DEVELOPMENT OF FUELS FOR SUPERSONIC AND HYPERSONIC COMMERCIAL TRANSPORTS

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Introduction

Since the early 1970s, studies of alternative aircraft fuels have focused on a scenario that assumed continually decreasing availability and increasing costs of conventional jet fuels -- a scenario that only briefly materialized. Currently, conventional fuels are plentiful, and their prices have dropped nearly to the 1976 level, when commercial supersonic service began. The current price of jet fuel is almost the same when the first supersonic transport commercial began. (See Figure 1.)

Since we cannot assume these availability and price conditions will continue indefinitely, trade studies directed toward a possible shortage should be pursued. However, studies based on this scenario typically assume that conversion to a particular alternative fuel will satisfy the needs for all or a major portion of the commercial aircraft fleet. This assumption leads to fuel selection criteria being developed to satisfy the broad economic and technical requirements of the entire aviation industry. However, supersonic and hypersonic transports have unique fuel requirements; therefore, data from such studies may not provide a good base from which to select a fuel for these vehicles.

The most publicized special fuel requirement for high speed transports is the need for a fuel that has a high heat absorption capability or, at least, a high thermal stability. An often overlooked and as important variable in the choice of a special fuel for high speed transports is the size of the fleet. This is important because the cost of a unique fuel developed for a small number of aircraft could be significantly greater than the identical fuel developed for the entire commercial aircraft fleet. Supersonic and hypersonic aircraft fleets may not be large enough to command a low fuel price (Figure 2).

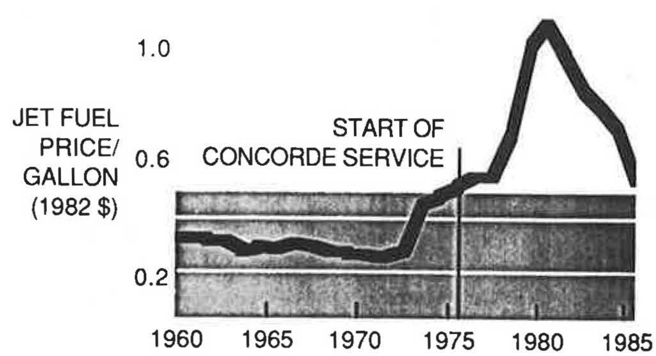


FIGURE 1. Jet Fuel Price per Gallon, 1960-1985

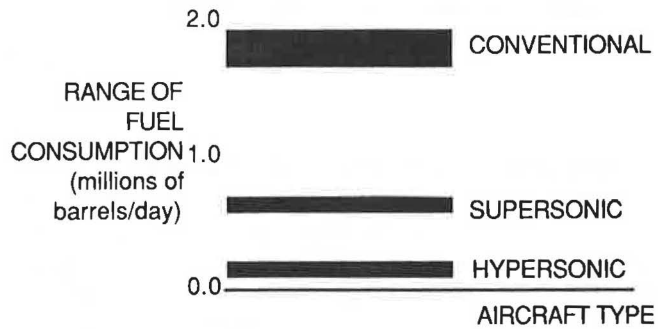


FIGURE 2. Range of Fuel Consumption by Aircraft Type

The disadvantages and cost penalties associated with the selection of a unique fuel for supersonic and hypersonic aircraft must be balanced against the cost and penalties associated with the use of new materials or techniques that allow the selection of more conventional fuel. Trade studies relating to supersonic aircraft will be strongly influenced by the cost and availability of high temperature materials and cooling requirements, while those relating to hypersonic vehicles may be equally influenced by the fuel properties required to satisfy engine requirements. In both cases, the cost associated with a requirement for a unique fuel must play an important part in concept selection as well as in the determination of commercial feasibility.

Fuels for high-speed aircraft fall under three categories:

- o Conventional fuels that satisfy current aircraft and fuel specifications,
- o Cryogenic fuels, such as liquid hydrogen and liquid methane (including liquefied natural gas), that must be stored in insulated containers,
- o Endothermic fuels, such as methylcyclohexane to toluene-plus-hydrogen, that are selected for their heat absorption capabilities and involve a change in chemical composition.

Other fuels being considered for high-speed aircraft, such as metal-organic, are not covered in this paper because they currently do not appear to be promising candidates for commercial transports.

Fuel Properties

Heat sink requirements for supersonic and hypersonic aircraft airframe, engine, and mechanical systems have stimulated many efforts to develop a new or different fuel. Searches for a heat-absorbing fuel began more than three decades ago. Both early and recent studies concluded that cryogenic fuels, particularly liquid hydrogen, were the most promising for aircraft in terms of heat absorption capacity, heat content per unit mass, and properties considered desirable for the design of an efficient clean-burning engine. Unfortunately, cryogens require insulated pressure vessel storage and have relatively poor energy content per unit volume. These characteristics force fuel tank placement and design compromises that are particularly detrimental to aircraft requiring a low-drag profile. Attempts to solve these problems resulted in development of concepts for cooling using the endothermic reaction that occurs when various hydrocarbons decompose.

In attempts to find an endothermic fuel that could satisfy aircraft requirements, a large number of compounds and reaction types have been analyzed. The more promising, in terms of amount of heat absorbed and ability to control the process, involve the use of a catalyst to stimulate the reaction. An example of this type of reaction is the conversion of methylcyclohexane to toluene and hydrogen. This fuel, like most endothermic fuels, would be pumped to a high pressure after it leaves the fuel tank, heated, decomposed, and then heated again. (See Figure 3.)

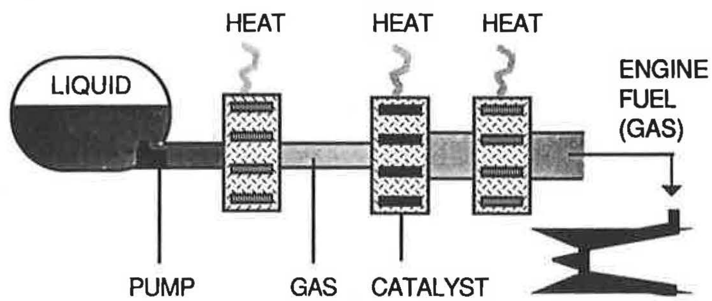


FIGURE 3. Endothermic Fuel System

Although endothermic fuels do not offer the cooling potential of liquid hydrogen, they offer an ability to absorb heat while maintaining many of the desirable properties of conventional jet fuels. (See Table 1.)

New, highly efficient, subsonic commercial jet engines are placing increasing heat load and high temperature demands on jet fuels. These demands are causing jet fuels delivered to current commercial aircraft specification limits to become marginal with respect to thermal stability and burning characteristics. New generation high-performance engines for supersonic aircraft will place even more stringent thermal loads and temperature demands on fuels.

Conventional fuels for future supersonic aircraft may require new limits for the components of jet fuels that cause high flame radiation or coking. Metal deactivator additives or more stringent composition control may be required to improve thermal stability. Synthesized conventional jet fuels that can satisfy thermal load and stability requirements for supersonic aircraft up to Mach 4 are already available in small quantities.

Most endothermic fuels considered for cooling the aircraft structure, engine, or both, require burning mixtures of aromatics and hydrogen or olefins and

Table 1. COMPARISON OF FUELS FOR HEAT ABSORPTION

FUEL	HEAT COMBUSTION		HEAT ABSORPTION	STORAGE TEMPERATURE
	Btu/lb	Btu/gallon	Btu/lb	°F
CONVENTIONAL	18,400 to 19,000	116,000 to 127,000	<400 **	AMBIENT
LIQUID HYDROGEN	51,500	29,675	5,900	-423
LIQUID METHANE	21,500	76,193	1,400 *	-259
ENDOTHERMIC	<20,000	116,000 to 127,000	500 to 1,800	AMBIENT

* To 1,200° F from 100° F ** To 650° F (decomposition limit)

methane. The higher the hydrogen content, the more desirable the fuel properties for aircraft using turbojet engines. (See Figure 4.) Jet fuels with a high aromatic content tend to burn with a high degree of radiation, while olefins tend to have a low thermal stability. The burning characteristics of these mixtures and their impact on engine design, efficiency, and mantainability require significant analysis and testing. As an example, consider a mixture of toluene which has very slow flame speed and long ignition time, and hydrogen, which has an extremely high flame speed and very short ignition time. When such a mixture is introduced into an engine, will the burning hydrogen suddenly create a high temperature that cokes the aromatic toluene? Questions such as this require answers before endothermic fuels can be considered suitable for aviation purposes.

Hydrogen is a clean burning, thermally stable fuel with no chance of coking or blocking passages due to decomposition, and the low radiation from its flame results in cooler engine parts. Methane is also a clean burning, thermally stable fuel. Because combustion product mass is an important performance property at hypersonic speeds, low molecular weight makes hydrogen a fuel of

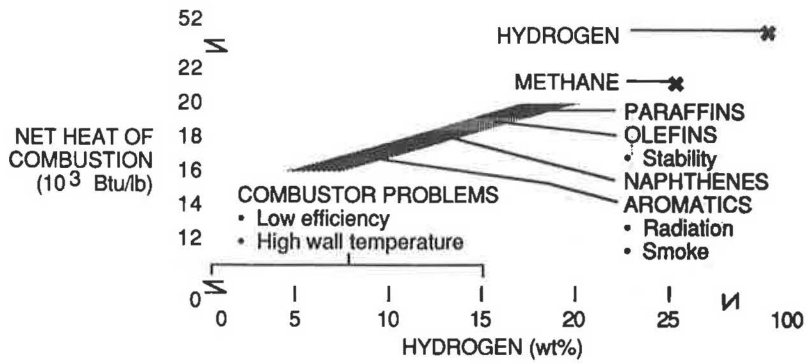


FIGURE 4. Importance of Hydrogen on Turbojet Engines

choice for this application -- particularly when excess fuel is used for cooling the engine. Hydrogen will give the lowest molecular weight products of combustion -- a significant advantage for high Mach numbers.

Fuel Production

One reason petroleum is highly desirable fuel source is that it is easy and inexpensive to process into useful products. Most alternative fuels will be more difficult to produce, primarily because of increased processing complexity. In general, the cost of processing alternative fuels will have a greater influence on their price that will the cost of raw materials.

Alternative fuels studies, when based on increasing cost and scarcity scenarios, assume that the conversion to a particular alternative fuel will satisfy the needs of all or a major portion of the commercial aircraft fleet. Processes that could only supply a small quantity of fuel or are limited to a local area are not considered an energy crisis solution. Supersonic and hypersonic aircraft are not likely to be major fuel users, and their operation will be limited to a relatively few locations in comparison to the overall air transport fleet. These demand and location requirements may make some of the alternative fuel processes rejected during energy crisis scenarios worthy of a second look.

Hydrogen. Although hydrogen is the most abundant element in the universe, it does not occur naturally in a form that can be used as a fuel. The least expensive method currently used for producing hydrogen is the steam reforming of natural gas and other petroleum products. The reforming process is simple, efficient, and adaptable to a wide range of quantity demand requirements.

The use of light hydrocarbons or natural gas as raw materials to produce hydrogen would not be reasonable solution to real worldwide shortage of petroleum-based jet fuels because new conversion processes have been developed that can efficiently and economically synthesize conventional jet fuels from these materials. These materials would also be in short supply or expensive in petroleum shortage situation. However, where the application of a fuel involves a relatively small demand, such as for supersonic and hypersonic aircraft, natural gas can be a logical choice for producing hydrogen.

The two production methods that have received the most recent attention for producing hydrogen for aircraft are the partial oxidation of coal and the electrolysis of water. Production facilities using either process can be built using existing technology.

Coal Oxidation. Coal is distributed worldwide -- nearly every nation has a secure access to commercially developed deposits. In many areas of the world, coal will be the most economical source for hydrogen. Like steam reforming, the partial oxidation process using coal to obtain hydrogen is relatively simple and efficient. The process is adaptable to a wide range of fuel demand requirements, but probably would not be practical for providing hydrogen to a few aircraft at a single airport. Incidently, a common misconception is that hydrogen is produced from coal. Actually, coal is used as a reducing agent to obtain hydrogen from water. Environmentally, processes involving coal are currently not considered "good neighbors" and in all cases require expensive pollution control equipment.

Electrolysis. The classic technique for extracting hydrogen from water is by electrolysis. This process uses an electric current to break water into its basic components of hydrogen and oxygen. The process is simple but requires an enormous amount of energy -- approximately 21 kilowatt hours per pound. Electrolysis is often touted as environmentally benign, but this is true only if the source of power is nonpolluting, such as hydroelectric or solar.

The suitability of electrolysis for producing hydrogen for supersonic or hypersonic aircraft will be strictly dependent upon the cost and availability of electricity. Hydrogen by electrolysis may be the best choice in areas of the world that have surplus electric power or a capability for the development of new hydroelectric power.

Liquefaction. Regardless of the process used to produce hydrogen, it must be liquefied before it can be used in an aircraft. The liquefaction process involves a series of compression, heat exchange, and expansion steps and in some processes a second refrigerant, such as liquid nitrogen. (See Figure 5.)

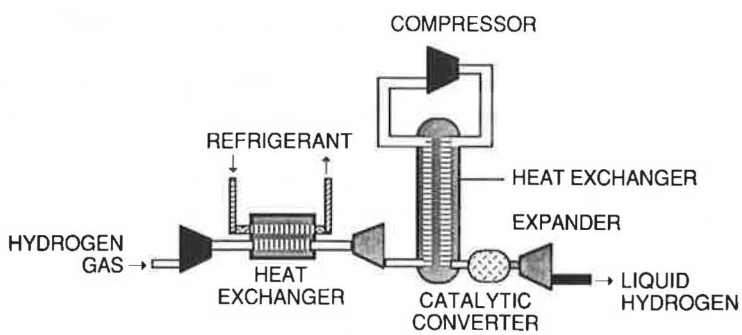


FIGURE 5. Liquefaction of Hydrogen

Liquefaction of hydrogen requires approximately 4.9 kilowatt hours per pound of hydrogen produced. The power required to liquefy hydrogen for a single supersonic aircraft flight per day would be 11 megawatts. If the hydrogen gas were obtained by electrolysis of water, the total power required would be 55 megawatts. In addition, the liquefaction facility would require a constant power input to obtain a reasonable production efficiency. Airports that involve more than a few flights per day generally would require a dedicated power plant.

Methane. Any carbon-organic material (such as coal, refuse, animal waste, or vegetable matter) can yield methane through various chemical processes or by bacterial action. The least expensive method is through the purification and liquefaction of natural gas, but methane also can be obtained from the partial oxidation of coal in a process similar to that described for hydrogen.

Methane takes less energy to liquefy than hydrogen -- a factor of 2.4 less in terms of equivalent energy (Figure 6). The power required to liquefy methane for a single supersonic aircraft flight per day would be 4.5 megawatts as compared to 11 megawatts for hydrogen. The source of this power could be electric or natural gas. The lower energy required to liquefy methane, as compared to hydrogen, increases the possibilities for using purchased power and sources of power that could not satisfy airport hydrogen demand. For example, Canada has some surplus nuclear and hydroelectric power.

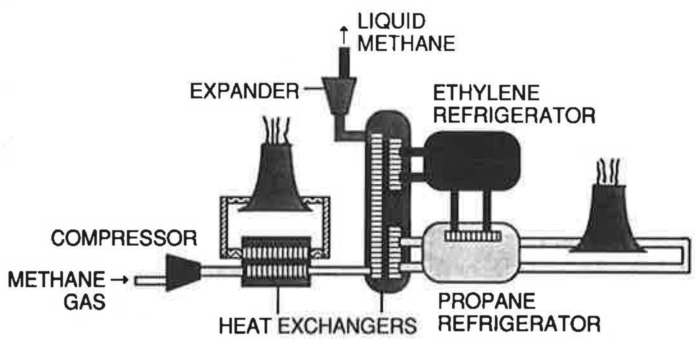


FIGURE 6. Liquefaction of Methane

Endothermic Fuels. Endothermic fuel processes range from those that have been developed only for small batch quantities to those that are commercially practiced in the chemical process industry. An example is the exothermic process required to manufacture methylcyclohexane which is the reverse of the endothermic process considered for use in cooling aircraft.

New processes must be developed before many of the endothermic fuel candidates could be considered practical for commercial aircraft applications. Some techniques for producing commercial quantities of endothermic fuels would include:

- Selected cuts from equipment at existing petroleum refineries,
- The addition of equipment to a petroleum refinery or petrochemical plant, and
- A new and dedicated facility.

Most investigations covering endothermic fuels were conducted in the early 1960s, at which time it did not appear that easily obtained products from existing refineries could satisfy endothermic fuel requirements. Petroleum refineries since have become more complex and offer significantly more product flexibility.

The development of dedicated facilities for endothermic fuel production may be impractical. The most cost-effective method for producing specific or narrow-cut hydrocarbons would be as one of many saleable products. The additional steps required to limit the output of a chemical processing facility to a single or relatively few products would in most cases be expensive. However, as in petroleum refining, major technical advances have occurred recently, and they include the development of new catalysts and techniques for their application. This has resulted in improvements of synthesis processes used to produce specific chemicals from the basic building blocks of carbon monoxide and hydrogen.

The synthesis approach to fuel development allows consideration of more than just petroleum for endothermic fuel development. This process is currently being used in South Africa to produce commercial quantities of transportation fuels including jet fuel, and in New Zealand to produce gasoline from natural gas.

It is not clear that an endothermic fuel that could satisfy commercial aircraft requirements has been identified. A new look at previously identified endothermic fuels, as well as new candidates, is certainly warranted based on recent technical advances in both the refinery and basic chemical product manufacturing areas.

Cost

The cost of the fuel consists of the cost of raw material, required energy, facilities, and distribution. The price of fuel is dictated by supply and demand, competition, and government policy, in addition to costs. The cost of jet fuel from petroleum is driven by the price of its raw material, i.e., crude oil. The cost of most alternative jet fuels will be driven by process energy requirements and the capital requirements for facilities. When fuel costs are based on a total conversion of a large segment of society to a particular alternative fuel, the criteria for accepting a new fuel would be price parity -- the price of the alternative that would allow it to compete with the existing fuel. The price of conventional petroleum-based jet fuels has almost risen to, but never reached, the point where the cost estimated for synthetic jet fuel would justify a commercial sector investment in production facilities. The price of a dedicated jet fuel for supersonic and hypersonic aircraft is likely to be higher than conventional jet fuel. (See Figure 7.) Price not cost, justifies an investment in new facilities, and this price must be high enough to compensate for the risk.

If a fuel is dedicated to a single use, such as supersonic or hypersonic aircraft, there is no other industry to share costs. Fuel suppliers must have an incentive to risk an investment in new or upgraded fuel production facilities. This incentive can be in the form of expectations of a major future growth in demand or, more likely, a fuel price that is considerably higher than fuel cost. This price-to-cost differential could be considerable since the supplier will probably have a monopoly and must ensure that his supply is adequate during periods of high demand and to protect his investment during airline industry recessions.

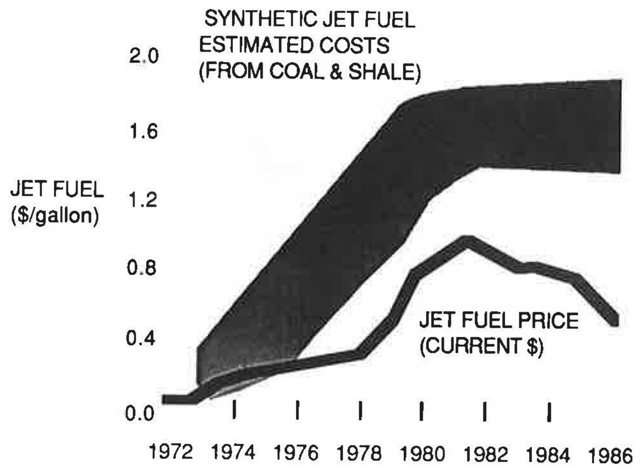


FIGURE 7. Relative Cost of Synthetic Jet Fuel

Hydrogen. The principal cost driver for each method of producing hydrogen differs as follows: (1) the raw material (natural gas) price for producing hydrogen from natural gas, (2) capital costs for producing hydrogen using coal, and (3) electric power for producing hydrogen from water using electrolysis. The cost of hydrogen from the various sources is influenced to different degree by the cost of raw materials, capital, and power. (See Figure 8.)

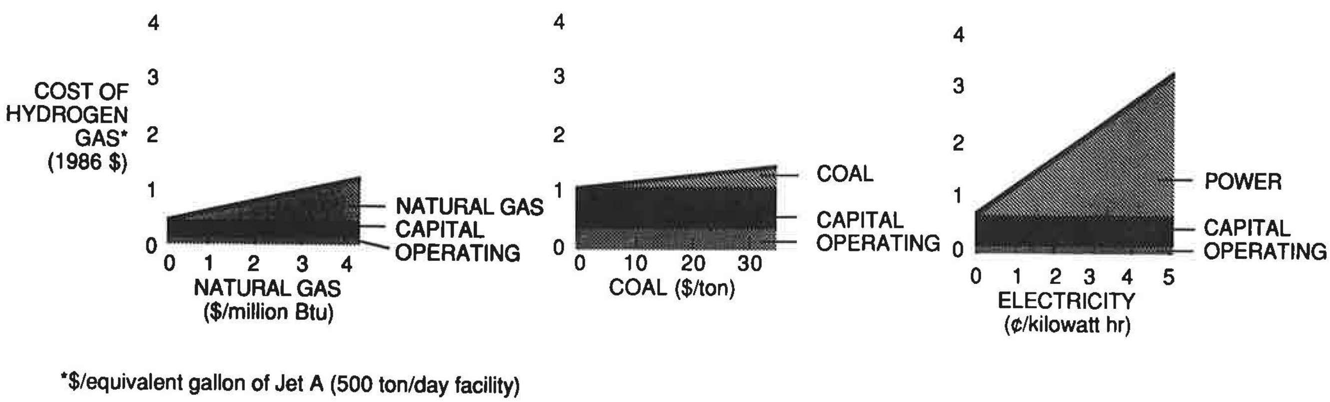
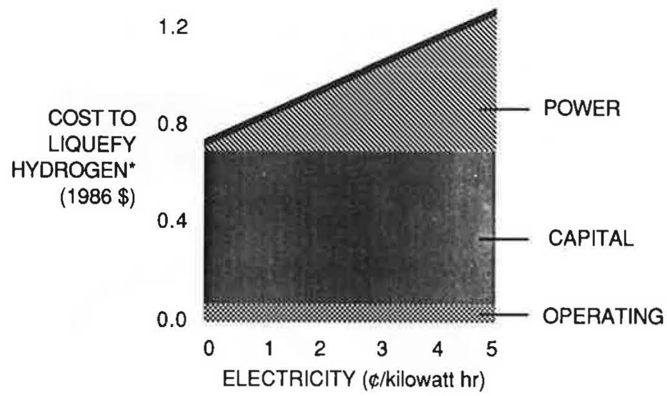


FIGURE 8. Hydrogen Cost Variations from (a) Natural Gas, (b) Coal, and (c) Electricity

Before hydrogen can be used as an aircraft fuel it must be liquefied, and the cost of liquefaction is driven by the cost of power. Power can be supplied to the liquefier as electricity, or the liquefier can be driven using hydrogen produced in the gasification plant as shown in Figure 9. Liquefaction using gaseous hydrogen from coal to drive turbo-compressors is more costly than using the coal to produce electric power for liquefaction.



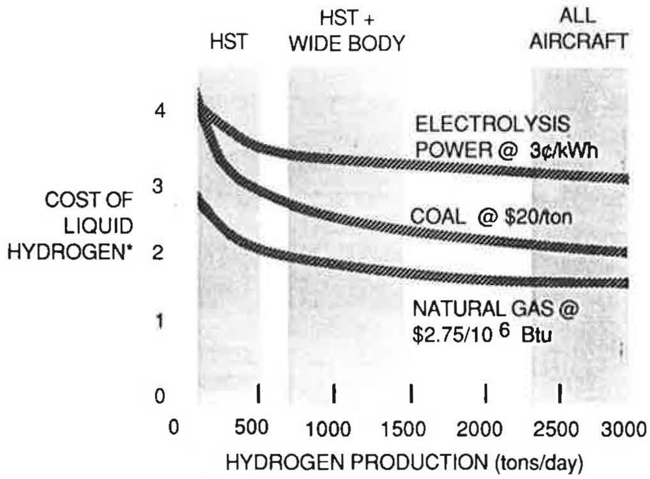
*$/equivalent gallon of Jet A (500 ton/day facility)

FIGURE 9. Liquefaction Cost Driven By Power Cost

The price of fuels is sensitive to local as well as total demand. The cost of fuels is also sensitive to the size of the production facility, particularly if the production unit is relatively small. This quantity sensitivity can be significant enough to impact the choice of fuel for the hypersonic and supersonic aircraft as well as the process chosen to produce the fuel in a particular area of the world. An estimated range of hydrogen requirements for hypersonic aircraft indicate that this demand may not be in the most cost-effective range for hydrogen production.

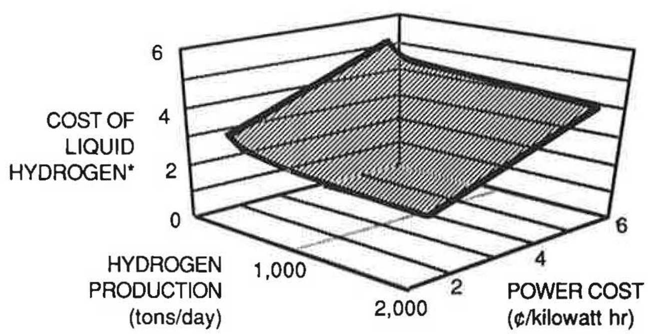
The global nature of supersonic and hypersonic aircraft, the relatively low individual airport fuel demand, and transportation considerations will not allow a blanket statement as to a single cost or best process. The selection of hydrogen process and the hydrogen cost must be based on individual airport or area studies that include the quantity of fuel required and the costs and availability of power and raw materials. For example, in an area with inexpensive electric power, hydrogen from water using electrolysis may offer an acceptably low cost even at low production levels. The size of the high-speed aircraft fleet may have a strong influence on the cost of hydrogen (Figure 10). The cost of liquid hydrogen will vary from location to location depending on the combination of demand and the cost of power (Figure 11).

Methane. There are two principal sources for obtaining methane in sufficient quantities to satisfy commercial aircraft requirements: directly from natural gas and from the partial oxidation of coal. The cost of gaseous methane obtained from natural gas will be close to the price of natural gas, depending upon the purity of the gas in terms of methane content and whether the aircraft really needs pure methane or can accept mixtures of methane and ethane. The production of methane from coal, like hydrogen from coal, is highly capital intensive. (See Figure 12.)



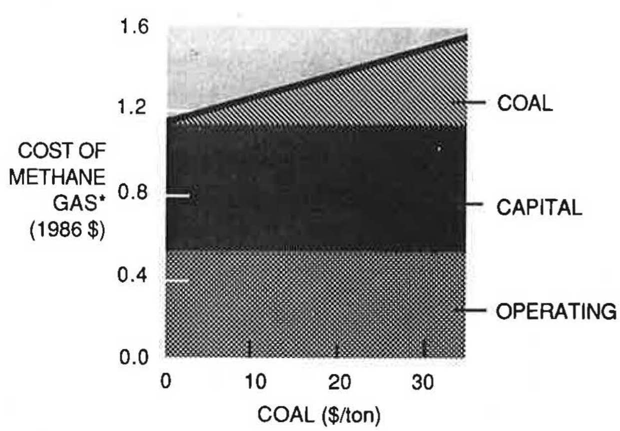
*$/equivalent gallon of Jet A.

FIGURE 10. Effect of Production Volume on Cost of Liquid Hydrogen



*$/equivalent gallon of Jet A (500 ton/day facility)

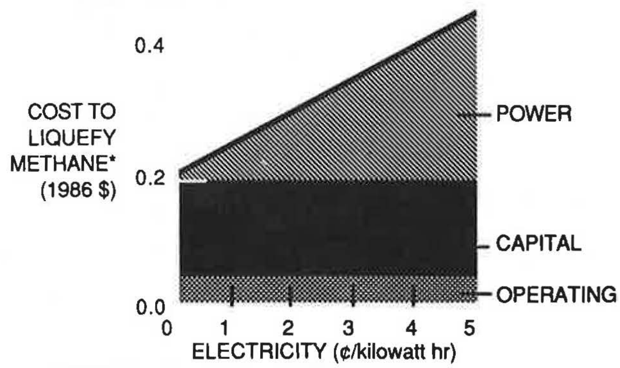
FIGURE 11. Effect of Demand and Cost of Power on Cost of Liquid Hydrogen



*$/equivalent gallon of Jet A (1200 ton/day facility)

FIGURE 12. Methane Gas Produce from Coal is Capital Intensive

Like hydrogen, methane must be liquefied before it can be used as an aircraft fuel, and cost of liquefaction is driven by the cost of power (Figure 13). Power can be supplied to the liquefier as electricity, or the liquefier can be driven by natural gas or methane produced using coal. The power required to liquefy methane is significantly lower than the power required to liquefy hydrogen -- 2.4 times lower; therefore the cost to liquefy methane is considerably lower than to liquefy hydrogen.



*$/equivalent gallon of Jet A (1200 ton/day facility)

FIGURE 13. Relative Cost of Liquid Methane Produced from Electricity

The liquefaction cost differences between methane and hydrogen will be quite significant in trade studies. Liquefaction costs must be accounted for twice -- once for the initial production of the fuel and a second time to reliquefy fuel that has vaporized during ground operations.

The cost of methane produced using coal shows the same quantity dependency as hydrogen in terms of cost. The cost of liquid methane from natural gas will be driven by the cost of the natural gas more than the size of the facility. A low demand that allows use of existing natural gas distribution systems is expected to result in the lowest methane price. While the size of the high-speed aircraft fleet may have an influence on the cost of methane from coal, local price of natural gas is likely to be a more important factor (Figure 14).

Endothermic Fuels The cost of endothermic fuels can range from slightly above the current price of Jet A to greater than $100 per gallon for the more exotic specialty products. (See Figure 15.) Realistically, any endothermic fuel that could be considered practical for commercial aircraft must be producible as a byproduct from an existing petroleum refinery or as a primary product in a continuous chemical process. A fuel like methylcyclohexane can be produced using toluene as the raw material with small modifications to the process currently used to produced cyclohexane from benzene. The cost of methylcyclohexane will vary with the price of petroleum, which is the basic raw material. As with conventional jet fuel, the cost of many endothermic fuels will be very sensitive to demand for the finished product.

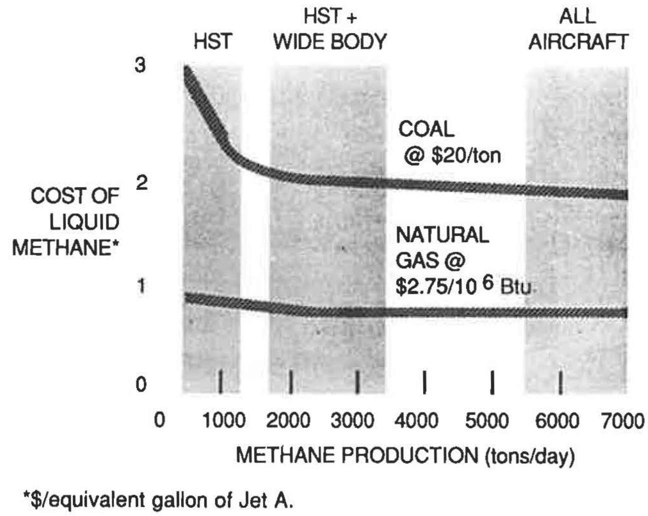


FIGURE 14. Effect of Production Volume on Cost of Liquid Methane

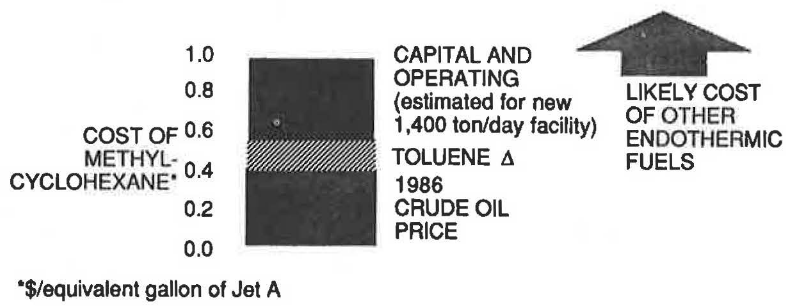


FIGURE 15. Relative Cost of Methylcyclohexane and Other Endothermic Fuels.

Cost Summary In terms of price, it is unlikely that any fuel dedicated for use only by supersonic or hypersonic transport could compete with the fuel used by conventional aircraft. This is particularly true for the current condition where kerosene-type aircraft fuels can be used for other applications in our society, and fluctuation in aircraft fuel demand can be satisfied by the flexibility built into the production (refining) industry (Figure 16).

Of the new fuels considered, none can be identified as preferable at this time. Special requirements of the aircraft must be balanced against basic fuel costs and the cost of new airport facilities. Considering just fuel cost, liquid methane has an edge over liquid hydrogen. Endothermic fuels have not been sufficiently evaluated to determine what fuel, if any, would be technically feasible. However, the cost of methylcyclohexane can be used to establish what is likely to be minimum cost for endothermic fuels.

Airports

Any nonconventional fuel will require a distribution and storage system that is independent and separate from the main airport fuel supply. This system can be

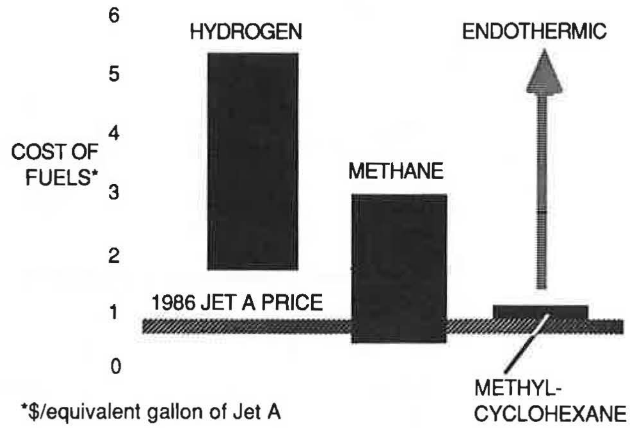


FIGURE 16. Relative Cost of Jet A, Hydrogen, Methane, Methylcyclohexane, and Endothermic Fuels

identical to the conventional fuel system or totally different in design and components. Most endothermic fuels are expected to require a relatively standard fuel system; the cryogens, liquid hydrogen and liquid methane, will require an entirely new and different system.

At any airport that requires hydrogen or methane for daily flights, gaseous hydrogen or methane would be delivered to the airport through a pipeline and liquefied at a facility located on or near airport property. Cryogenic fuels will require totally new fuel delivery, distribution and storage facilities, as well as extensive gate and terminal modifications. At many airports gaseous methane could be obtained from additions to or spurs from existing natural gas transmission systems; however, hydrogen would require a totally new distribution system from the gas production plant to the airport-located liquefaction facility. In all but the lowest demand cases, the liquefaction facility would be required to reliquefy gases vented from the aircraft loading operations and from the normal boiloff from the aircraft and the storage and distribution system.

The fuel distribution system must be insulated and will require vents and purging systems for the safe handling of both hydrogen and methane. Return vent gas lines must be provided to capture fuel vented from the aircraft and airport storage and distribution system. In most cases, this gas would be routed to the liquefaction facility; however, it can also be burned at a remote site.

Cryogen liquefaction facilities have little flexibility for adjusting to wide variations in aircraft fuel demand. The cryogen storage system must be sized to handle the peaks and valleys of traffic and airport shutdowns resulting from weather and adverse conditions. Airport personnel must be trained to handle the unique properties of the cryogens, and aircraft operations must allow for fuel tank and fuel system cooldown.

There always will be some heat leak to the liquid cryogen in the airport fuel delivery lines which will cause the bulk temperature of the liquid to increase.

This increase in temperature, and associated increase in cryogen saturation pressure, would result in rapid vaporization of the liquid in the aircraft fuel tanks during loading. The problem would be particularly severe during periods of low aircraft activity where liquid trapped in delivery lines would pick up an appreciable amount of heat. One solution would be to add a flash vaporizer at the aircraft connect point. This unit would subcool the cryogen by vaporization to a pressure at or lower than the vent setting of the aircraft fuel tank. A cryogen must be subcooled immediately prior to entering the aircraft tanks. This can be accomplished by a vaporizer mounted at the airport-aircraft fill interface.

Studies were carried out in 1975 for NASA to identify the costs required to convert airports for cryogenic fuels. These studies, updated by Boeing in 1986, indicate the costs would be very significant in terms of what airports spend today for fueling facilities. The studies addressed Chicago's O'Hare Airport as an example situation. O'Hare's entire operations converted for use of hydrogen would require 3,000 tons of hydrogen per day and would involve over $800 million in conversion costs (Figure 17). This does not include the cost of either a liquefaction or a reliquefaction plant. As indicated in Figure 17, the minimum cost for such a conversion on any airport would be about $200 million.

Cryogen-fueled aircraft would necessitate extensive modifications to ground support equipment and maintenance facilities (virtually an entirely new hardware system) from those presently in operation. Airports with daily high-speed aircraft service must have land available for liquefication and storage facilities. Depending upon the daily requirement, this could involve devoting between 10 and 35 acres for such facilities. This land many not be available at many existing airports, especially those located in urban areas. The use of long pipelines to transfer cryogens as liquids from remote storage areas would increase distribution losses and significantly add to final cost.

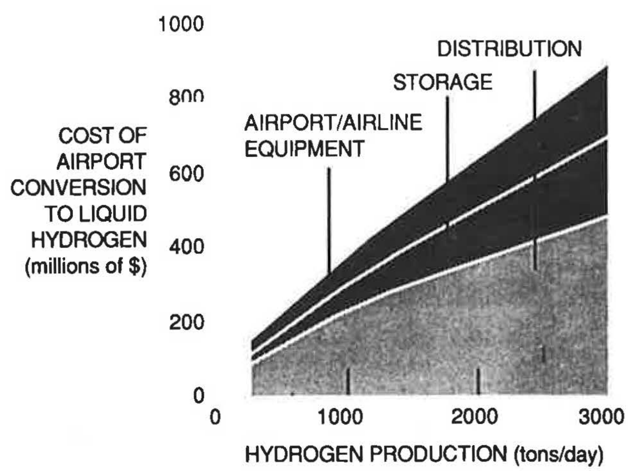


FIGURE 17. Cost of Airport Conversion to Liquid Hydrogen

The airport facilities required for most endothermic fuels will be essentially the same as for conventional fuels. However, some candidate fuels require the special provisions at airports, including a vapor scavenging and recovery system for highly volatile or toxic fuels and a refrigeration plant and insulated distribution system for fuels that require subcooling prior to loading.

Public acceptance of highly toxic fuels in commercial aircraft or at public airports is not likely. The selection of a fuel that requires significant subcooling prior to loading would most likely be a quick fix to a marginal commercial aircraft design. Both endothermic and conventional fuels may require some refrigeration to satisfy maximum temperature loading requirements in hot climates.

Aircraft

Neither the cryogenic nor the endothermic fuels can be handled by a conventional fuel system. Both will require the development of new technology or significant improvements in existing technology before a fuel system that satisfies realistic commercial aircraft requirements can be designed. The use of fuel as a refrigerant adds to the complexity of the aircraft.

Unlike conventionally fueled aircraft, duty cycle (the demand for fuel during taxi, takeoff, cruise, and descent) will play an import part in selecting the fuel and establishing fuel system concept feasibility.

If the fuel, either cryogenic or endothermic, is intended to be used as a coolant for the airplane, it must be pumped to a highpressure (approximately 1,000 psi) to avoid its going through a phase change when transferred around the airplane. If the aircraft body is to be cooled, as on military vehicles, the fuel must pass through a heat exchanger on the body. At higher Mach numbers, the aircraft nose might even have to be cooled. The fuel must also pass through several heat exchangers on the engine to cool it. As a result, the transfer of all the fuel around the total aircraft system becomes a very complex operation.

The fuel tanks of aircraft using cryogenic fuels must be insulated pressure vessels. Because of their large size, these tanks would have to be located in the fuselage instead of the wings to minimize boiloff losses. A larger fuselage would be required to accommodate the greater volume of cryogen necessary for payload and range performance equal to conventional or endothermic fuels. However, the gross weight of the aircraft using cryogenic fuels, particularly hydrogen, may be less than those using conventional fuels because of the greater energy content per unit weight.

The complex nature of the thermodynamic processes associated with the storage and use of cryogens in a commercial aircraft offers many challenges for the design of a fuel system. For the fuel system to behave in a stable manner, the fuel storage and pumping system must be designed as a unit. The amount of insulation must be sufficient to minimize vaporized fuel losses while satisfying the pressure inlet requirements of a pump that must deliver the fuel over a wide range of flow rates. The design of a cryogenic fuel system involves balancing the inlet requirements of the pump, the tank pressure, and the losses due to vaporized liquid.

No existing pumps satisfy commercial aircraft weight, life, cost, and delivery requirements. The pumping of cryogens in space vehicles is state-of-the-art. However, space vehicle flow rates vary over a relatively narrow range, pump life requirements are counted in seconds, and cost is a secondary consideration. In addition, the acceleration vector of a space vehicle is directed toward the pump inlet and increases as the fuel is used--thus the pump has at least some effective liquid head for subcooling. Pumps that satisfy weight, life, cost, and delivery requirements for commercial aircraft still require a significant extension of existing technology for both hydrogen and methane.

Another design challenge that must be met before either methane or hydrogen can be considered for commercial aircraft is the development of a workable insulation concept. Vacuum jackets would be too heavy or delicate, and currently available foam insulation cannot withstand the imposed temperature variations without unacceptable repair and inspection periods. Currently, it is not clear how much insulation is required. Too little insulation results in the venting (hence loss) of fuel -- particularly during the taxi phases of operation. Too much insulation can cause the tank pressure to drop to the saturation point of the liquid, which can cause unstable system operation or pump cavitation. In any case, the sizing of insulation must satisfy all mission phases -- taxi, ascent, cruise, and descent. (See Figure 18.)

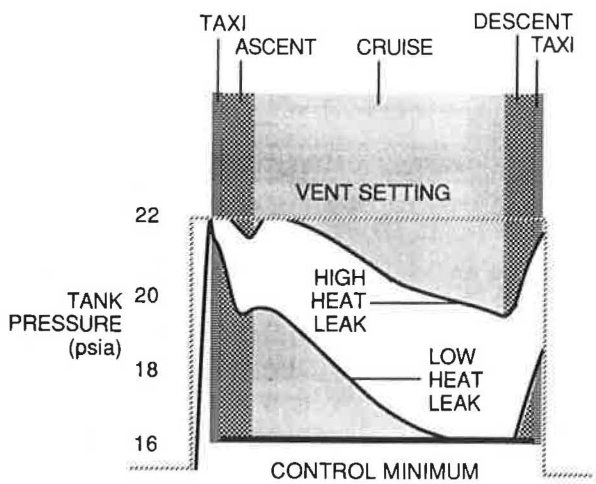


FIGURE 18. Aircraft Fuel Tank Insulation Considerations

A selling point for cryogenic fuels is their potential use for cooling aircraft engines and structure. Taking advantage of a significant percentage of this cooling capacity in a practical commercial aircraft may prove to be quite costly. Detailed design studies must be conducted before a practical and cost-effective percentage can be determined for use of the available cooling capacity. These studies must include heat exchangers and fuel delivery techniques that allow matching the engine duty cycle to cooling requirements.

Endothermic fuels can be handled more like conventional fuels than the cryogens; however, they will share some common problems. The endothermic fuels will require pumping to the engine operating pressure at the fuel tank and will have the same or a more severe problem of matching cooling to engine requirements. The matching problem could be more critical for endothermic fuels because they are reacted to products that differ from the stored fuel and most of the fuels require a three-stage process to take advantage of their maximum cooling capability.

It will be extremely difficult to match endothermic fuel cooling stages with aircraft engine fuel demand or aircraft cooling requirements. (See Figure 19.)

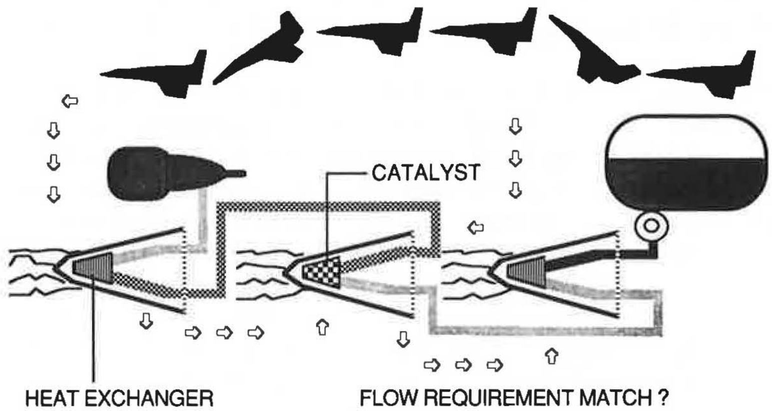


FIGURE 19. Matching Endothermic Fuel Cooling Stages with Engine Fuel Demand and Aircraft Cooling

It is currently not clear how the performance of engines designed for high-speed aircraft will be affected by a fuel composition that varies during the various phases of the mission. Also, it is not clear how to take advantage of the heat absorption capabilities of all three stages of the cooling processes.

Major advances in catalyst technology have been made since the time of endothermic fuel studies. These advances were the result of needs generated by the synthetic fuels industry and the government-forced demand for unleaded gasoline. The catalytic reforming processes used to improve octane by increasing the aromatic content gasoline are similar to the endothermic fuel processes proposed for aircraft. Prior to the latest advances in catalyst technology, catalyst life was identified as a major problem and it was suggested that the catalysts would require frequent replacement, which is an unsatisfactory requirement for commercial aircraft. New studies are required to determine the impact of newly developed technology on both the selection of an endothermic fuel and the manner in which it can be used in a practical aircraft cooling system.

Review

Technologies required to produce and use fuels and fuel systems being considered for supersonic and hypersonic aircraft are at various stages of development.

- Commercial processes for producing and liquefying hydrogen and methane are available now. Because a best-choice endothermic fuel has not been identified, process readiness is yet an unknown.

- The design of tank-to-engine aircraft fuel systems for cryogens is in the concept development stage. Design studies for systems that can use the cooling potential of cryogen fuels have recently been started. Advances in technology are required to further develop insulation and pumping systems that can meet commercial standards of reliability and maintainability.

- o Design studies for aircraft systems using endothermic fuels have not yet progressed to the point where feasibility can be established or requirements for new technology identified.

If the requirements of supersonic and hypersonic aircraft demand a unique fuel, the price will likely be higher than the price of conventional fuels for commercial aircraft The price penalty for the dedicated fuel will be riven by several factors. Among them:

- Basic processing costs
- Demand
- Risks considerations
- Local availability of resources
- Requirements for new airport and distribution system.

In addition to price factors, the selection of a fuel must be based on a study that balances realistic commercial aircraft duty cycles with specific fuel property benefits.