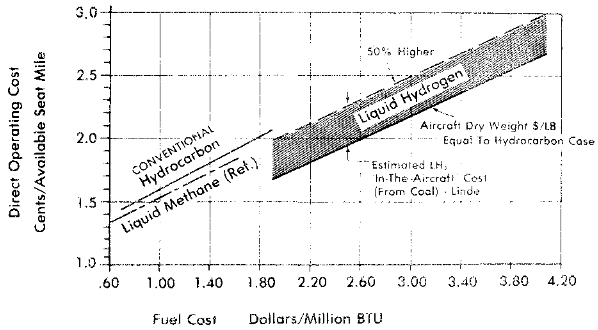

Fig. 7 Effect of fuel cost on direct operating cost.

jet fuel for the supersonic transport mission, Fig. 7 was developed. The aircraft model studied in this reference was a Mach 2.7 250-passenger airplane with a 4000 naut. miles range. Advanced high-turbine inlet temperature engines of the duct-burning turbofan type were used (2725°F). All in all, this was a comparable aircraft to that depicted in Fig. 4 and Table 2. Shown here, for 3 separate aircraft types based on the fuels assessed, is an estimate of aircraft direct operating cost (DOC) as it varies with fuel cost. DOC is a term of merit calculated on a specified Air Transport Association of America (ATA) formula. It includes: fuel and oil, insurance, flight crew salaries, direct maintenance, and depreciation expenses. The anticipated higher cost of liquid hydrogen ($/million Btu) over conventional fuel is clearly evidenced in Fig. 7. Since the time of the Lewis study, jet-fuel cost escalation has increased remarkably and this picture is rapidly changing. Recall, we are addressing a period of use no sooner than the period of the 1990's (Fig. 6) when hydrocarbon fuel costs will be much higher than the $1.10/million Btu of the ca. 1970 time-period. Presently, in a period of steep price-escalation for fuels, it is difficult to pin down the anticipated cost of even near-term conventional jet-fuels. A recent figure of $1.70/million Btu was quoted in the aviation press (Ref. 22, p. 42). Clearly, hydrocarbon fuel derived from domestic nonpetroleum sources (coal, oilshale) will be much more costly than this. If this is so, and if the $2.50/million Btu estimate presented by Johnson[5] is used (as noted on the figure), the hydrogen airplane is already in a parity situation with the jet-fuel airplane on a DOC basis today. This statement is based on the lower "equal dry weight cost" edge of hydrogen aircraft band in Fig. 7; the Ames/Lockheed study tends to support this over claims that the hydrogen airplane hardware costs (specific) would be "much higher" than a hydrocarbon counterpart.

As a consequence of recent events on the energy front, and specifically in petroleum, the variable to be watched is, perhaps, less the anticipated cost of liquid hydrogen, but the escalating cost of petroleum-based jet fuel! In any event, it is no longer the case that liquid hydrogen's cost will summarily take it out of the competition. Indeed, projecting to the 1990s and beyond (as we should when addressing an American SST) hydrogen may be the "economy fuel" of the future. What has yet to be evaluated, however, is the overall impact of the relatively massive capital investment required for the implied hydrogen production, logistical and airport storage and distribution system. Technoeconomic analysis of this is called for at an early data in order to provide a basis for judgment.

The required growth of the liquid hydrogen industry to support a fleet of hydrogen-fueled supersonic transports would be tremendous. The fact that the single largest liquid hydrogen plant placed into operation in support of the U.S. Space Program at about 60 T/Day would support about one flight per day by a single airplane of the type described in this paper (Fig. 4 and Table 1) places this fact in striking perspective. On the other hand NASA sponsored a study of worldwide fueling of liquid hydrogen hypersonic transports requiring a production rate of 8000 T/Day which indicated overall feasibility.[23] Such a production level would support some 160 daily maximum range flights of the hydrogen supersonic transport aircraft. Fossil fuels entirely constituted the energy source (feedstocks) for the case study cited.[23]

Johnson[5] examines a production rate of 2500 T/Day of liquid hydrogen using nuclear-electrolysis. This equates to an electrical output requirement of 6200 MW, or about six 1000 MWe nuclear units of the size-class currently being installed into our electrical utility system. This would service about 50 aircraft flights daily on the same basis as described above. No adequately thorough assessment of solar production of liquid hydrogen has been published. However, in a preliminary "concept paper"[24] by one of the authors (Escher) the proposition of an ocean-based solar-to-hydrogen (cryogenic) facility was looked at briefly. For this particular concept, a production level of 2500 T/Day as used by Johnson would equate to a total thermal collector area requirement of a 14 × 14 Km array and a capital investment approaching $6 billion.

A pertinent observation here is based on the fact that the supersonic transport is, in relation to prospective subsonic airplanes, uniquely an intercontinental, hence international transportation unit. This means that adequate liquid hydrogen production facilities and fueling points must be established (and paid for presumably) by each and every nation taking advantage of this transportation function. This suggests an opportunity to sell, license, and otherwise involve U.S. participating industries in the setting up of hydrogen production, transport, liquefaction and ground service facilities on an international basis.

VI. Conclusions (Closing Scenario)

Hydrogen is the make-sense fuel for an American supersonic transport, were this project to be undertaken, because the selection of hydrogen fuel would: 1) Avoid automatically any commensurate increase in demand on U.S. and World petroleum supplies (LH_2 would use coal, nuclear/solar sources); 2) Minimize absolutely adverse environmental impact vis-a-vis first-generation SST's (no CO, HC, CO_2, less NO_x; noise amelioration); 3) Provide for a technically superior aircraft in terms of performance and operational capability (equivalent range/payload at lower DOC); 4) Reconfirm the United State's World-leadership position in the aviation field (with concommitant economic benefits); 5) Establish a technically substantial and economically sound beginning-basis for evolving more generally out of our present, self-limited fossil fuel era into tomorrow's "Hydrogen Economy."[25]

"An unusually large crowd awaited its first arrival at Beirut International Airport. Among the passengers were a number of local-region people returning from the United States, many of whom were directly or indirectly in the oil business. Several Concordes and a TU-144 were at the ramps, long a commonplace sight. In contrast the new supersonic visitor bearing the U.S. flag was much longer and bore a double row of windows over its relatively small wings. Faces could be seen at those windows. Even while passengers disembarked to their receptions of greetings and acknowledgments of a smooth, short flight, ground servicing personnel approached the aircraft for the onset of refueling. The flight was scheduled to continue within the hour on its next nonstop leg to Tokyo. From the various fill- and vapor-return hoses and connections came the occasional telltail white vapors denoting the "new fuel." The well-advertised fact that this new fuel was not dependent on traditional petroleum feedstocks—coupled with the impressive physical presence of the airplane itself before them—seemed to invoke an aura of deeper significance among the spectators and disembarked passsengers. Already liquid hydrogen flowed full-force into the superchilled tanks of the American supersonic transport. . . "

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