Chapter VI

# ENERGY: FUEL PRICE AND AVAILABILITY

Of all the uncertainties confronting the future of commercial aviation, the most serious are the future availability and price of fuel. Recent temporary shortages of petroleum have driven up prices and prompted industrial nations to take conservation measures. Total world production of oil is leveling off and is expected to begin declining over the next decade.

If limitations are imposed upon aviation fuel supplies in the future or prices rise too high, the projected growth in air traffic over the next 30 years may not materialize. This, in turn, would restrict any major expansion in the market for new advanced aircraft and significantly affect the prospects for developing an advanced supersonic transport (AST), which would have higher fuel consumption rates than a subsonic jet.

## PRESENT FUEL CONSUMPTION

The world now uses about 305 quadrillion Btu (Quads) of energy from all sources each year. The United States consumes about 25 percent of this (or 78 Quads). About half of U.S. energy consumption derives from petroleum. In 1977, the U.S. used 17.5 million barrels per day (MMbbl/d) of petroleum equivalent. Transportation needs accounted for slightly over half this amount, or **9.2** MMbbl/d. Commercial aviation used 0.5 MMbbl/d, 5.4 percent of the transportation figure and 2.9 percent of all petroleum used in the United States. By comparison, private passenger automobiles used about **5.2** MMbbl/d of petroleum in 1977, or 10 times as much as U.S. commercial aviation.[1,2]

The worldwide commercial aviation fleet of about **4,700** jet aircraft (excluding the U.S.S.R. and the People's Republic of China) consumes 1.5 MMbbl/d or **3** percent of the world's daily petroleum use. In the period from 2000 to 2010, utilizing the projections indicated in chapter IV, about 8,100 commercial jet aircraft would be in service. Such a fleet, depending on the fuel efficiency achieved by aircraft at the time, would consume between **3.5** and **4.4** MMbbl/d, or 3.8 to 4.8 percent of daily world petroleum consumption.[3,4] However, according to current predictions, unless the percentage of petroleum fuels available to aviation is increased (perhaps as other energy-consuming sectors convert to alternative sources), world production capabilities will not satisfy these needs. Thus, although these numbers were used to perform an analysis of the impact of supersonic aircraft on energy use, it is unclear where this petroleum will be coming from and whether it actually will be available.

The long-haul portion of the present world market —transcontinental and transoceanic flights with stage lengths of **2,700** to **3,000** nautical miles or more—now consumes approximately **0.2** MMbbl/d or 15 percent of all commercial aviation fuel. Given the projected growth in air travel, long-haul aircraft would use between 0.5 and 0.7 MMbbl/d by 2000-10, again 15 percent of projected total fuel usage by commercial aviation. The portion of the com-

[1]D. B. Shenka, ed., *Transportation Energy Conservation Data Book,* Edition 3, Oak Ridge National Laboratory for the U.S. Department of Energy, ORNL-5493, February 1979.

[2]*Changes in the Future Use and Characteristics of the Automobile Transportation System* (Washington, D. C.: U.S. Congress, Office of Technology Assessment, February 1979), vol. I, OTA-T-83, p. 6.

[3]OTA Working Paper, Boeing Commercial *Airplane Co.,* March 1979.

[4]OTA Working Paper, Pratt and Whitney Engine Co., Jan. 17, **1979.**

mercial jet fleet now serving long-haul routes is about 33 percent, a percentage expected to diminish to about 25 percent by the period 2000-10. Table 7 compares present and projected commercial air service and fuel consumption.

**Table 7.—Present and Projected Commercial Air Service and Fuel Consumption**

| Commercial fleet[a] | 1976 | 2000-2010 |
|---|---|---|
| Short and medium range | 3,200 (67%) | 6,000 (74%) |
| Long range | 1,500 (33%) | 2,100 (26%) |
| Total | 4,700 | 8,100 |
| Route air miles (billion)[b] | 5.05 | 10.7 |
| Available seat-miles (billion)[b] | 798.5 | 3,170 |
| Revenue passenger miles (billion)[b] | 463.1 | 2,150 |
| Load factor | 58% | 67% |
| Weekly departures | | |
| Short and medium range | 130,400 (840/o) | 220,600 (870/o) |
| Long range | 24,800 (16%) | 32,700 (13%) |
| Total | 155,200 | 253,300 |
| Fuel consumption (MMbbl/d) | | |
| Short and medium range | 1.3 (85%) | 3.0- 3.7 (85%) |
| Long range | 0.2 (15!40) | 0.5- 0.7 (15YO) |
| Total | 1.5 | 3.5 4.4 |

MMbbl/d = millions of barrels per day.
a Base case, subsonic aircraft only.
b Scheduled air carriers plus charter.

SOURCE: OTA Working Paper, Boeing Commercial Airplane Co., Working Group A, "Advanced High-Speed Aircraft, " January 1979.

## FUEL PRICE EFFECTS

The rise in fuel price since 1974 has intensified the importance of fuel economy in commercial aviation. The price of jet fuel has dramatically increased since 1974 to over $1.00 per gallon in early 1980. The continuing rise in jet fuel prices is cited as a major cause for the 6- to 8-percent increase in airfares observed by the end of 1979. Opinion varies about what will happen to the price of petroleum in both the short and long run, making analysis of possible impacts extremely difficult.

Rising fuel prices have particular effects on prospects for supersonic transport. Although it can be shown that, through technological improvements, total operating costs (TOC) for a supersonic aircraft may continue to converge over time with those for a subsonic aircraft (see figure 2, ch. I), such a convergence would be threatened by rising fuel prices. The supersonic aircraft is more sensitive to fuel price increases because it uses more fuel than a subsonic aircraft of the same size.

Thus, a key factor in assessing the feasibility of supersonic aircraft is fuel efficiency. * Fuel

*For purposes of this analysis fuel efficiency is generally expressed in Btu per seat-mile, although in actual airline service a more appropriate measure is Btu per passenger-mile, a function of attained load factor and design efficiency. However, to eliminate having to guess future airline passenger patronage and thus simplify the later analysis, all comparisons are made in terms of Btu per seat-mile, which is a measure of the fuel efficiency designed into an aircraft.

adds weight, so that the more fuel an aircraft of given size and range requires, the smaller the payload. Reduced payload results in reduced productivity, as does inefficient fuel use (say, on account of wasteful operational procedures). The amount and cost of fuel consumed per seat-mile bear directly on operating costs and, hence, on an aircraft's profitability in airline service.

Most commercial aircraft introduced during the past **40** years have been successful, in part, because they offered greater fuel efficiency per seat-mile than older aircraft they replaced. For example, the latest generation of passenger jets (B-747, DC-10, L-1011) are about 30 percent more fuel efficient than the first generation of passenger jets (B-707, DC-8).[5 6] One of the major operational disadvantages of the Concorde is its high fuel consumption in comparison with that of competing subsonic aircraft. Assuming a full load for each aircraft, the Concorde obtains **15.8** passenger-miles per gallon of fuel, compared to 33.3 for the B-707, 44.4 for the DC-8-61, 46.3 for the B-747, and **53.6** for the DC-10.[7]

5A. B. Rose, "Energy Intensity and Related Parameters of Selected Transportation Modes: Passenger Movements, " Oak Ridge National Laboratory for the U.S. Department of Energy, ORNL-5506, January 1979.

6J. M. Swihart, *The Boeing New Airplane Family*, paper presented to AIAA 15th annual meeting, Washington, D. C., Feb, 6, 1979, pp. 3-6.

7*Secretary Decision 0 ) 1 Concorde Supersonic Transport* (Washington, D. C.: U. S. Department of Transportation, Feb. 4, 1979), p. 29.

## COMPARATIVE FUEL EFFICIENCY

Estimates of the technological improvements possible for supersonic aircraft vary widely. Projections for fuel usage per seat-mile range from a low of 1.2 to a high of 2.0 times that of present subsonic aircraft. However, supersonics of the future would likely be competing not with present subsonics but the advanced and more fuel-efficient versions of the subsonics, using **20** to **30** percent less fuel per seat-mile than current subsonics.

These estimates are reflected in table **8,** which shows fuel-efficiency values that might be attainable by each of the ASTs considered in this assessment. For the AST-III, the table indicates high, medium, and low fuel-efficiency values based on the possible technological improvements. In the interest of simplifying the analysis of energy impacts, the later comparison of fuel usage in each scenario will be based on single-point estimates. These assumed values must be regarded with caution since they may vary by as much as **25** to **50** percent. Where this variance has a particularly important influence on the outcome of the analysis, the reader will be reminded again of the magnitude of the uncertainty.

Given the projected fuel efficiencies arrayed in table **8,** it is possible to assess the impact of the several scenarios described in chapter IV with regard to fuel use. Four assumptions are made in this analysis. First, for all comparisons, it is assumed that 75 percent of the world fleet will operate on short- and medium-haul routes and, thus, that the AST will be in competition with, and replace some portion of, the **25** percent of the fleet operating at stage lengths of 2,700 nautical miles or longer. Second, it is assumed that short- and medium-haul aircraft will consume **85** percent (3.7 MMbbl/d) of the fuel estimated in the base case for an all subsonic fleet. Third, it is assumed that the AST will capture a 40-percent share of the long-haul travel market, i.e., **400** ASTs will replace 850 long-haul subsonic aircraft as discussed in chapter **IV.**

The fourth assumption is that the AST will be competing against and replacing a 300-passenger advanced subsonic transport (ASUBT), that is, an aircraft with a seating capacity equivalent to the AST-III. In reality, the ASTs will be replacing less efficient, older subsonic aircraft of various sizes rather than the more efficient

**Table 8.—Estimated Fuel Efficiency of Advanced Subsonic and Supersonic Aircraft**

| Parameters | Present subsonics[a] | ASUBT | Concorde | AST-I | AST-II | AST-III |
|---|---|---|---|---|---|---|
| Passengers | 200-400 | 400-800 | 100 | 200 | 225 | 300 |
| Maximum range (rim) | 5,000 | 5,500 | 3,200 | 4,200 | 4,800 | 5,500 |
| Speed (Mach) | 0.85 | 0.85 | 2.0 | 2.0 | 2.2 | 2.4 |
| Fuel-efficiency | | | | | | |
| Btu/seat-mile | 2,450 | 1,700[b] | 6,000 | 4,900 | 4,400 | 2,900<br>3,900<br>4,900 |
| Load factor | 58% | 67% | 60% | 67% | 67% | 67% |
| Btu/passenger mile | 4,225 | 2,550 | 10,000 | 7,350 | 6,600 | 5,850<br>4,350<br>7,350 |
| Relative fuel-efficiency (per seat-mile) | | | | | | |
| v. present subsonics[a] | 1 | 0.70[b] | 2.45 | 2.0 | 1.8 | 1.2<br>1.6<br>2.0 |
| v. ASUBT | 1.4 | 1 | 3.5 | 2.9 | 2.6 | 1.7<br>2.3<br>2.9 |
| v. Concorde | 0.4 | 0.28 | 1 | 0.8 | 0.75 | 0.5<br>0.65<br>0.8 |

[a] B-747, DC-10, L-1011.
[b] Upper bound of a 20- to 30-percent improvement in ASUBT fuel efficiency

SOURCES: Present aircraft: A. B. Rose, *Energy Intensity and Related Parameters of Selected Transportation Modes,* U.S. Department of Energy, ORNL-5506, January 1979 Projections: OTA, Working Group A.

ASUBTs. However, this assumption allows a comparison of the AST scenarios with the base case in which, assuming no ASTs were built, **850** ASUBTs would be produced. The last assumption represents a major simplification. Some of today's aircraft can carry 400 passengers, and it is projected by some that subsonic transports with a seating capacity of up to 800 may be developed for use on high-density, long-haul routes by **2010.** Eliminating such very large aircraft from the analysis allows direct comparison of subsonic and supersonic aircraft fuel usage, without the confounding but significant effect of productivity differences arising from size as well as speed differences.

## ANALYSIS OF ENERGY IMPACTS

Scenario 1 envisions the operation in 2010 of 400 U.S.-built AST-IIIs, which would replace 850 of the long-haul subsonic fleet projected for the base case and so reduce this fleet from 2,100 to 1,250 aircraft. Thus, the split in the long-haul market would be **60** percent for the subsonic and 40 percent for the supersonic. The fuel efficiencies of the ASUBT and the AST-III are estimated to be, respectively, 1,700 Btu and 2,900 to 4,900 Btu per seat-mile. The AST-III would therefore use between 1.7 and 2.9 times more fuel per seat-mile than the ASUBT. Table 9 shows fuel consumption increases over the base case if scenario 1 eventuates. (The fuel efficiency of the ASUBT is based on a 30-percent decrease in fuel usage over the present subsonics. If there is only a 20-percent decrease, the AST-III would use 1.5 to 2.5 times more fuel per seat-mile than the ASUBT.)

In scenario 2, the United States would refrain from an AST program, but foreign manufacturers would develop and introduce a version of a supersonic aircraft by 2010. If they were to develop an aircraft roughly equivalent to an AST-111, the effect of this scenario on the energy situ-

**Table 9.—Energy Impacts of AST-III: Scenario 1**

| | | Scenario 1: AST-III fuel efficiency | | |
|---|---|---|---|---|
| Fuel consumption | Base case | High | Medium | Low |
| Short and medium range (MMbbl/d) . . . . . . . | 3.74 | 3.74 | 3.74 | 3.74 |
| Long range (MMbbl/d). . . . . . . . . . . . . . . . . . | 0.66 | 0.84 | 1.00 | 1.15 |
| Increase over base case (MMbbl/d). . . . . . . . . | – | 0.18 | 0.34 | 0.49 |
| Percent of increase. . . . . . . . . . . . . . . . . . . . . | — | + 27% | + 50% | + 75% |
| All commercial aviation (MMbbl/d) . . . . . . . . | 4.40 | 4.58 | 4.74 | 4.89 |
| Percent of increase. . . . . . . . . . . . . . . . . . . . . | — | + 40/0 | + 8% | + 11% |
| Percent of increase in world petroleum use. | — | + 0.2% | + 0.30/0 | + 0.5% |

MM bbl/d = millions of barrels per day
Assumptions:
1 Short- and medium-range aircraft make up 75 percent of the fleet and use 85 percent of the fuel ın the base case
2 Base case fleet = 6,000 short- and medium.range and 2,100 long-range subsonics.
3 Scenario 1 fleet = 6,000 short- and medium-range, 1,250 long-range subsonic, and 400 AST-III.
4 Long. range subsonic fuel efficiency = 1,700 Btu/seat.mile
5 AST-III fuel efficiency (Btu/seat-mile). High = 2,900, Medium = 3,900; Low = 4,900
6 Long. range subsonic and AST-III are 300-passenger aircraft
SOURCE Off Ice of Technology Assessment

ation would be identical to that projected for scenario 1. If the foreign manufacturers were to develop an AST-I, the impact on the energy situation would probably be somewhat less because in reality fewer aircraft may be sold. The effect also would be minimal because the AST-I would be less fuel efficient than the AST-III; however, detailed estimates for this case have not been calculated.

Competition in the supersonic market (scenario 3) would result, according to our assumptions, in a foreign-built AST-I introduced in the late 1980's and a U.S.-built AST-III introduced **5** to 7 years later. It is calculated that by **2010, 1,250** ASUBTs, **250** AST-Is, and **250** AST-IIIs would be in service. The assumed fuel efficiency of the AST-I is 4,900 Btu per seat-mile and that of the AST-III 2,900 to 4,900 Btu per seat-mile (3,900 Btu per seat-mile was estimated for simplicity in this analysis). Assuming an ASUBT fuel efficiency of 1,700 Btu per seat-mile, the ratios of the fuel efficiencies of the supersonics to the fuel-efficiency of the ASUBT would be, for the AST-I, 2.9 and, for the AST-III, 2.3. Table 10 shows the increases in fuel consumption over the base case if scenario 3 were to occur.

Scenario 4 projects a joint program by U.S. and foreign manufacturers resulting in the introduction of either an AST-II in **1990** (scenario 4a) or an AST-III in the mid-1990's (scenario 4b). Scenario 4a estimates that by 2010, 450 AST-IIs are in operation replacing 850 long-haul

**Table 10.—Energy Impacts of AST-I and AST-III: Scenario 3**

| | | Scenario 3: fuel efficiency | | |
|---|---|---|---|---|
| Fuel consumption | Base case | All aircraft | AST-I port ion | AST-III port ion |
| Short and medium range (MMbbl/d) . . . . . . . | 3.74 | 3.74 | — | — |
| Long range (MMbbl/d). ., . . . . . . . . . . . . . . . . | 0.66 | 1.06 | 0.30 | 0.36 |
| Increase over base case (MMbbl/d). . . . . . . . . | – | 0.40 | 0.20 | 0.20 |
| Percent of increase. ... , . . . . . . . . . . . . . . . . . | — | + 61 %. | + 30% | + 30% |
| All commercial aviation (MMbbl/d) . . . . . . . . | 4.40 | 4.80 | — | . |
| Percent of increase. . . . . . . . . . . . . . . . . . . . . | — | + 9% | + 4.50/o | + 4.5% |
| Percent of increase in world petroleum use. | — | + 0.4% | + 0.2% | + 0.2% |

MMbbl/d = millions of barrels per day
Assumptions.
1. Short- and medium-range aircraft make up *75* percent of the fleet and use 85 percent of the fuel in the base case,
*2* Base case fleet = 6,000 short- and medium-range and 2,100 long-range subsonics.
3. Scenario 3 fleet = 6,000 short- and medium-range, 1,250 long-range subsonic, 250 AST-I, and 250 AST-III.
4. Long-range subsonic fuel efficiency = 1,700 Btu/seat.mile
5 AST-I fuel efficiency = 4,900 Btu/seat-mile, AST-III fuel efficiency = 3,900 Btu/seat.mile
6. Long. range subsonic and AST-III are 300-passenger aircraft, AST-I IS a 200-passenger aircraft.
SOURCE Off Ice of Technology Assessment

subsonics. AST-II fuel consumption is considered to be 4,000 Btu per seat-mile which is 2.6 times an ASUBT fuel efficiency of 1,700 Btu per seat-mile. Scenario 4b differs from scenario 1 only in the matter of timing in that a joint venture could introduce 400 AST-IIIs earlier than a unilateral undertaking by the United States. Table 11 shows the results of fuel consumption analyses for either of the consortium cases.

Table 12 summarizes fuel consumption in the base case and in the four scenarios. Any scenar-

**Table 11 .—Energy Impacts of AST-II or AST-III: Scenario 4**

| Fuel consumption | Base case | Scenario 4a: fuel efficiency AST-II | Scenario 4b AST III: fuel efficiency High | Medium | Low |
|---|---|---|---|---|---|
| Short & medium range (MMbbl/d) | 3.74 | 3.74 | 3.74 | 3.74 | 3.74 |
| Long range (MMbbl/d) | 0.66 | 1.19 | 0.84 | 1.00 | 1.15 |
| increase over base case (MMbbl/d) | – | *0.53* | *0.18* | *0.34* | *0.49* |
| Percent of increase | — | *+ 80%* | *+ 27%* | *+ 50%* | *+ 75%* |
| All commercial aviation (MMbbl/d) | 4.40 | *4.93* | *4.58* | *4.74* | *4.89* |
| Percent of increase | — | *+ 12%* | *+ 4%* | *+ 8%* | +11% |
| Percent of increase in world petroleum use | — | + 0.6% | + 0.2% | + 0.3% | + 0.5% |

MMbbl/d = millions of barrels per day.
Assumptions:
1. Short- and medium-range aircraft make up 75 percent of the fleet and use 85 percent of the fuel in the base case.
2. Base case fleet = 6,000 short- and medium-range and 2,100 long-range subsonics,
3 Scenario 4a fleet = 6,000 short- and medium-range, 1,250 long-range subsonic, and 450 AST-II.
Scenario 4b fleet = 6,000 short- and medium-range, 1,250 long-range subsonic, and 400 AST-III.
4. Long-range subsonic fuel efficiency = 1,700 Btu/seat-mile
5. AST-II fuel efficiency = 4,400 Btu/seat-mile; AST-III fuel efficiency (Btu/seat-mile): High = 2,900; Medium = 3,900; Low = 4,500.
6 Long-range subsonic is a 300-passenger aircraft; AST-II is a 225-passenger aircraft; and AST-III is a 300-passenger aircraft.

SOURCE: Off Ice of Technology Assessment.

**Table 12.—Summary of Energy Impacts**

| Impacts | Base case | Scenarios: 1 U.S. only | 2 Foreign only | 3 Competition | 4 Consortium a | 4 Consortium b |
|---|---|---|---|---|---|---|
| **Fleet characteristics** | | | | | | |
| Number & type of long-haul aircraft | 2,100 ASUBTs | 1,250 ASUBTs 400 AST-IIIs | 1,250 ASUBTs 400 AST-Is or 400 AST-IIIs | 1,250 ASUBTs 250 AST-Is 250 AST-IIIs | 1,250 ASUBTs 450 AST-IIs | 1,250 ASUBTs 400 AST-IIIs |
| Fuel efficiency (Btu/seat-mile) | 1,700 | AST-III; 3,900a | AST-I; 4,900 AST-III; 3,900 | AST-I; 4,900 AST-III; 3,900 | AST-II; 4,400 | AST-III; 3,900a |
| Fuel-efficiency ratio (AST/ASUBT) | | 2.3 | AST-I; 2.9 AST-III; 2.3 | AST-I; 2.9 AST-III; 2.3 | 2.6 | 2.3 |
| **Fuel consumption** | | | | | | |
| Long-haul fuel (MMbbl/d) | *0.66* | 1.00 | NE[b] | *1.06* | 1.19 | 1.00 |
| Increase over base case (MMbbl/d) | — | 0.34 | NE[b] | 0.40 | **0.53** | **0.34** |
| Percent of increase | — | + 500/0 | NE[b] | + 600/0 | **+ 800/0** | **+ 500/0** |
| Total commercial fleet (MMbbl/d) | *4.40* | 4.74 | NE[b] | **4.80** | **4.93** | 4.74 |
| Percent of increase | — | + 8% | NE[b] | **+ 9%** | **+ 12%** | + 8% |
| Percent of increase in world petroleum use | — | **+ 0.3%** | NE[b] | **+ 0.40/o** | + 0.60/0 | + 0.3% |

MMbbl/d = millions of barrels per day.
[a]Middle value of estimated range of 2,900 to 4,900.
[b]Not estimated

SOURCE Off Ice of Technology Assessment

io involving the introduction of a supersonic transport will involve greater overall fuel consumption than if no supersonic is developed. The percentage of fuel use increase in the long-haul market (which consumes about 15 percent of the total commercial fleet fuel) ranges from a high of 80 percent in the case of a consortium-built AST-II (scenario 4a) to a low of 50 percent in the case of a U.S.-built AST-III (scenario 1). These values depend heavily on estimates of fuel efficiency for the various aircraft. Because these estimates are uncertain, the fuel consumption figures may vary by 20 to 25 percent.

According to table 12, the impact of supersonic aircraft on the total amount of fuel consumed by the commercial aviation fleet would be approximately 8 to 12 percent—if the market estimates for supersonics are reasonably accurate. Likewise, the impact of supersonic aircraft on worldwide consumption of petroleum fuels would be miniscule —0.3 to 0.6 percent, figures much smaller than the probable error in the estimation process used here.

If supersonic aircraft were introduced and used in numbers comparable to those assumed in these scenarios, overall worldwide fuel consumption by commercial aviation would approach 5 MMbbl/d by **2010.** This figure is equivalent to the amount of petroleum-based fuel anticipated to be used by all private automobiles in the United States at that time. If these types and numbers of supersonics were not introduced, worldwide commercial aviation fuel consumption would be 4.4 MMbbl/d, or about 10 percent less.

## ALTERNATIVE FUELS

The rising cost of petroleum-based fuels and the uncertainty of the long-term supply of petroleum have prompted all sectors of the economy to intensify the search for alternative energy sources. The need for substitute fuel is keenly felt in the air transportation industry, which is particularly dependent on an assured supply of a low-cost fuel that is equivalent to kerosene in weight and energy content. Because air transportation is a world activity, it is also of critical importance that the substitute fuel—whatever it is—be a uniform and generally available product .

The prospect facing the aircraft and airline industries has been summarized by one observer thus:

> The question is, in view of the grim outlook for the future of petroleum-based fuel, what are the alternatives facing the air transport industry? What other fuels offer more promise and what are the criteria that should serve as a guide in making the choice of a fuel in the future? The design and development cycle for large commercial transport aircraft of advanced design is approximately 10 years. The normal design life expectancy for aircraft of this type is about 20 years. Assuming a production cycle of 10 years, any new commercial transport aircraft whose design is started in 1976, for example, would normally be in service from 1986 through 2015, at a minimum. It is not realistic to assume that current quality fuel will continue to be generally available around the world at economically acceptable prices that far into the future.[8]

The question of alternative fuels is a general one that will affect the development of all types of advanced aircraft, and future decisions concerning supersonic aircraft will be conditioned by broader trends and developments in the aviation industry. Thus, it seems unlikely that supersonic aircraft would evolve toward the use of one fuel and subsonic aircraft toward another. More likely both forms of air transport technology will follow a single course and the fuel *eventually* selected will be one compatible for all advanced aircraft operating in the period 2000 to 2010. Questions that will have to be addressed in making a transition to an alternative fuel are:[9]

- What is the preferred fuel for commercial aviation from the standpoints of cost, per-

“D. G. Brewer, Hydrogen Fueled *Transport Aircraft, paper pre*sented at the U.S.-Japan Joint Seminar on “Key Technologies for the Hydrogen Energy System, ” Tokyo, Japan, July **1979, p. 7.**

‘Ibid.

formance, emissions, energy, noise, and long-range availability?

- How can the transition to a new fuel be implemented without serious disruption of existing commercial airline service?
- How much will it cost to provide facilities to store and handle the new fuel at airports, and how should this process be financed?
- Recognizing that the problem is international and that the choice of the new fuel requires cooperation among the principal nations, how can this choice best be accomplished?

At present, several candidate fuels are being considered. Generally they fall into two categories: synthetic liquid fuels with properties similar to kerosene, and cryogenic fuels such as liquid hydrogen or methane. These fuels could be derived from a number of sources—oil shale, tar sands, coal, or heavy crude oils. Table 13 summarizes the properties of some of the candidate fuels.

The National Aeronautics and Space Administration (NASA) has conducted and sponsored several studies of coal-derived aviation fuels.[10] Coal has been identified **as** one of the more plentiful remaining U.S. energy resources (at an order of magnitude greater than crude oil). The fuels considered were synthetic aviation kerosene, because it appears more compatible with the present air transportation system than other fuels, and liquid methane and liquid hydrogen, because they offer high energy content per pound. The investigations addressed the areas of fuel production, air terminal requirements for aircraft fueling, and the performance characteristics of aircraft designed to utilize alternate fuels. In the fuel production studies, the energy requirements associated with the production of each of the three selected fuels have been determined, as have estimates of the fuel prices. In the area of air terminal requirements for alternate fuels, only liquid hydrogen has been assessed thus far. Subsonic commercial air transports, designed to utilize liquid hydrogen fuel, have been analyzed and their performance characteristics have been compared to aircraft utilizing conventional aviation kerosene. Environmental and safety aspects were addressed as were key technical and economic issues.

Lockheed-California Co. has produced information on the processes and costs of production of several alternate fuels .11 When conventional crude oil is refined into a variety of fuels, including jet fuel, the energy content of fuels coming out of the refinery can vary from about 88 to 95 percent of the energy input to the refinery depending on the type of crude oil being refined and the mix of products. When fuels are produced from coal, an even smaller percentage of

[10] R. D. Witcofski, "Alternate Aircraft Fuels—Prospects and Operational Implications, " NASA TMX-7403, May 1977.

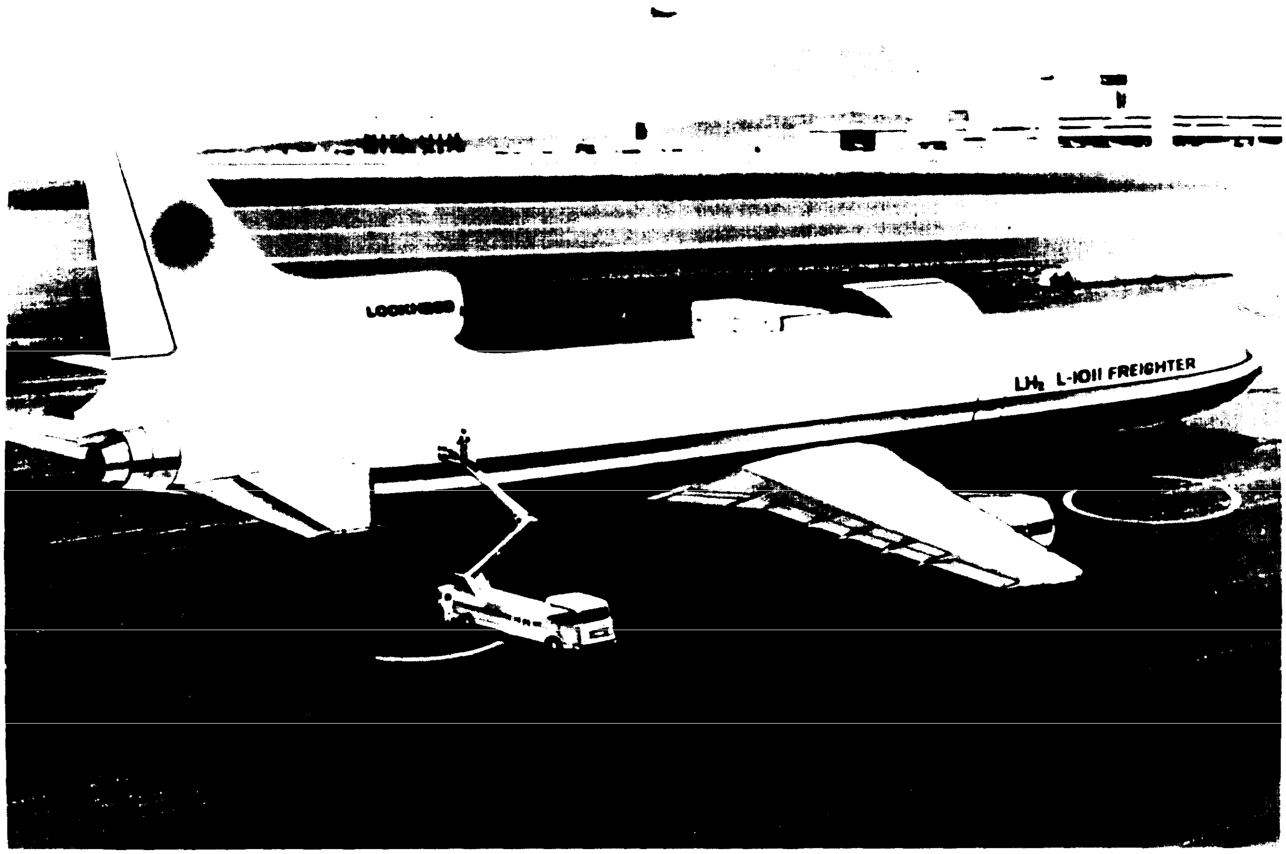
“OTA Working Paper, Lockheed-California Co., Feb. 5, 1979.

**Table 13.-Properties of Some Candidate Fuels**

| | Synthetic jet fuel[a] | Methane | Ethyl alcohol | Methyl alcohol | Ammonia | Hydrogen |
|---|---|---|---|---|---|---|
| Nominal composition . . . . . . . . | $C\,H_{194}$ | $CH_4$ | $C_2H_5OH$ | $CH_3OH$ | $NH_3$ | $H_2$ |
| Molecular weight, . . . . . . . . . . . | 120 | 16.04 | 46.06 | 32.04 | 17.03 | 2.016 |
| Heat of combustion (Btu/lb). . . | 18,400 | 21,120 | 12,800 | 8,600 | 8,000 | 51,600 |
| Liquid density (lb/cubic ft at 50° F) . . . . . . . . . . . . . . . . . | 47 | 26.5[b] | 51 | 49.7 | 42.6[b] | 4.4[b] |
| Boiling point (°F at 1 atmosphere) . . . . . . . . . . . . | 400 to 550 | – 258 | 174 | 148 | - 2 8 | – 423 |
| Freezing point (°F) . . . . . . . . . . | – 58 to – 90 | – 296 | – 175 | – 144 | – 108 | – 484 |
| Specific heat (Btu/lb °F) . . . . . . | 0.48 | 0.822 | 0.618 | 0.61 | 1.047 | 2.22 |
| Heat of vaporization (Btu/lb). . . | 105 to 110 | 250 | 367 | 474 | 589 | 193 |

[a] Derived from coat or shale.
[b] At boiling point.

SOURCE: D. G. Brewer and R. E. Morris, *Tank arrd Fuel Systems Considerations for Hydrogen Fueled Aircraft,* Society of Automotive Engineers, paper No. 751093, November 1975.



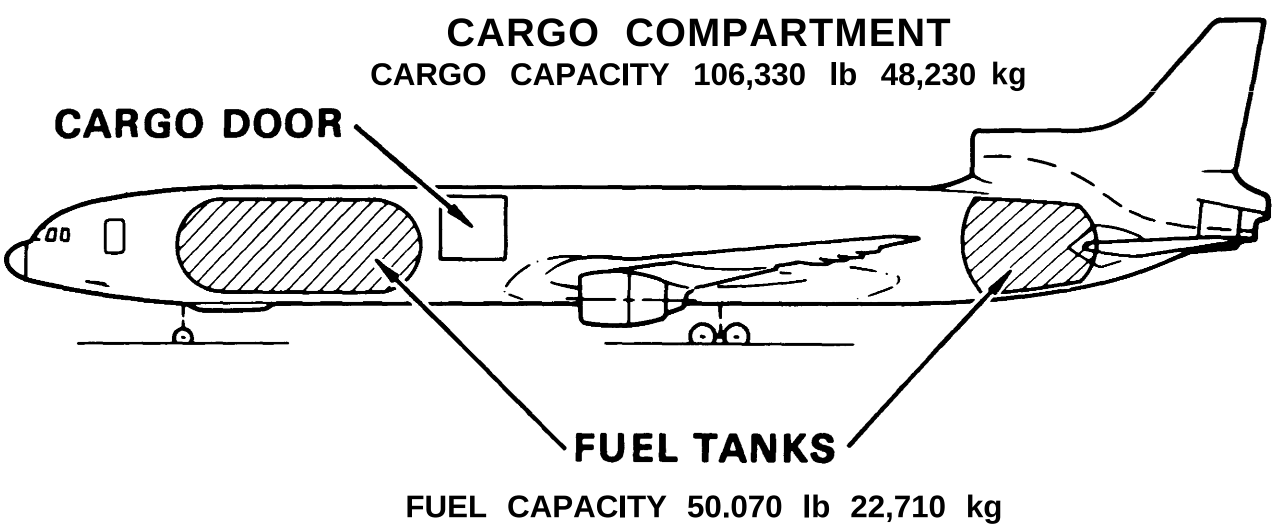




*Illustration. Courtesy 01 Lockheed Aircraft Corp.*

Artist's concept of hydrogen-fueled cargo aircraft the energy in the coal feedstock actually comes out the plant as useful fuel.

The thermal efficiency of the consol synthetic fuel (CSF) process for producing aviation kerosene from coal is about 70 percent. After hydrogen has been produced from the high-Btu gas product and used to hydrocrack and hydrogenate the heavy oil from the CSF process to produce a synthetic aviation kerosene, the overall thermal efficiency is 54 percent.

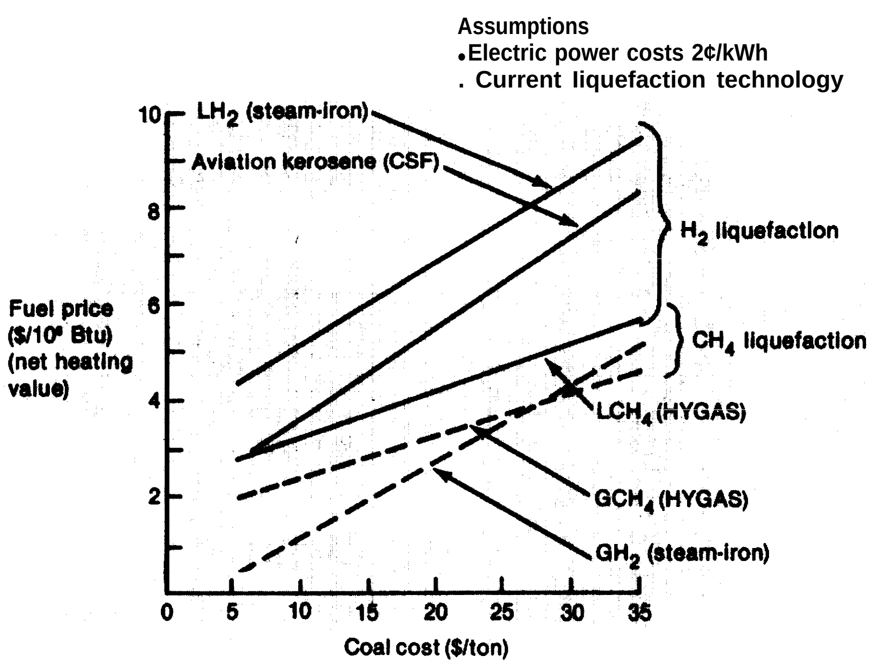
Of all the fuels and fuel processes investigated, liquid methane produced by the HYGAS process is the most thermally efficient coal-derived liquid fuel (64 percent). The relatively low energy requirements for liquefying methane (reported at 12.2 kWh per million Btu of liquid product) account for this efficiency.

Of the hydrogen production processes considered, the most thermally efficient process is the steam-iron process. Depending on whether the byproduct gas (heating value plus sensible heat) or electrical power generated from the gas is credited as the byproduct energy, the thermal efficiency of liquid hydrogen product via the steam-iron process is 49 or 44 percent. The energy requirements for hydrogen liquefaction were determined to be 104.7 kWh per million Btu of liquid product.

At the time of the Lockheed study (1977) domestic airlines were paying about $0.32 per gallon ($2.60 per million Btu) for aviation kerosene. The price in early 1980 was over $1.00 per gallon. The price of synthetic fuels will be determined by a number of factors, including the cost of the energy source from which they are produced (coal in the present discussion), the cost of labor and materials for constructing the plants, the cost of a method of financing the construction of plants, and the price of competitive fuels.

A summary of fuel prices as a function of coal cost is presented in figure 14. Although not based on current prices, the data are still useful in comparing one fuel or fuel production process against another. As a point of reference, Virginia Electric and Power Co. was paying be-

Figure 14.— The Price of Coal-Derived Aviation Fuels as a Function of Coal Cost




SOURCE: OTA Working Paper, Lockheed-California Co., Feb. 5, 1979.

tween **$20** to **$25** per ton for mine-mouth coal in May 1977. The figure shows that, for the processes and fuels considered, liquid methane produced by the HYGAS process is the least expensive, and the price increase on account of increased coal cost would be less than for the other fuels and fuel processes. Liquid hydrogen is the most expensive fuel within the range of coal costs considered. Synthetic aviation kerosene (produced from the CSF process) falls between liquid hydrogen and liquid methane.

Figure 14 also shows that the price of gaseous hydrogen and methane are comparable and, at the lower coal costs, gaseous hydrogen is less expensive than gaseous methane. The reason that the liquid hydrogen prices are so high in comparison to the other two fuels is the cost of liquefying the hydrogen. At $25 per ton, the cost of coal represents more than half of the total cost of liquid hydrogen produced by liquefaction. Studies are currently underway at Linde to assess the possibility of reducing the cost of hydrogen liquefaction. These studies include an analysis of the idea of joining to the liquefaction plant a heavy water plant from which byproduct heavy water would be sold.

In summary, at a coal cost of **$20** per ton, Lockheed estimates that liquid hydrogen would be priced at $7 per million Btu, synthetic kerosene at **$5.50,** and liquid methane at **$4.30.** However, a later study conducted by NASA[12] has indicated that at a coal cost of $18 per ton, liquid hydrogen would be priced at $11 per million Btu, synthetic kerosene at $8.47, and liquid methane at $8.00. The variance surrounding these estimated costs indicates the uncertainty in this area.

## Application to Supersonic Transports

Studies of the use of synthetic fuels and liquid hydrogen for supersonic aircraft have been conducted by NASA,[13] Boeing,[14] Lockheed,[15] and EXXON. I' Lockheed has probably been the most active supporter of hydrogen-fueled aircraft, and table **14** summarizes some of their findings. The Lockheed view is that liquid hydrogen is superior to other fuels as a long-term substitute for petroleum, especially as a fuel for supersonic aircraft, Among liquid hydrogen advantages cited by Lockheed are reduced aircraft weight, lower engine thrust requirements, better specific fuel consumption, lower direct operating cost, and reduced sonic boom overpressure.

However, EXXON in a study comparing alternative aviation fuels has reached opposite conclusions concerning the relative advantages of hydrogen. The study pointed out that, on a volume basis, the heat content of liquid hydrogen is 25 percent that of synthetic jet fuel and, thus, more storage volume would be required for a given flight. Other disadvantages of liquid hydrogen are low density and boiling point, as well as being very expensive fuel compared to liquid fuels from coal or shale. Table 15 summarizes advantages and disadvantages of liquid hydrogen enumerated in the EXXON study. It should be remembered that disagreement remains within the industry over findings in both the Lockheed and the EXXON studies.

The following summation, excerpted from the EXXON study, highlights some of the major points of comparison among the various alternative aviation fuels that might be used for supersonic and subsonic aircraft.

- Of the cryogenic and the synthetic jet fuels considered, hydrogen has the highest heat of combustion on a weight basis and the highest specific heat (a measure of its ability to be used as a coolant), but it has the

[12] R. D Witcofski, "Comparison of Alternate Fuels for Aircraft, " NASA Technical Memorandum, September 1979.

[13] R. D. Witcofski, "Hydrogen Fueled Subsonic Aircraft, " NASA Langely Research Center, presented at the International Meeting on Hydrogen and Its Prospects, Liege, Belgium, November 1976.

[14] G. J. Schott, "Alternate Fuels for Aviation, " Boeing Commercial Airplane Co., presented at the 29th annual conference, California Association of Airport Executives, July 1975.

[15] G. D. Brewer and R. E. Morris, *Tank and Fuel Systems Considerations for Hydrogen Fueled Aircraft,* Society of Automotive Engineers, paper No. 751093, November 1975.

[16] EXXON Engineering and Research Company, *Alternate Energy Sources for Non-Highway Transportation,* for U.S. Department of Energy, contract No. **EC-77-C-05-5438,** December 1978.

**Table 14.—Comparison of a Supersonic Transport Aircraft Fueled With Liquid Hydrogen or Jet A Fuel**
**(Mach 2.7,4,200 nm, 234 passengers)**

| Parameters | Unit | $LH_2$ | Jet A | Ratio Jet A / $LH_2$ |
|---|---|---|---|---|
| Gross weight | lb | 394,910 | 762,170 | 1.93 |
| Operating empty weight | lb | 245,240 | 317,420 | 1.29 |
| Block fuel weight | lb | 85,390 | 330,590 | 3.88 |
| Thrust per engine | lb | 52,820 | 86,890 | 1.64 |
| Wing area | $ft^2$ | 7,952 | 11,094 | 1.39 |
| Span | ft | 113 | 113.5 | 1.18 |
| Fuselage length | ft | 304.2 | 297 | 0.87 |
| Field length required | ft | 7,800 | 9,490 | 1.22 |
| Lift/drag (cruise) | — | 7.42 | 8.65 | 1.17 |
| Specific fuel consumption (cruise) | lb/hr /lb | 0.575 | 1.501 | 2.61 |
| Aircraft price | $10' | 45.5 | 61.4 | 1.35 |
| Direct operating cost | ¢/seat nm. | 3.40' | 3.86[b] | 1.14 |
| Energy utilization | Btu/seat nm. | 4,483 | 6,189 | 1.38 |
| Noise, sideline | EPNdB | 104.0 | 108.0 | — |
| Flyover | EPNdB | 102.2 | 108.0 | — |
| Sonic boom overpressure (start of cruise) | psf | 1.32 | 1.87 | 1.42 |

[a]Based on a cost of $3.00 per 10⁶ Btu.
[b]Based on a cost of $2.00 per 10⁶ Btu.

SOURCE: OTA Working Paper, Lockheed-California Co., January 1979

**Table 15.—Advantages and Disadvantages of Liquid Hydrogen Compared to Synthetic Jet Fuel**

| Advantages | Disadvantages |
|---|---|
| • Lighter weight aircraft than synthetic jet fuel aircraft. | • Airport modification to add hydrogen storage and handling facilities would be a major undertaking. |
| • Longer range possible. | • Overall economics unfavorable compared to shale oil based fuel for subsonic and supersonic aircraft. * |
| • Greatest performance advantage is with supersonic flight | • Overall economics unfavorable with coal-based liquids for subsonic, but close for supersonic. * |
| • Emission of CO, $CO_2$, HC, and odor eliminated; $NO_x$ emission equal to or less than synthetic jet fuel. | • Requires more energy from mine to engine. |
| • Reduction in noise and sonic boom due to smaller size aircraft. | • Amount of water vapor emitted in flight is higher. |
| • Initial cost lower for supersonic aircraft, about same for subsonic. | • Handling liquid hydrogen is more hazardous than synthetic jet fuel. |
| • Maintenance cost may be lower. | |
| • Can use shorter runways.[a] | |

'Based on a ratio of coal based liquids to shale oil fuel cost per gallon of 1.8 to 1.

SOURCE" EXXON Research and Engineering Co., *Alternate Energy Sources for Non-Highway Transportation,* December 1978.

disadvantage of a low density and so low volumetric heat content and also a low boiling point.

- Liquid methane is 15 percent more energetic on a weight basis and has a specific heat 1.7 times greater than synthetic jet fuel. It is six times more dense than liquid hydrogen.
- The fuel costs, on a per-flight basis for a subsonic aircraft, are lowest for shale-derived jet fuel, followed by an indirect coal-liquid jet fuel. A direct coal-liquid jet fuel

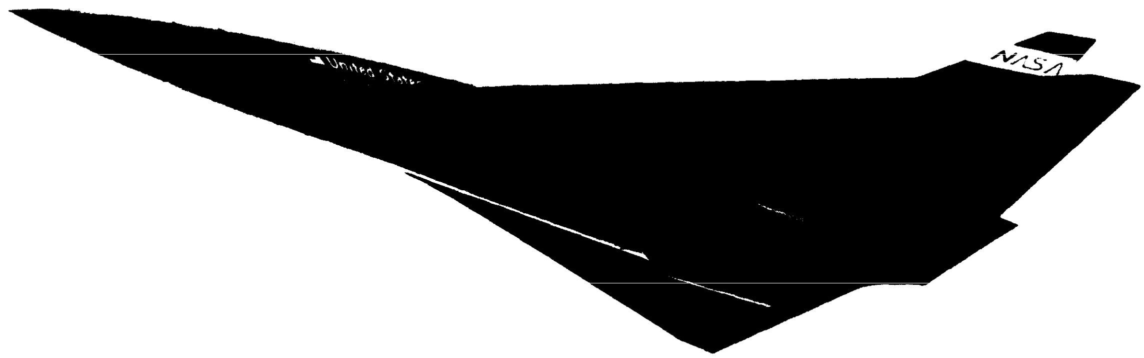



*Illustration: Courtesy of Lockheed Aircraft Corp*

Artist's concept of hydrogen-fueled hypersonic aircraft

and liquid methane are roughly equal in cost. The hydrogen-fueled aircraft would be the most expensive to operate—over three times the cost of operating an aircraft fueled with a shale-derived liquid. *

- For a supersonic aircraft (Mach 2.7, 4,200 nautical miles, and **234** passengers), the design advantages with hydrogen are greater than for a subsonic aircraft. However, the fuel cost per flight still favors the synthetic liquid fuels—shale oil first, followed by coal-derived jet fuel and then hydrogen. *
- With regard to natural resources and the resources required between the mine and the aircraft, a shale-oil-derived jet fuel is the most efficient. Hydrogen requires about double the amount of natural resources as shale oil.
- Laboratory tests have shown that acceptable jet fuels can be made from either coal or shale. Production of aircraft fuels from shale oil should be more straightforward than from **coal.**
- Coal-based jet fuels will have poorer combustion properties than shale oil fuels because they form naphthenes rather than paraffins when the coal liquids are hydrogenated.
- An economic comparison between upgrading fuels to meet current hydrogen levels and modifying the engine shows that there are incentives to develop an engine that can accept **a** poorer quality fuel. If a fuel of 12 percent hydrogen can be used, the incentive would be about $170,000 per year per engine to operate an engine capable of using a fuel with a lower hydrogen content.

The Federal Government currently is planning to launch a large-scale synthetic fuel production program. But the details of the plan and where this new fuel would be allocated have not been worked out, so they cannot be related to development of a supersonic aircraft at this time. However, due to the uncertainty of the energy picture, it seems quite appropriate to continue the examination of alternative fuels to ensure fuel availability for any new type of advanced air transport—either subsonic or supersonic.

*Based on the following cost ratios per $10^6$ Btu: liquid hydrogen from coal (3.8); jet fuel from coal liquefaction (1 **.8);** and jet fuel from shale oil (1 .0).