

NASA Technical Memorandum 80155

(NASA-TM-80155) COMPARISON OF ALTERNATE
FUELS FOR AIRCRAFT (NASA) 38 p
HC A03/MF A01

N79-32637

CSCL 21D

Unclas
G3/44 35816

COMPARISON OF ALTERNATE FUELS FOR AIRCRAFT

ROBERT D. WITCOFSKI

SEPTEMBER 1979

NASA

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665



COMPARISON OF ALTERNATE FUELS FOR AIRCRAFT

Robert D. Witcofski
Aerospace Technologist
Langley Research Center
National Aeronautics & Space Administration
Hampton, Virginia, USA

ABSTRACT

The results of efforts conducted for and by the Langley Research Center and industry form the basis for a comparison of candidate alternate fuels for aircraft. The fuels addressed include liquid hydrogen, liquid methane, and synthetic aviation kerosene. An assessment is made of the viability of each fuel from the standpoint of cost, capital requirement, and energy resource utilization, as influenced by fuel production, transmission, airport storage and distribution facilities, and use in aircraft. Technology deficient areas for cryogenic fuels, which should be advanced prior to the introduction of the fuels into the aviation industry, are identified, as are the cost and energy penalties associated with not achieving those advances. Environmental emissions and safety aspects of fuel selection are discussed. A detailed description of the various fuel production and liquefaction processes and of their efficiencies and economics is given in an appendix.

INTRODUCTION

Growing concerns over the depletion of naturally occurring crude oil resources in the United States, coupled with a growing United States dependence upon oil imported from other countries which themselves recognize oil production limitations in the foreseeable future, have prompted NASA to look at energy resources other than naturally occurring crude oil for the production of

aviation fuel. Oil shale and coal are the two largest remaining fossil fuel resources in the United States(1). Prior NASA studies(2) have determined that liquid hydrogen (LH₂), liquid methane (LCH₄) and synthetic aviation kerosene (referred herein as "Synjet") are the three most promising alternate fuels for future aviation. Coal can be used as an energy source for producing all three fuels and oil shale shows promise for production of Synjet.

This paper addresses many of the aspects which must be evaluated, over the long term, in selecting an alternate fuel(s) for aviation use, including the following: the efficiency with which the primary energy sources (coal or oil shale) are utilized, fuel price, capital requirements, the potential environmental impact associated with each fuel, and safety. Each fuel is examined from the standpoint of fuel production, transmission of the fuel to the airport, the ground facilities required at the airport, and the ultimate use of fuel in the aircraft. Technology-deficient areas associated with each fuel are identified, as well as technology advances which, if achieved, could significantly enhance the viability of each. The penalties associated with failure to achieve a required technology are also evaluated. A detailed description is provided in the appendix of: the complex fuel production and liquefaction processes and their by-products; and the methodology used in arriving at values of process efficiencies and economics.

PROCESS ABBREVIATIONS

K-T	Koppers-Totzek
S-I	Steam-Iron (continuous process)
PAR. OX.	Partial Oxidation
ELECT.	Water Electrolysis
C.S.F.	Consol Synthetic Fuel
D.S.	Donor Solvent
S.S.	SASOL Synthesis
S.R.	Surface Retort

PRODUCTION EFFICIENCIES AND ECONOMICS

Thermal Efficiencies

In order to use our natural energy resources in the most efficient manner, one figure of merit that may be used is the thermal efficiency of the fuel production processes. Thermal efficiency is defined herein (unless otherwise noted)

as the lower heating value of all energy products coming out of a fuel production process, divided by the lower heating value of all the energy going into the process.

Fuel production thermal efficiencies have been developed for twelve processes, using production process information (3-5) and an unpublished Boeing study. The results for all twelve processes are presented in bar graph form in figure 1 to provide an overview of the relative thermal efficiencies of the three fuels. The thermal efficiency data, in tabular form, (including a breakout of synthetic crude oil, gaseous hydrogen and methane), are given in table 1. All of the fuel production processes reported in the Boeing study either are, or are very near to being, commercially available processes, whereas those reference 3 vary as to development status. Descriptions of the processes and thermal efficiency calculations are contained in the appendix.

The advanced technology, continuous Steam-Iron process has, by far, the highest thermal efficiency of the LH₂ processes, 42 to 60 percent whereas water electrolysis has the lowest thermal efficiency by a substantial amount. For liquid hydrogen, the shaded portions of the LH₂ bars represent incremental improvements in thermal efficiency (about 5 percentage points) which may be obtainable through the development of advanced hydrogen liquefaction technologies which have been identified. Koppers-Totzek, a commercially available process, U-GASTM, an advanced technology process, and the Partial Oxidation process have thermal efficiencies which range from 30 to 40 percent.

For liquid methane, the advanced technology production processes, HYGAS[®] and CO₂-Acceptor are being developed to have relatively high thermal efficiencies compared to the Partial Oxidation process. HYGAS[®] has the highest thermal efficiency of all (63 percent), followed closely by the CO₂ Acceptor process. The Partial Oxidation process has a thermal efficiency considerably lower, but is an essentially commercially available process.

The Synjet production processes reported herein would produce a synthetic jet fuel having the same properties as current commercial aviation kerosene (Jet-A). All Synjet processes range from 46 to 56 percent in thermal efficiency, with Synjet from oil shale having a slightly higher thermal efficiency. For oil shale, a surface retort process was used in lieu of an in situ process. For coal-derived Synjet, the SASOL Synthesis type process (similar to that currently employed in South Africa) and the Consol Synthetic Fuel process each

had a thermal efficiency of 54 percent while the Donor Solvent process had a thermal efficiency of 46 percent.

Of the processes that are or near a commercially available status, thermal efficiency is the highest for Synjet, followed closely by liquid methane, with liquid hydrogen being the lowest. When advanced processes are considered, substantial improvements in thermal efficiency are potentially obtainable for both LH₂ and LCH₄, with LCH₄ having the greatest potential.

Production Prices

The prices of synthetic fuels associated with each production process identified in figure 1 are shown in figure 2 in bargraph form and reflect the price as delivered to the aircraft. Tables 2 and 3 present the price data in tabular form and include a breakout of all pricing elements (e.g. fuel, production, pipeline). A detailed description of the methods and assumptions employed in deriving fuel prices for table 2 is given in the appendix.

For liquid hydrogen, lower prices are indicated for the advanced technology U-GASTM and continuous Steam-Iron processes, than for the commercially available Koppers-Totzek process. It is not clear at present why the price of the essentially commercially available Partial Oxidation process, from the Boeing study, is as low as the advanced technology processes, but this may be attributed to the two studies being completely independent and utilizing different data bases. The LH₂ prices are seen to range from about \$12.00 to \$20.00/GJ, depending upon the process and technology assumed. Hydrogen liquefaction accounts for \$6.17/GJ of the total LH₂ price. The manufacture of heavy water⁽⁶⁾ during the liquefaction process, and its subsequent sale at \$220/kg was found to be an effective means of lowering (by \$1.62/GJ) the hydrogen liquefaction price.

For liquid methane, the prices for the two processes are nearly equal and range from about \$8.00 to \$9.00/GJ.

For coal-derived Synjet, prices range from about \$6.50 to \$9.00/GJ, with the SASOL Synthesis process being the least expensive. Synjet from oil shale is seen to be the least expensive (\$6.20/GJ) of all alternate fuels and is about equal in price to Jet-A selling for \$0.75 per U.S. gallon.

Capital Requirements

The capital requirements of the systems required to manufacture, transport, and store LH₂, LCH₄, and Synjet at a major airport are shown in bar graph form on figure 3. The data were taken from the Boeing study which assumed that fuel requirements for the airport were 325 TJ per day, a value of comparable to current fuel requirements for all aircraft at the Chicago-O'Hare International Airport. The total capital requirements are shown for six processes, with the shaded portion of the bars representing that portion of the capital requirement which would be the responsibility of the manufacturer (energy company). Current practice is generally for the airport authority or air carrier's to purchase fuel delivered to the airport. The portion of the capital requirements representing the liquefaction and storage facilities at the airport is assumed to be the airports responsibility, and is shown by the nonshaded bottom portion of the bars. For Synjet, which may represent only 25 percent of the total fuel output of the manufacturing process, the solid portion of the bars represents the Synjet share of the total capital requirements, while the dashed line portion represents the non-Synjet share. Details of the capital requirements breakdown are given in the appendix.

The lowest capital requirements associated with the alternate fuels derived from coal would be 2849, 2509, and 2376 million dollars for LH₂, LCH₄, and Synjet, respectively. For LH₂ and LCH₄, the airport's share would be 1122 and 597 million dollars, respectively and negligible for Synjet. The lowest capital requirement is for Synjet from oil shale which would be 1669 million dollars.

USE OF SYNTHETIC FUELS IN AIRCRAFT

An important aspect of selecting an alternate aviation fuel is that of how well aircraft can utilize each fuel. Prime concerns are fuel consumption, and how fuel selection may impact the price paid by an airline passenger for a ticket. Three NASA-sponsored studies of LH₂ fueled subsonic transport aircraft have been conducted by Lockheed⁽⁷⁻⁹⁾, who is also currently conducting a NASA-sponsored study of LCH₄ fueled aircraft (Contract NAS1-15239). For the preliminary assessments reported herein, it is assumed that aircraft fueled with Synjet would have the same performance characteristics as those fueled with Jet-A fuel.

The initial Lockheed study determined that the aircraft should be configured to locate the very low density LH₂ fuel in large tanks within the fuselage both fore and aft of the passenger compartment. Such a configuration makes LH₂ particularly attractive from the standpoint of onboard energy consumption for long-range, high-payload combinations. The performance of a variety of range payload combinations have been investigated, with up to 18,000 km in range and up to 800 passengers in payload. The performance data in the early studies⁽⁷⁻⁸⁾ were subsequently found to require refinement resulting from better definition of the onboard LH₂ fuel system and the desirability to be more consistent with real world conditions in the values used for takeoff field length (increased to 3200 m) and for maximum approach speed (relaxed to 72 m/s). The refined performance data are reported⁽⁹⁾ for only one combination (400 passengers, 10,190 km). The ongoing Lockheed study, which is nearing completion, updates the performance information for the remaining combinations to provide comparison with LCH₄ aircraft configurations, on which the study is focussed.

The ongoing study of LCH₄ aircraft indicates fuselage-located fuel tanks to be preferred even though the greater density of LCH₄ results in a smaller fuel volume requirement than when LH₂ is used. Preliminary performance data from this study are included in the following assessment of onboard energy utilization.

Energy Consumption

The onboard energy consumption of LH₂ and LCH₄ fueled aircraft, relative to that of Jet-A fueled aircraft is shown in figure 4 as a function of aircraft design range. Onboard energy is defined herein as the heating value of the fuel required for the mission, and does not include the energy required to produce the fuels. The locations of the symbols indicate the design ranges investigated, and a comparable technology Synjet aircraft was defined at each range in order to make the comparison. Relative energy consumption is defined herein as the onboard energy required by the LH₂ or LCH₄ fueled aircraft, divided by the onboard energy required by the Synjet fueled counterpart aircraft. Those aircraft whose design ranges exceed 18,000 km actually represent aircraft with the capability of flying 9260 km and returning without refueling. LCH₄ fueled aircraft show no onboard energy savings over Synjet fueled aircraft but the LH₂ fueled aircraft consume from 2 to 33 percent less energy, with energy saving increasing with range.

The relative efficiency with which the prime energy resource (coal and/or oil shale) can be converted to LH₂, LCH₄ or Synjet, and utilized by the aircraft is depicted in figure 5 as a function of aircraft design range. Relative resource utilization is defined herein as the total energy (including that of the coal or oil shale used in fuel production) required by the LH₂ and LCH₄ fueled aircraft, divided by the total energy (including the coal or oil shale used in fuel production) required by the Synjet fueled counterpart aircraft. Two curves are shown for both LH₂ and LCH₄. The upper and lower LH₂ and LCH₄ curves reflect the lowest and highest values of fuel production thermal efficiency reported herein for LH₂, LCH₄, and Synjet. Not included is the value for hydrogen produced by water electrolysis. The band of uncertainty (between the curves) is relatively narrow for LCH₄ but relatively broad for LH₂, which makes difficult any meaningful comparisons for hydrogen. LCH₄ fueled aircraft would appear to be moderately (0-15 percent) energy conservative throughout the aircraft design range. If the higher fuel-production thermal efficiencies can be achieved for hydrogen, LH₂ fueled aircraft would utilize from 10 to 20 percent less energy resources than would Synjet fueled aircraft for design ranges typical of those of present aircraft.

Fuel Price Effects

The passenger ticket price is affected by fuel price. Figure 6 presents mission fuel price (based on the most optimistic fuel price of figure 2) for the three alternate fuels. The mission fuel price for both cryogenic fuels is greater at all ranges than for Synjet. The fuel price per seat for a 2800 km flight would be \$21.50 for LH₂, \$15.50 for LCH₄, and \$11.80 for Synjet. Assuming that all other elements entering into ticket price are unaffected by the type of fuels, the passenger would pay about \$10.00 more on the LH₂ fueled aircraft than on the Synjet fueled aircraft and about \$4.00 more on the LCH₄ fueled aircraft. For a 10,000 km flight, the ticket price differential would increase to about \$30.00 and \$16.00, respectively.

Airport Fuel Facilities

Consideration of airport facilities for alternate fuels is limited to LH₂ and LCH₄ since Synjet can use existing facilities without modification. For the two cryogenic fuels, NASA-supported studies were carried out several years ago for LH₂ and similar studies are presently underway for LCH₄ (with only preliminary information available).

In dual studies of the requirements for LH₂ fueled aircraft at the airport^(10,11), it was determined technically feasible to modify two major airports (O'Hare International in Chicago, and San Francisco International) for LH₂ fuel use, and that generally, technical problems lent themselves to straightforward engineering solutions.

A schematic view of the LH₂ fuel facilities envisioned at the airport is shown in figure 7. Gaseous hydrogen is delivered to the airport via pipeline and thence to a liquefaction plant, where the hydrogen is liquefied and stored in large cryogenic vessels. The LH₂ is pumped through vacuum-jacketed pipelines and is continuously circulated around the perimeter of the air terminal and returned to the storage vessels, with two LH₂ lines for redundancy. About 15 percent of the LH₂ placed in the aircraft will evolve as hydrogen vapor, as a result of tank cool-down, resaturation of the LH₂ in the aircraft fuel tank, boil off prior to fueling, and displaced ullage gas. The studies showed that it is desirable, from the standpoints of cost and energy conservation, to collect the cold hydrogen vapors and to reliquefy them. Hydrogen vapor created by boil-off in the storage vessels is also reliquefied. The distribution and collection lines are located either in open trenches or in positively ventilated tunnels, the construction of which would not interrupt airport operations. The ground systems defined in the airport studies are completely enclosed and permit essentially no hydrogen to escape.

Figure 8 illustrates in more detail a process at each refueling hydrant. Each airline is provided with an appropriate number of fueling hydrants. A hydrant truck is used to connect the hydrant to the aircraft. Two lines are connected to the aircraft, one for delivering the LH₂ fuel to the aircraft and one for returning the cold hydrogen vapors for reliquefaction. It was determined that turnaround times (including fueling) for LH₂ fueled aircraft are consistent with those of Jet-A fueled aircraft. The most economical and energy efficient method for handling the cold vapors would be a system which uses conventional equipment and represents no particular technical or operating difficulties⁽¹²⁾.

The ground systems evolving from the LCH₄ aircraft systems study currently being conducted by Lockheed, are quite similar to those defined for LH₂. Both the size and cost of storage and distribution facilities will be less than for LH₂.

ENVIRONMENTAL CONSIDERATIONS

Combustion products and emissions resulting both from use of the three candidate fuels in aircraft engines, and from the production of the fuels from coal, oil shale, or other prime energy sources, are potentially important environmental factors which warrant consideration.

Carbon-based emissions from LCH₄ fueled engines will be less than those from engines fueled with Synjet, whereas LH₂ fueled engines would have none. All fuels will produce oxides of nitrogen (NO_x) but lean burning⁽¹³⁾ offers the potential for drastic reduction in NO_x emissions from LH₂ fueled engines. Water vapor emissions from LH₂ and LCH₄ fueled engines will be approximately 100 and 40 percent greater, respectively, than that of Synjet fueled engines. The environmental effects of such an increase in water vapor emissions remains a moot question.

The total amount of CO₂ which is ultimately deposited in the atmosphere, by both engines and fuel production plants, is, for fuels derived from carbon sources, roughly inversely proportional to the thermal efficiency with which the fuels are produced. This stems from the fact that virtually all the carbon in the prime energy source eventually ends up in the form of CO₂. Because oil refineries operate at thermal efficiencies on the order of 95 percent, compared to about 50 percent for alternate fuel plants, the total CO₂ emissions from alternate fuels from coal or oil shale will be on the order of twice those from fuels produced from crude oil. Should practical means be found for utilizing or disposing of CO₂, LH₂ appears attractive since all of the CO₂ is formed during production, and could be readily captured.

LH₂ can, of course, be produced via water electrolysis, utilizing nuclear fission power or possibly future fusion power, thus avoiding any CO₂ production.

The importance of CO₂ emissions in fuel and process selection must await the findings of further investigations into the question of the Earth's CO₂ balance.

TECHNOLOGY DEFICIENCIES AND OPPORTUNITIES

The following discussion addresses some of the technology deficiencies and opportunities associated with alternate fuel production and cryofueled aircraft.

Fuel Production

The potentially least expensive and most thermally efficient process for generating hydrogen identified herein is the continuous Steam-Iron process. This technique has been employed in "batch" type operations. Extending the technique to a continuous flow process requires generation of new technology which has been addressed by the Institute of Gas Technology in Chicago, Illinois. Recently, they operated a small pilot plant continuously for a 10-12 day time period and considerable encouraging information was obtained. There is much more to be learned, however, before the technology will be sufficient for full-size plant design and operation.

Hydrogen liquefaction has been shown to be both a costly and energy-consuming process; however, potential reductions in both cost and energy have been identified. Potential liquefaction price reductions on the order of eighteen percent have been identified, with five percent achievable through the substitution of centrifugal compressors for the piston compressors used in the hydrogen recycling section of the liquefier. Most of the remaining thirteen percent is associated with only partial ortho-to-para conversion of the hydrogen during liquefaction, and potential improvements in compressor and turbine efficiencies. Potential reductions in liquefaction energy requirements on the order of twenty-five percent have been identified, and are tied to partial ortho-to-para conversion, improved compressor and turbine efficiencies, and reduction of leaks.

In the production of methane, major opportunities lie in potential improvements in thermal efficiency through the development of advanced technology gas production processes. Present information indicates little difference in methane price between the current process and the advanced processes; however, the price of methane from the more thermally efficient processes will be less sensitive to increases in coal price.

Cryofueled Aircraft

Two prime technology-deficient areas identified for LH₂ fueled aircraft are fuel pumps and cryoinsulation for the fuel tanks. Both must be reliable, flight weight, and long lived.

Pumps: A technology deficiency exists for LH₂ pumps. The problem lies with high pump speeds (50,000 to 80,000 rpm), and ineffectiveness of LH₂ as a pump

lubricant. While LH₂ pumps for space craft have design lives on the order of ten hours, most aircraft equipment entering airline service for the first time has a minimal overall life expectancy of 1000 hours with good reliability. Prior experience indicates very significant problems when ball bearings are used in LH₂ pumps, and suggests use of other bearing types. Compliant foil bearings, currently used as air bearings in the environmental support systems of some aircraft, have exhibited lives many times that of conventional bearings. A NASA-sponsored effort (contract NAS1-15807) to assess the feasibility of compliant foil bearing for application to LH₂ pumps for aircraft is currently underway.

Liquid methane's order of magnitude higher viscosity, and the relative success already achieved in LCH₄ pump development ⁽¹⁴⁾ indicate that the technology requirements for satisfactory LCH₄ pumps will be less than for LH₂.

Insulation: The LH₂ aircraft fuel system study⁽⁹⁾, after screening some fifteen candidate fuel tank insulation systems, identified four systems as being superior. Two of these concepts were basically closed cell foam systems, and the other two were vacuum insulation systems. A difference of only three and four percent in direct operating cost and fuel consumption, respectively, existed between the four systems. Because the vacuum systems may have somewhat unforgiving features should the vacuum be lost, the use of closed-cell foam may be a more reliable approach. Permeation of air into foam insulations poses a potential problem in that selective liquefaction of the constituents of air causes excessive cryopumping, eventually adds mass to the system, and could cause the insulation to pop off when the aircraft is taken out of service and the tank is allowed to warm up. Development of gas permeation barriers may be required for foam insulation systems.

NASA-sponsored experimental studies⁽¹⁵⁾ subjected 13 foams to the equivalent of 4400 flight cycles (exterior temperatures cycled between 316K to simulate ground hold, and 266K to simulate cruise altitude), 990 aircraft refuelings, and thirteen tank warmups (inspection and maintenance simulation). The results were encouraging in that two of the foams endured the cycles while providing good thermal performance. The foam specimens tested were flat specimens and no attempt was made to simulate the effects of penetrations such as fuel lines or tank support struts. Further testing is required to ascertain the viability of foam insulations for practical application to LH₂ fuel tanks.

Cryoinsulation for LCH₄ fuel tanks poses much fewer problems than does LH₂. The combined effects of higher temperature, higher heat of vaporization, lower gas thermal conductivity and specific volume, and lower tank surface area for LCH₄ greatly reduce the insulation requirements. In addition, the higher temperature of LCH₄ precludes the selective liquefaction of the nitrogen and oxygen of any air which might permeate the insulation.

Engines: As stated in reference 16, much of the technology required to utilize LH₂ in commercial transport aircraft engines either exists or appears possible to be generated through straightforward developmental programs. There are, however, opportunities for increasing the performance of LH₂ fueled engines by taking advantage of the cooling capacity and combustion characteristics of LH₂. Preliminary studies⁽⁹⁾ indicate about a five percent decrease in specific fuel consumption may be possible by utilizing LH₂ to cool the turbine cooling air and by heating the fuel with the engine exhaust gas. These and other potential engine performance benefits warrant further study.

SAFETY

Safety is of prime importance in considering the use of any new fuel for aircraft. Replacement of gasoline with Jet-A fuel (kerosene) decreased aircraft fire hazards. A great deal of safety related information exists for Jet-A fuel, and efforts to improve its safety aspects continue. Any fuel which decreases safety from the present level faces an uphill battle in achieving acceptability. Of the three alternate fuels, only Synjet has well defined safety characteristics since its properties essentially match those of Jet-A. The safety of both of the cryofuels is poorly defined for aircraft and needs examination in each of three areas: fuel spills occurring at the airport; system failures onboard the aircraft; and post-crash aircraft fires.

Fuel Spills

Fuel spills occurring due to accidents or unplanned incidents at the airport can release great quantities of fuel. For LH₂ and LCH₄, detailed knowledge is required of the physical behavior of the fuel following its release. One important factor is the buoyancy or nonbuoyancy of the ensuing vapor cloud which critically influences the hazard time and area affected by cloud drift. More is known about LCH₄ than LH₂, since it is essentially liquified natural gas (LNG) which is being transported, stored and used throughout the world. Following a spill, it is known to form a nonbuoyant cloud, but the physical

characteristics and behavior of the cloud as it spreads and mixes with the air require better definition. Toward this end, the United States Department of Energy is generating such information relative to the safety aspects of LNG(17).

For LH₂, no quantitative large-scale post-spill behavior data are available. Qualitative observations following LH₂ spills have been conflicting, with at least partial evidence of neutral buoyancy of the vapor cloud existing for a period of time. A NASA effort has recently been initiated to define the hazards associated with large ground-based spills of LH₂. These studies include vapor cloud behavior prior to ignition, and detonation and deflagration phenomena of the cloud should it ignite. A key experiment is planned utilizing spills up to 5.7 m³ of LH₂, in which time-history measurements of vapor cloud concentration and temperatures will be made to provide data for the formulation and verification of vapor cloud dispersion models capable of handling cloud buoyancy effects. The experiments are to be carried out early in calendar year 1986.

Onboard Fuel System Malfunctions

Uncertainties arise regarding potential fuel problems onboard aircraft when the fuel is stored within the fuselage. The storage of fuel within the wing, normally employed for transport aircraft, is not practical for LH₂ because of the large fuel volume (four times that of Jet-A for a given energy content), and the sizable volume of tank insulation required. Studies indicate that use of external wing tanks would seriously degrade LH₂ aircraft performance (32 percent more fuel burned) as compared to aircraft with fuselage tanks. LCH₄, while having much less volume for a given energy content than LH₂, also requires at least some fuselage fuel storage. Lines, valves, and other equipment would necessarily be located within the fuselage and extend the length of the passenger compartment when both fore and aft tanks are utilized. The lines and equipment operate at cryotemperatures and must be insulated. Little is known about the long term operational problems and reliability of such configurations.

Planning has been initiated by the NASA Lewis Research Center for studies related to the safety aspects of onboard fuel system malfunctions for LH₂ and LCH₄.

Post-Crash Fires

The degree of hazards accompanying post-crash fires of aircraft are critically dependent on the time history of combustion and associated physical properties of the products of combustion. Thus the likelihood, manner and severity of fuel system rupture is of prime concern. For LH₂ and LCH₄ aircraft, the location of fuel tanks and other system components within the fuselage introduces additional considerations. The post-crash behavior of transport aircraft fuselages is not considered to be defined in sufficient detail, backed by accident statistics, to carry out meaningful hazard analyses of such fuel systems.

The mixing of spilled fuel with air, and subsequent combustion will likely be considerably different for LH₂ and LCH₄ than for Synjet because of differences in factors such as fuel temperature, mixing rate, and buoyancy. The unpublished Boeing study, referred to earlier, considered these factors. Tentative conclusions were as follows: loss of life, injury and damage resulting from aircraft crash may well be less with LH₂ than with Jet-A, also, loss of life, injury and damage resulting from aircraft crash may be greater with LCH₄ than with LH₂.

The NASA Lewis Research Center is also initiating studies to address the hazards associated with post-crash fires of cryofuels.

CONCLUDING REMARKS

Liquid hydrogen (LH₂), liquid methane (LCH₄), and synthetic aviation kerosene (synjet) have been evaluated and compared as potential alternate fuels for commercial aviation. The evaluation, based upon information derived from both government and industry studies, indicates all three fuels to be technically viable.

Synjet is considered to be the most attractive alternate fuel for near term use. Current technology makes possible its production with the most efficient use of coal or oil shale resources and at the lowest prices (about \$0.75 per U.S. gallon for Synjet from oil shale). The capital requirements for its production and transportation to the airport would also be the least, if the production capital requirements are prorated according to the Synjet fraction (about 25 percent) of the total energy products manufactured. The capital requirements would amount to 1581, 1727 and 1927 million dollars for Synjet,

hydrogen and methane, respectively, sufficient to supply the 325 terrajoules of energy per day required for the Chicago O'Hare Airport. Since it can be produced with properties identical to Jet-A fuel, it can be used in present day aircraft with no modification to the aircraft or to the airport fuel storage and distribution system.

With regard to cryogenic fuels, the technology state of the art is considerably behind that for Synjet. Identified advanced technology production processes for methane and hydrogen require further development to reach their potential which could result in savings of 10 to 20 percent over Synjet in energy resource utilization. Liquefaction and storage of the cryogenic fuels are also required with additional facilities needed at the airport (which for the Chicago O'Hare Airport would amount to 1122 and 597 million dollars for liquid hydrogen and liquid methane respectively). New aircraft, designed specifically for the cryogenic fuels, will be required in fleet operations to accommodate the much greater tankage volume (less energy per unit volume for cryofuels plus cryoinsulation on the outside of the tanks). Technology deficiencies exist for cryoinsulation and cryopumps. Also the safety aspects associated with the use of cryofuels are poorly understood at best.

Of the two cryofuels, liquid hydrogen promises advantages through: less aircraft onboard energy consumption (up to 20 percent for long range flights) and energy resource utilization; and less environmental emissions and combustion products.

By the same token, liquid methane promises advantages over liquid hydrogen through: better fuel production thermal efficiencies; a 35 percent lower fuel price; slightly lower capital requirements; a somewhat lower passenger ticket price (\$4 more than Synjet for a 2800 km trip versus \$10 more for liquid hydrogen); and considerably less severe problems in aircraft cryoinsulation and cryopumps.

The overriding factors which make Synjet the most attractive alternate fuel for near term use are its superior production economics and efficiencies. New technologies for producing the cryofuels may change this picture in the future, but the development of such technologies is not generally considered to be in the province of NASA. Should a decision be made to pursue a near-term cryofueled aircraft flight demonstration program, liquid hydrogen would appear to be a logical choice, since solutions to the aircraft-related

problems for liquid hydrogen would, in general, provide solutions for those of liquid methane. The technical problem areas identified for cryofueled aircraft and for safety are being addressed by NASA at a deliberate research pace. This pace would have to be increased substantially if commitment were made to support a program of cryofueled transport aircraft development, system demonstration and operation.

APPENDIX

This appendix provides a more detailed description of the various alternate fuel production and liquefaction processes and of the methodology and assumptions used in arriving at values of fuel production efficiency, and the economies of fuel production, liquefaction, storage, and distribution.

Fuel Production Processes

Gaseous hydrogen: Of the three hydrogen production processes investigated, only the continuous Steam-Iron process was specifically developed for hydrogen production. The other two processes, Koppers-Totzek and U-GASTM, although not developed specifically for the production of hydrogen, lend themselves quite readily to its production. Koppers-Totzek is a commercially available process, and the U-GASTM and continuous Steam-Iron processes have reached the pilot plant stage of development.

For the continuous Steam-Iron process, hydrogen is generated by reacting iron oxide (ferrous oxide, FeO) with steam and decomposing the steam to produce H₂ and ferrosiferrous oxide (Fe₃O₄). The H₂ is removed and the Fe₃O₄ is sent to a reductor where it reacts with a producer gas. The CO and H₂ in the producer gas react with the Fe₃O₄ to produce CO₂, H₂O, and the FeO required for reuse. The producer gas is supplied to the reductor by a gasifier which is in turn fed by coal, steam, and air. Because hydrogen is not derived from the producer gas, air can be used in the gasifier in place of oxygen; and nitrogen cannot contaminate the hydrogen because of the iron oxide barrier. The spent producer gas, having reduced the Fe₃O₄ to FeO still contains some CO and H₂ and can be burned to produce a large amount of electricity as a by-product.

The Koppers-Totzek Process has been a commercially available process for about 25 years. The gasification occurs at a slightly positive pressure and at a temperature of 2089k, producing a gas whose composition is about 27 molecular

percent H₂ and 51 molecular percent CO. The steps which follow the primary gasification are basically a water-gas shift where CO is combined with steam to produce more H₂, and a methanation step (a process whereby the remaining CO is reacted with H₂ to produce CH₄). For the case of hydrogen production, the methanation is merely a cleanup step to get rid of the excess CO.

The U-GASTM process is typical of newer coal gasification processes which are being developed to produce synthetic natural gas. The gasification occurs at a pressure of 2413 kPa and at a temperature of 1311K, producing a gas whose composition is 31 molecular percent H₂ and 43 molecular percent CO. Again, the steps which follow the primary gasification are a water-gas shift to produce more H₂, and a methanation step for cleanup of the remaining CO.

Gaseous methane: The two methane production processes investigated were the HYGAS[®] and CO₂-Acceptor processes, both of which are representative of advanced technology processes for producing synthetic natural gas (which is mostly CH₄). These processes have both reached the pilot plant stage of development.

In the HYGAS[®] process, two reaction zones are stacked on top of a gasifier. The producer gas from the gasifier rises up through the upper zones and the H₂ from the gas reacts with the coal to produce CH₄. About half of the CH₄ produced by the HYGAS[®] process is produced in the gasifier/reaction vessel, while the other half is produced by methanation of the remaining effluents of the gasifier/reaction vessel.

The CO₂-Acceptor process uses no oxygen. The heat required to drive the reaction of steam with coal is provided by the highly exothermic reaction of CO₂ with dolomite (MgO-CaO), which is showered into the gasifier. Part of the CO₂ is supplied by the reaction of the steam with the coal and the rest is supplied by a separate regenerator vessel where CO₂ is driven out of the spent dolomite by heat. About 37 percent of the CH₄ is formed in the gasifier and the remainder by methanation of the remaining gasifier effluents. No CO shift is required.

Synjet: In the analysis of coal-derived Synjet, it was assumed that the feedstock used for the production of the Synjet would be produced by the Consol Synthetic Fuel (CSF) process. The CSF process is representative of the "extraction" type processes in which coal is dissolved by being mixed with a liquid solvent. Hydrogen is transferred to the dissolved coal either by

introducing hydrogen gas into the mixing process or by prehydrogenating the solvent, after which the solvent acts as a hydrogen donor during the mixing process. The required hydrogen is produced by the gasification of char (devolatilized coal) with steam and oxygen. The effluent from the CSF reactor yields a variety of hydrogenated gases and liquids, plus the solvent itself, which is then rehydrogenated and recycled to the reactor. The heavy oil liquid product of the CSF process is hydroprocessed to produce Synjet. The hydrogen for hydroprocessing is manufactured from 65 percent of the high Btu gas product of the CSF process. High Btu gas, naphtha, sulfur, and ammonia are credited as by-products.

Fuel Production Thermal Efficiencies

Thermal efficiency¹ is defined herein (unless otherwise stated) as the lower heating value of all energy products coming out of a process, divided by the lower heating value of all the energy going into the process. Data⁽³⁾ were modified to reflect the lower heating values of the fuels since the latent heat of vaporization of water in the combustion products is not recovered in the actual combustion process in an aircraft powerplant. All calculations were done in engineering units and later changed to the International System of Units. The thermal efficiencies derived from the fuel production studies⁽³⁻⁵⁾ are listed in table 1. In the case of hydrogen and methane, thermal efficiencies are listed for production of fuels in both their gaseous and liquid forms. In the case of Synjet, thermal efficiencies are shown for the production of synthetic crude oil (Syn crude) and Synjet.

Gaseous hydrogen and methane: Two thermal efficiency values are shown in table 1 for the production of gaseous hydrogen produced via the Steam-Iron process (58 and 75), and for gaseous methane produced via the CO₂-Acceptor process (63 and 66). A by-product of the Steam-Iron process⁽³⁾ is a low Btu gas known as "spent producer gas." The spent producer gas is available at a pressure of 2515 kN/m² and a temperature of 1100K, and its lower heating value plus sensible heat correspond to approximately 50 percent of the lower heating value of the coal input to the process. Systems studies⁽³⁾ determined the spent producer gas could be best utilized by burning it with compressed air in a combustor, followed by an expansion through gas turbines to produce electricity and shaft power for air compression. The expanded gas is then used in a steam-power cycle to generate steam and more electricity. After all plant energy requirements have been fulfilled, a large electrical power by-product still remains. Depending upon whether the remaining electrical power or the

spent producer gas (heating value plus sensible heat) utilized in its generation is credited as a by-product, the thermal efficiency of producing gaseous hydrogen is 58 percent or 75 percent. A somewhat similar situation existed in the case of the CO₂-Acceptor process when a by-product low Btu gas at elevated temperature and pressure is converted to by-product electrical power. Depending upon whether the by-product electrical power or the gas (heating value plus sensible heat) utilized in its generation is credited as a by-product, the thermal efficiency of producing gaseous methane via the CO₂-Acceptor process is 63 percent or 66 percent.

LH₂ (Koppers-Totzek and U-GASTM): Four thermal efficiencies are listed for both the Koppers-Totzek and U-GASTM processes for producing LH₂, two of which assume current hydrogen liquefaction technology (30, 35 & 33, 35), and two of which assume advanced liquefaction technology (34, 40 & 38, 40). The two thermal efficiencies listed for each liquefaction technology relate to the manner in which a by-product ("tail gas") of the liquefaction process is credited, and the manner in which electrical power for the liquefaction process is generated. The first stage of the liquefier consists of a purification unit whose purpose is to purify the hydrogen to liquefaction-grade quality to permit cooling to the hydrogen liquefaction temperature without plugging the equipment with freeze-out. Impurity levels in the order of one part per million total content of nonhydrogen species are typical for this purpose. The impurities in the hydrogen feedstock emerge from the purifier in a product called "tail gas." The heating value and constituents of the tail gas depend upon the composition of the hydrogen feedstock. The combustibles in the tail gas consist of the CH₄, and CO present in the feedstock, plus, in the case of the purification process⁽⁴⁾, a volume of hydrogen equal to 45 percent of the total volume of the tail gas. The heating value of the tail gas can be as much as 20 percent of the heating value of the liquid hydrogen product.

The lower value of thermal efficiency listed for each liquefaction technology represent the on-site conversion of the tail gas to electrical power (assuming a 40 percent conversion efficiency) to supply part of the liquefaction energy requirements. It is assumed herein that the balance of the electrical power for liquefaction is supplied by off-site generation at 40 percent efficiency. The higher values of thermal efficiency listed for each liquefaction technology represent total off-site electrical power generation at 40 percent efficiency, and the crediting of the heating value of the tail gas as a by-product. Although the generation of electrical power at an efficiency

of 40 percent exceeds that which is currently obtained in practice, achievement of such an efficiency appears relatively close at hand (18). Total off-site electrical power generation is probably a more reasonable approach because the construction of an electric generating plant within the confines of an airport would require land area for the plant site, and land area is a prime concern of many airports. In addition, the operation of an electrical generating plant at the airport would add additional complexities to the total airport system.

LH₂ (Steam-Iron).- The thermal efficiencies listed in table 1 for LH₂ produced by the Steam-Iron process require further explanation. As mentioned previously, a spent producer gas evolves as a by-product from the Steam-Iron process. Because of the very low heating value of the spent producer gas (1.92 MJ/m³ and 3.2 MJ/m³ including sensible heat), it is somewhat impracticable to transport the gas to a potential off-site user, and thus credit it as a by-product. However, because the gas emerges at an elevated temperature and pressure, considerable electrical power could be generated at the gaseous hydrogen production site as described previously. The electrical power generation potential is approximately twice that required to liquify the hydrogen.

There are a variety of bookkeeping methods which can be utilized in calculating the thermal efficiency of LH₂ produced via the Steam-Iron process. Four such methods and the resulting calculated thermal efficiencies are shown in table A-1, for both current and advanced liquefaction technologies. In method (A), it is assumed that an appropriate amount of electrical power from the power recovery section of the Steam-Iron process is transmitted (with no line losses assumed) to the point of liquefaction, and that the electrical power in excess of that required for liquefaction is credited as a by-product. The tail gas from the liquefaction process is credited as also a by-product. Method (B) is the same as method (A) except the excess electrical power is credited as a by-product and is expressed as the heating value plus the sensible heat of the portion of the spent producer gas which is used to produce the excess power. This method does not amount to double bookkeeping, since the only reason the spent producer used to produce the excess power is not transmitted out of the plant as a by-product is that its sensible heat (which is of value in the electrical generation process) would be lost in transmission, and that the low heating value of the gas makes it somewhat impracticable to transmit over significant distances. In method (C), it is assumed that electrical power for hydrogen liquefaction is generated off-site at 40 percent efficiency. The spent producer gas is converted to electrical

power, all of which is credited as a by-product. The tail gas is also credited as a by-product. Method (D) is the same as method (C) except the electrical power by-product is credited as the heating value plus the sensible heat of spent producer gas used to produce the electrical power. The calculated thermal efficiencies for LH₂ produced via the Steam-Iron process are seen to range from 42 to 55 percent for current liquefaction technology, and from 47 to 60 percent for advanced liquefaction technology.

LCH₄.- It has been assumed herein that 10.6 percent of the gaseous methane from the HYGAS[®] and CO₂-Acceptor processes was utilized to liquefy the methane. This value is in keeping with current large scale natural gas liquefaction plants. Liquid methane produced by the HYGAS[®] process had the highest thermal efficiency (63 percent) of all the liquid fuel processes investigated.

Boeing Study: Listed in table 1 are the results of heretofore unpublished thermal efficiency data from an in-house study of LH₂, LCH₄, and Synjet, conducted by the Boeing Commercial Airplane Company. Commercial process names were not assigned, but, instead, generic terms were used to describe what are essentially commercially available processes. Partial Oxidation, the production of a synthesis gas by combining coal air, and steam in a gasifier, is followed by appropriate water-gas shifts and methanation steps to produce gaseous hydrogen or methane. Three Synjet processes were included in the Boeing study, two using coal as an energy source and one using oil shale. One coal-to-Synjet process was the Donor Solvent type, where hydrogen, produced within the process, is added to a solvent and the solvent in turn transfers the hydrogen to the coal to produce a syncrude, which in turn, is upgraded to produce Synjet. The other coal-to-Synjet process, generically referred to as the SASOL Synthesis, was an adaption of the Fischer-Tropsch process whereby coal is essentially completely gasified to a synthesis or producer gas (a gas rich in CO and H₂). The gas is purified and then converted to liquid hydrocarbons by reaction in the presence of a suitable catalyst. By proper selection of catalysts and operating conditions (pressure and temperature), a large variety of products can be made, including chemicals, substitute natural gas, liquefied petroleum gas, gasoline, kerosene, diesel oil, fuel oil, and Synjet. Upgrading of the Synjet is not required. This type of process has been in commercial use for two decades at a plant of the South African Coal, Oil and Gas Corporation, Ltd. (SASOL). The oil shale-to-Synjet process was described merely as surface Retort, to distinguish it from an in-situ process where the oil is extracted from the shale without removing the shale from the ground.

Fuel Prices: The price an airline must pay for fuel is a vital factor in commercial aviation, particularly since the price of aviation kerosene has increased by a factor of about five over the past seven years. Alternate fuels will be even more expensive. The price an airline pays for fuel must include the pricing elements associated with the manufacture of the fuel, its transmission to the airport, the fuel storage and distribution facilities, and the fueling, services at the airport. Table 2 contains a breakdown of the elements associated with the price the airline might expect to pay for LH₂, LCH₄, and Synjet. The pertinent fuel production studies⁽³⁻⁶⁾ included economic analyses which have been updated to reflect projected mid-1980 dollars and a 15 percent discounted cash flow financial accounting method, a method which is more in keeping with current practice. Basic features of the financial accounting method are as follows:

Project life	20 years
Depreciation	16-year sum of digits on total plant investment
Capital	100 percent equity
DCF return rate	15 percent
Federal income tax (FIT)	48 percent
Return on investment during construction	DCF return rate X 1.876* years X total plant investment

Other factors we used in the cost estimates are:

Plant stream factor	90 percent
Contingencies	15 percent of installed plant cost
Contractor's overhead & profit	15 percent of total plant cost
Start-up cost	5 percent of total plant investment
Working capital	Coal inventory (60-day feed at full rate) Material and supplies (0.9% of total plant investment) Net receivables (1/24 X annual revenue received)

* 10 percent for 3 years, 90 percent for 1.75 years.

The fuel costs shown in table 2 are based on a coal cost of \$0.85/GJ, and it is assumed that electrical power is both purchased and sold for \$8.33/GJ (3¢/kWh). It is also assumed that the tail gas from the hydrogen liquefier is sold as a by-product for \$4.74/GJ. Economic analyses were not performed on the CO₂-Acceptor process for methane production. It was assumed that gaseous

hydrogen and methane, and Synjet would be produced at the site of the coal mine and would be transported via pipeline over an arbitrarily selected distance of 1600 km. The pipeline transmission data are derived from the Boeing study (unpublished data). The slightly higher transmission cost for hydrogen via the Koppers-Totzek process results from the fact that the economic analyses were done for a process⁽⁴⁾ whose product gas evolved at a lower pressure than the other two hydrogen processes. This gas would require additional compression.

Results of the economic analyses, from the previously discussed unreported fuels study conducted by Boeing, are shown in table 3. The fuel price data have been revised, by Boeing, to reflect mid-1980 dollars and the same financial accounting method, coal cost, and electrical power costs used herein. The price element associated with the 1600 km pipeline transmission have been scaled down to reflect the shorter distance than the original 2092 km. Two methods of hydrogen and methane liquefaction were considered. One method utilized purchased electrical power (\$8.33/GJ) for liquefaction of the gases, and the other (integration system) utilized part of the gaseous feedstock to provide the power for gas liquefaction. The Boeing study also considered Synjet derived from oil shale and assumed that the oil-bearing shale cost \$7.72/Mg and had an oil content of 0.146 M³/Mg. Synjet produced either from coal via SASOL Synthesis, from oil shale were the lowest priced fuels of the Boeing study.

Hydrogen Liquefaction: The three values shown for the price of liquefying the hydrogen reflect current and advanced liquefaction technologies, and the production and sale (at \$220/kg) of heavy water as a by-product. The heavy water price benefits shown here are based on current liquefaction technology, and show the greatest potential for lowering the price of hydrogen liquefaction.

Heavy water: Heavy water (deuterium oxide), D₂O, because it has a neutron-capture cross section only about 600 times less than the capture cross section of light water, is used in some nuclear power plants as a moderator; that is, a substance that is effective in slowing the high velocity neutrons released in the fission of U-235 so that they are maximally effective in splitting other nuclei of U-235. The use of heavy water permits the use of natural uranium as a fuel and avoids the expensive uranium enrichment process required to produce fuel for light water reactors. Early in the development of nuclear power sources, when heavy water was used as a neutron moderator, the distillation of liquid hydrogen was recognized as the most attractive of several available methods for the recovery of deuterium. The attractiveness of this

method exists, however, only for situations where liquid hydrogen production is the principle activity and the deuterium recovery unit is parasitic to the liquid hydrogen plant. With the installation of massive production facilities, each of which could supply 26.25 kg/s of liquid hydrogen to meet commercial aviation needs, there is a potential source of deuterium of 1.053 Gg of heavy water from each facility per year.

A study⁽⁶⁾ investigated the addition of a heavy water plant to a hydrogen liquefaction plant. The cost and energy requirements for such a plant and the economics of producing heavy water as a salable by-product were determined. Basically, the process consists of the fractional distillation of liquid hydrogen to recover deuterium, D₂, and the subsequent reaction of D₂ with oxygen in a burner to form D₂O. It was determined that 1.42 kg of D₂O would be produced for each Mg of hydrogen liquefied. Addition of the heavy water plant resulted in a 12 percent increase in total plant investment, and increased the total electrical power requirement by 9 percent. It was assumed that oxygen for deuterium combustion is purchased at a cost of \$0.11/m³. In the United States, D₂O currently sells for about \$220/kg. It was determined that the sale of D₂O at \$220/kg has the potential of reducing the price element associated with hydrogen liquefaction by \$1.62/GJ.

Recovery of deuterium from large liquid hydrogen installations is seen to be highly profitable; however, such profitability is quite dependent upon maintaining the assumed market price of \$220/kg under the assault of producing such large quantities of heavy water. The annual output of 1.053 Gg from a single 26.25 kg/s liquid hydrogen facility is about equal to the total current output of the Canadian heavy water industry and about 20 percent of the total planned capacity for the early 1980's. No profit can be made from the sale of heavy water if its price falls below \$62/kg.

CH₄ Liquefaction: The methane liquefaction cost is obtained from a prior study⁽¹⁹⁾ with the exception that 10.6 percent of the gaseous methane feedstock is used to generate power for liquefaction, rather than 13 percent.

Fuel Storage and Distribution.- NASA-sponsored studies⁽¹⁰⁻¹¹⁾ have been made of the price of storing and distributing LH₂ to hydrogen-fueled aircraft at airports. In a United States Department of Energy-sponsored study⁽¹⁹⁾ the cost data of two prior studies by Boeing⁽¹⁰⁾ and Lockheed⁽¹¹⁾ were updated to reflect 1980 dollars and a discounted cash flow (DCF) method of financial accounting method quite similar to that used herein. The updated LH₂ storage

and distribution price from the Boeing study was determined to be \$2.04/GJ, approximately twice that of Lockheed, thus leaving great uncertainty as to the price which should be assigned to this element. Furthermore, in the United States it is a common practice for airports to fund facilities through revenue bonds issued by the airport authority⁽¹⁰⁾. Usually, this yields lower interest rates for the required capital, and offers favorable tax advantages when compared to direct private financing (DCF method). Fuel storage and distribution price can be approximately halved if financing is handled via the revenue bond method, yielding a fuel price element, based on the facility costs⁽¹⁰⁾, of about \$1.00/GJ for LH₂. As a compromise, a value of \$1.50/GJ is used herein for LH₂.

The NASA-sponsored study currently being conducted by the Lockheed-California Company includes an assessment of LCH₄ storage and distribution price, but the results are not available at this time. The LCH₄ storage and distribution price used herein is \$0.75/GJ, or one-half that of LH₂, which is the fraction used in the U.S.D.O.E. study⁽¹⁹⁾. A price of \$0.08/GJ is assigned to the storage and distribution of Synjet.

CAPITAL REQUIREMENTS

The capital requirements of the systems required to manufacture, transport, and store LH₂, LCH₄, and Synjet at a major airport are shown in table 4. The data were taken from the unpublished Boeing study, which assumed that fuel requirements for the airport were 325 TJ per day, a value comparable to current fuel requirements for all aircraft at Chicago's O'Hare International Airport. No adjustments were made for any differences in aircraft fuel requirements between LH₂, LCH₄, and Synjet aircraft, and fuel distribution system costs within the airport were not included. The Boeing data have been escalated from 1978 dollars to 1980 dollars, assuming eight percent escalation per year, and pipeline transmission distances have been adjusted to 1600 km.

The total capital requirements for synthetic fuels plants, pipelines, liquefaction plants, and storage facilities for each fuel are those listed at the bottom of table 4. The electricity used in production of hydrogen by water electrolysis can be generated from various sources. For this analysis, only nuclear generation is considered, to cover the options which would avoid dependence on fossil fuels. The capital requirements shown are about 30 percent greater than if coal were used and roughly three times that required for producing LH₂ from coal by the Partial Oxidation process. The capital requirements for producing liquid methane were obtained for only one process. For Synjet, two values of

total capital requirement are shown for each of three processes. The higher values shown represent the capital requirements for the entire plant, whose Synjet product may represent perhaps only 25 percent of its total fuel product output which would be sold. Thus, the capital requirements for Synjet considered appropriate are the lower values shown in parenthesis, which represent the fractional share associated with only the production of Synjet.

REFERENCES

- (1) United States Energy Research and Development Administration, Washington, DC, ERD-48, Vol. 1, June 28, 1975.
- (2) Witcofski, Robert D., NASA TM 78696, 1978.
- (3) Tsaros, C. L.; Anora, J. L.; and Burnham, K. B., NASA CR-145028, 1975.
- (4) Anon, NASA CR-132631, 1975.
- (5) Anon, NASA CR-145077, 1976.
- (6) Baker, C. R., NASA CR-145282, 1977.
- (7) Brewer, G. D., and Morris, R. E., Lange, R. H., and Moore, J. W., NASA CR-132559, January 1975.
- (8) Brewer, G. D., and Morris, R. E., NASA CR-144935, 1976.
- (9) Brewer, G. D., etal, NASA CR-145369, 1978.
- (10) Boeing Commercial Airplane Company, NASA CR-2699, 1976
- (11) Brewer, G. D., NASA CR-2700, 1976.
- (12) Baker, C. R., NASA CR-158991, 1979.
- (13) Witcofski, R. D., NASA TM X-74030, 1977.
- (14) Goldsmith, J. S., and Bennett, G. W., NASA CR-121247, 1973

- (15) Sharpe, Ellsworth L., NASA Langley Research Center, and Helenbrook, Robert G., Bell Aerospace, Buffalo, NY: Nonmetallic Materials and Composites at Low Temperatures, July 10, 1978.
- (16) Conrad, W. E., NASA TM-79196, 1979.
- (17) Anon, Liquefied Gaseous Fuels Safety and Environmental Control Assessment Program: A Status Report. DOE/EV-0036, May 1979.
- (18) Stambler, I., EPRO Gas Turbine Outlook, Gas Turbine World 5, (5), 19 (1975).
- (19) Cart, E. N., Jr.; Carter, D. A.; and Cunningham, A. R., Alternate Energy Sources for Non-Highway Transportation. Contract DE-ACOR-77CS05438, 1979.

TABLE 2

PRICES OF COAL-DERIVED FUELS DELIVERED TO AIRCRAFT

PRICES EXPRESSED AS 1980 \$/GJ

PRICING ELEMENTS	HYDROGEN			SYNJET
	KOPPERS-TOTZEK	U-GAS TM	STEAM-IRON	
COAL-TO-GAS OR SYNJET	8.18(a)	6.70(b)	5.08(b)	7.82(b)
1600 km PIPELINE	1.02	0.87	0.87	0.14
LIQUEFACTION OPTIONS(a)				
I. CURRENT TECHNOLOGY	6.17	6.17	6.17	1.85
II. ADVANCED TECHNOLOGY	5.04	5.04	5.04	-
III. CURRENT TECH. + D2O SALE	4.55	4.55	4.55	-
TAIL GAS SALE CREDIT	-0.22	-0.64	-0.42	-
STORAGE AND DISTRIBUTION	1.50	1.50	1.50	0.75
TOTAL PRICE				0.08
I. CURRENT LIQUEFACTION	16.65	14.60	13.20	8.39
II. ADVANCED LIQUEFACTION	15.52	13.47	12.07	-
III. CURRENT LIQ. + D2O SALE	15.03	12.98	11.58	-

ASSUMPTIONS: COAL AT \$ 0.85/GJ, ELECTRICAL POWER SOLD AND PURCHASED AT \$8.33/GJ (3¢/kWh)

- (a) Linde (4-6)
- (b) IGT(3)
- (c) D2O sold at \$220/kg

TABLE 3
BOEING ALTERNATE FUELS STUDY PRICE RESULTS
PRICES EXPRESSED AS 1980 \$/GJ

PRIME ENERGY SOURCE	NUCLEAR		HYDROGEN		COAL		METHANE		SYNJET		OIL SHALE	
	ELECTROLYSIS	PARTIAL OXIDATION	PARTIAL OXIDATION	PARTIAL OXIDATION	DONOR SOLVENT	SASOL SYNTHESIS	SURFACE RETORT					
COAL TO GAS OR SYNCRUDE	13.93	5.83	5.59	5.93	6.31	4.46						
1600 km PIPELINE(a)	-	0.87	0.63	0.14	0.14	0.14						
SYNCRUDE UPGRADING	-	-	-	2.56	-	1.52						
<u>LIQUEFACTION</u>												
PURCHASED ELEC. POWER	5.19	5.19	2.06	-	-	-						
INTEGRATED SYSTEM(b)	-	9.84	3.45	-	-	-						
STORAGE AND DISTRIBUTION(c)	1.50	1.50	0.75	0.08	0.08	0.08						
TOTAL PRICE				8.71	6.53	6.20						
WITH PURCHASED ELEC POWER	20.62	13.44	9.03	-	-	-						
INTEGRATED SYSTEM	-	18.09	10.42	-	-	-						

ASSUMPTIONS: Coal at \$0.85/GJ, electrical power purchased \$8.33/GH (3¢/kWh)

- (a) Scaled down from 2092 km pipeline
- (b) Power for liquefaction supplied by part of gaseous feedstock
- (c) Values assumed in current study

TABLE 4

CAPITAL REQUIREMENTS FOR ALTERNATE FUELS DELIVERED TO AIRPORT STORAGE
MILLIONS OF 1980 DOLLARS FOR 325 TJ OF FUEL PER DAY

PRIME ENERGY SOURCE	NUCLEAR		COAL		LCH ₄		SYNJET		OIL SHALE		
	ELECTROLYSIS	PARTIAL OX.	PARTIAL OX.	DONOR SOLVENT	SASOL SYNTHESIS	SURFACE RETORT	ELECTROLYSIS	PARTIAL OX.	DONOR SOLVENT	SASOL SYNTHESIS	SURFACE RETORT
COAL OR OIL SHALE CONVERSION PLANT	-	1348	1590	11,500 (2211)(a)	7965 (1503)(a)	7142	-	-	-	-	-
NUCLEAR ELECTIC PLANT FOR ELECTROLYSIS OF H ₂ O	5627	-	-	-	-	-	-	-	-	-	-
ELECTROLYZER PLANT	903	-	-	-	-	-	-	-	-	-	-
1600 km PIPELINE	-	379	322	63	78	63	-	-	-	-	103
REFINERY	-	-	-	103	-	-	-	-	-	-	-
NUCLEAR ELECTIC PLANT FOR H ₂ LIQUEFACTION	1065	-	-	-	-	-	-	-	-	-	-
MANUFACTURING SUBTOTAL	<u>7605</u>	<u>1727</u>	<u>1927</u>	<u>11,666</u>	<u>8043</u>	<u>7308</u>	-	-	-	-	-
LIQUEFIER	1050	1050	583	-	-	-	-	-	-	-	-
STORAGE	<u>72</u>	<u>72</u>	<u>14</u>	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE
AIRPORT SUBTOTAL	<u>1122</u>	<u>1122</u>	<u>597</u>	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE
TOTAL	<u>8717</u>	<u>2849</u>	<u>2509</u>	<u>11,666</u> (2377)(a)	<u>8043</u> (2376)(a)	<u>7308</u> (1669)(a)	-	-	-	-	-

(a) Cost share for Synjet production

TABLE A-1

STEAM-IRON PROCESS THERMAL EFFICIENCIES
FOUR BOOKKEEPING METHODS

	THERMAL EFFICIENCY, PERCENT	
	<u>WITH CURRENT LIQ. TECH.</u>	<u>WITH ADV. LIQ. TECH.</u>
(A) H ₂ LIQUEFIED VIA ELECTRICAL POWER FROM SPENT PRODUCER GAS (S.P.G.), EXCESS ELECTRICAL POWER AND TAIL GAS CREDITED AS BY-PRODUCTS	43	48
(B) SAME AS "A" EXCEPT EXCESS ELECTRICAL POWER EXPRESSED AS THE HEATING VALUE PLUS SENSIBLE HEAT OF THE S.P.G. USED TO PRODUCE THE EXCESS POWER	49	57
(C) H ₂ LIQUEFIED WITH OFF-SITE ELECTRICAL POWER GENERATED AT FORTY PERCENT EFFICIENCY; TAIL GAS AND ELECTRICAL POWER FROM S.P.G. CREDITED AS BY-PRODUCTS	42	47
(D) SAME AS "C" EXCEPT S.P.G. EXPRESSED AS ITS HEATING VALUE PLUS SENSIBLE HEAT, AND CREDITED AS BY-PRODUCT	55	60

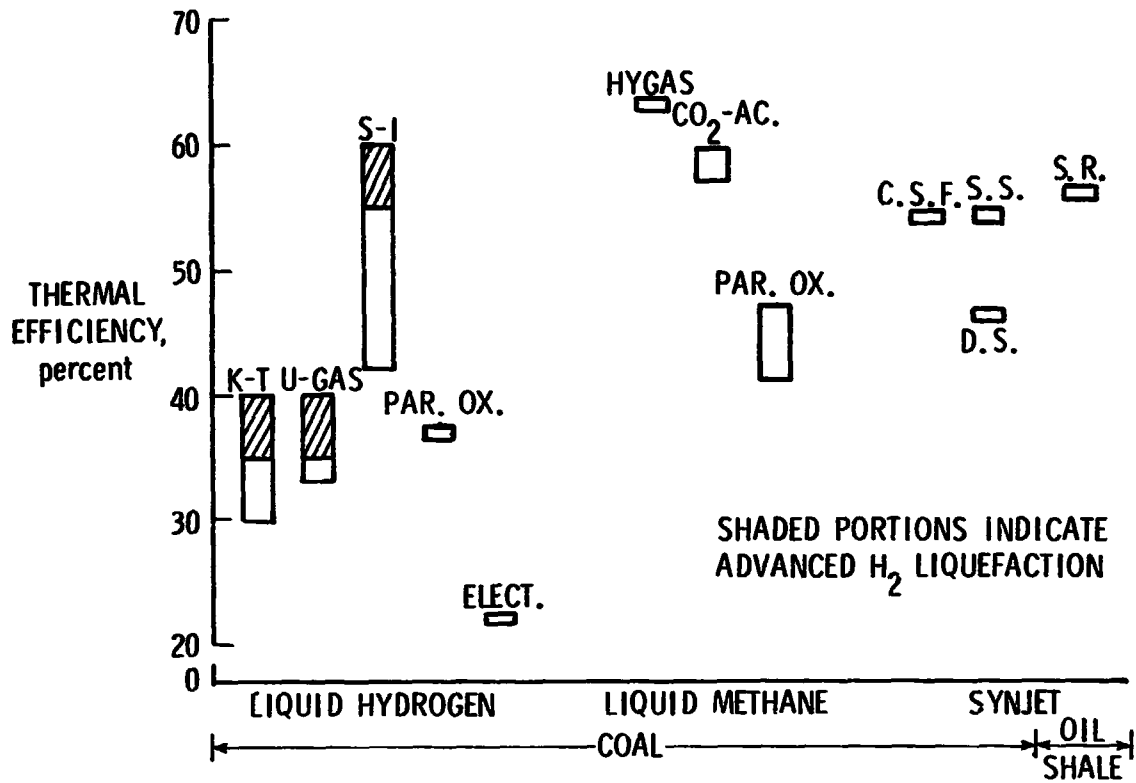


Figure 1. - Thermal efficiencies of alternate fuels production processes.

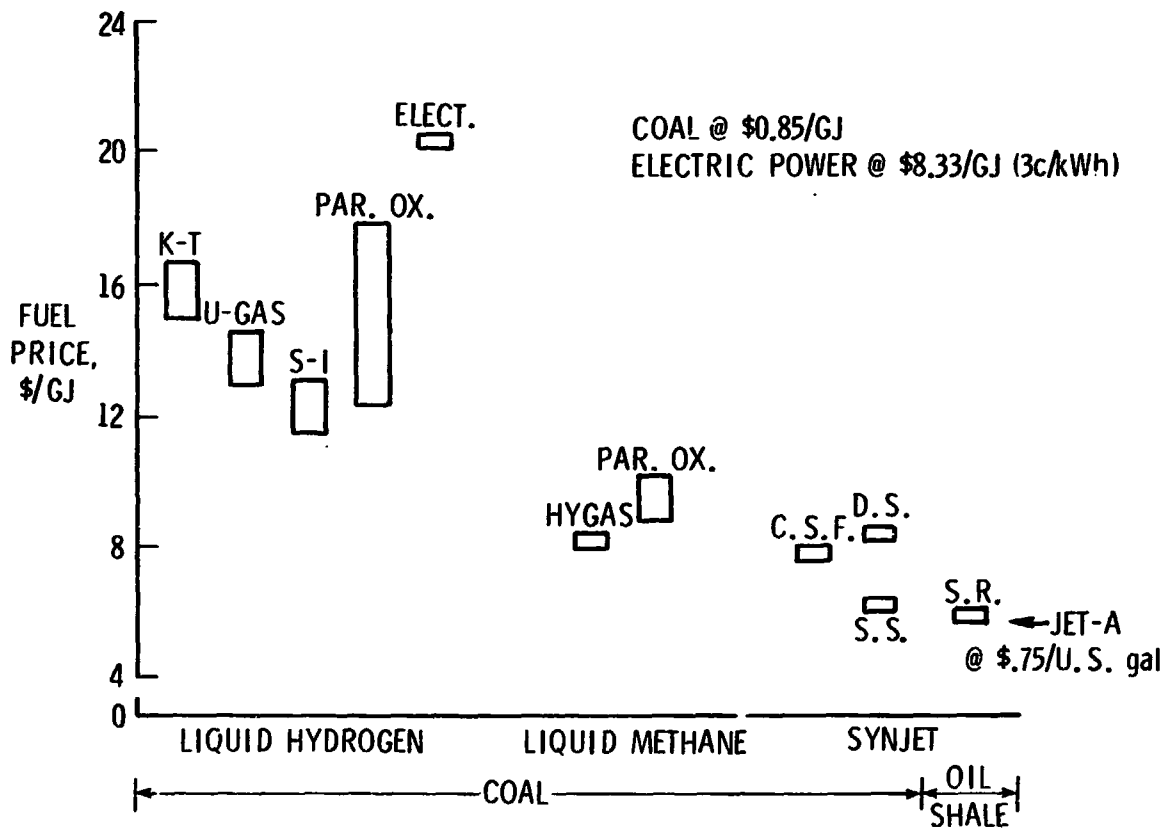


Figure 2. - Prices of alternate fuels delivered to the aircraft (1980 dollars).

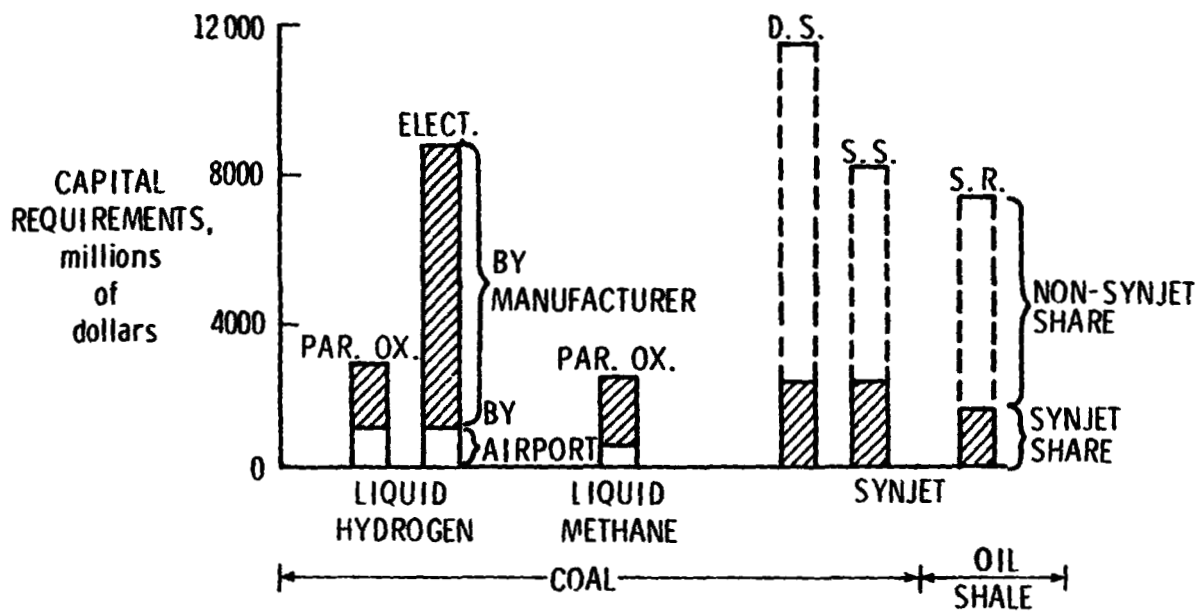


Figure 3. - Capital requirements of alternate fuels delivered to the airport (1980 dollars, 325 TJ of fuel per day).

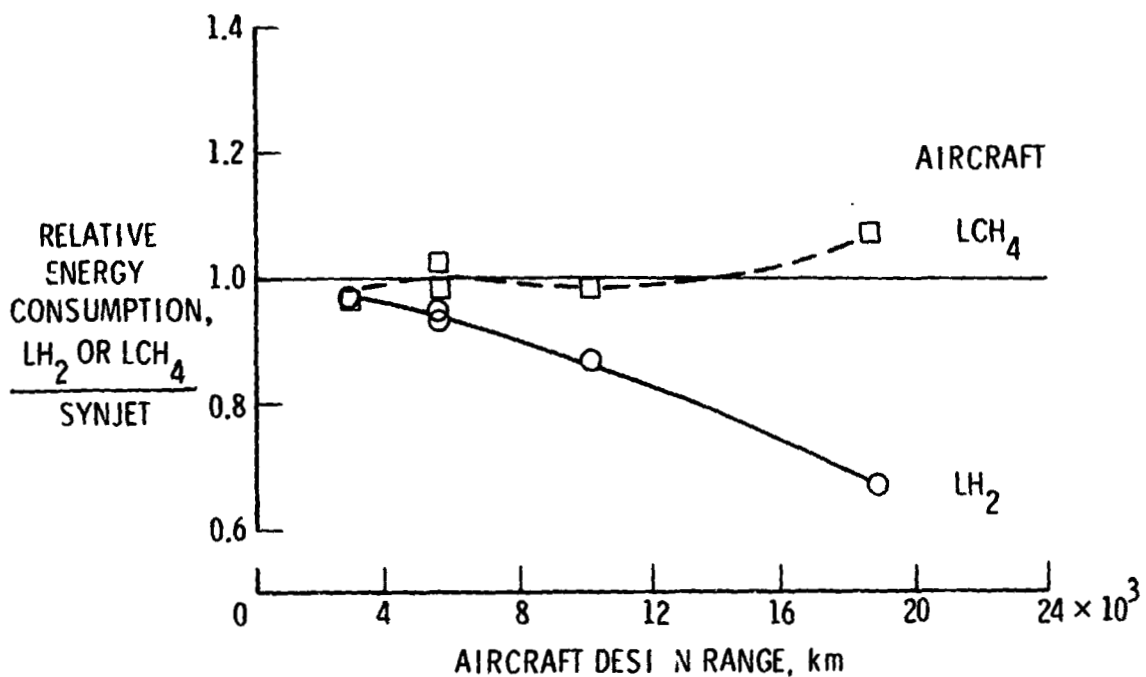


Figure 4. - Onboard energy consumption of liquid hydrogen and liquid methane aircraft, relative to Synjet aircraft. Fuel production energy not included.

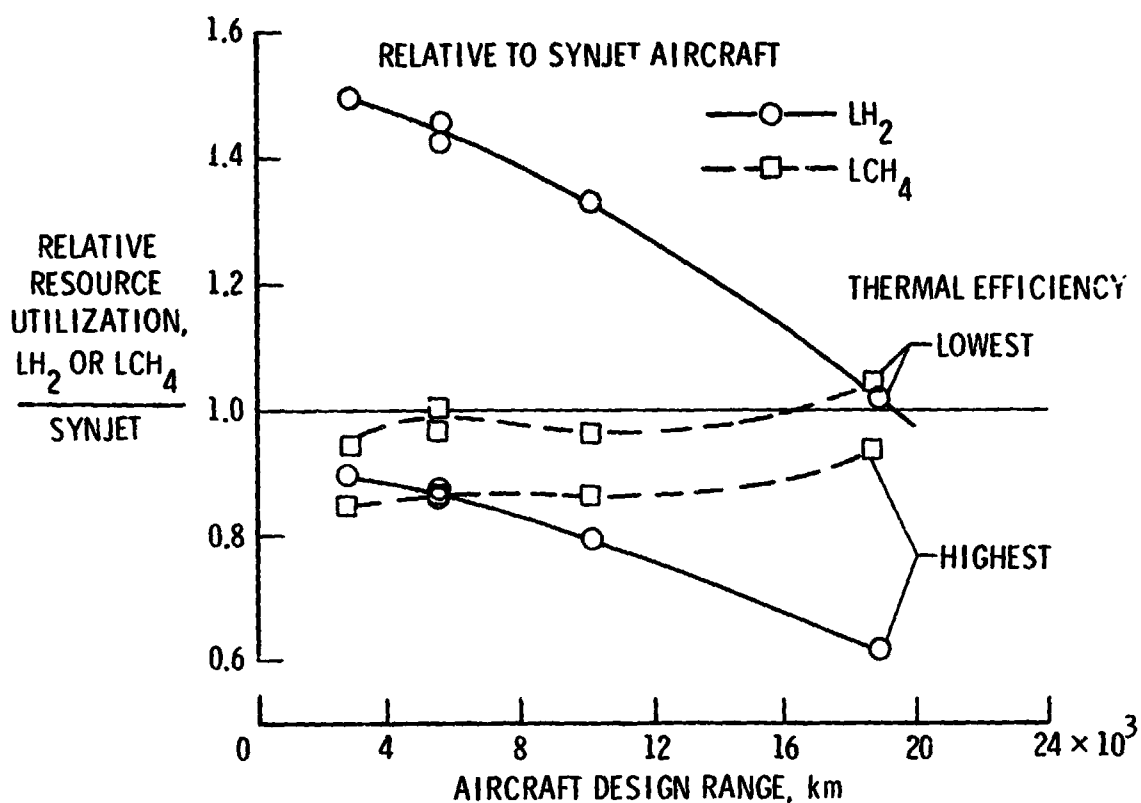


Figure 5.- Energy resource utilization efficiency of liquid hydrogen and liquid methane aircraft, relative to Synjet aircraft. Fuel production energy included.

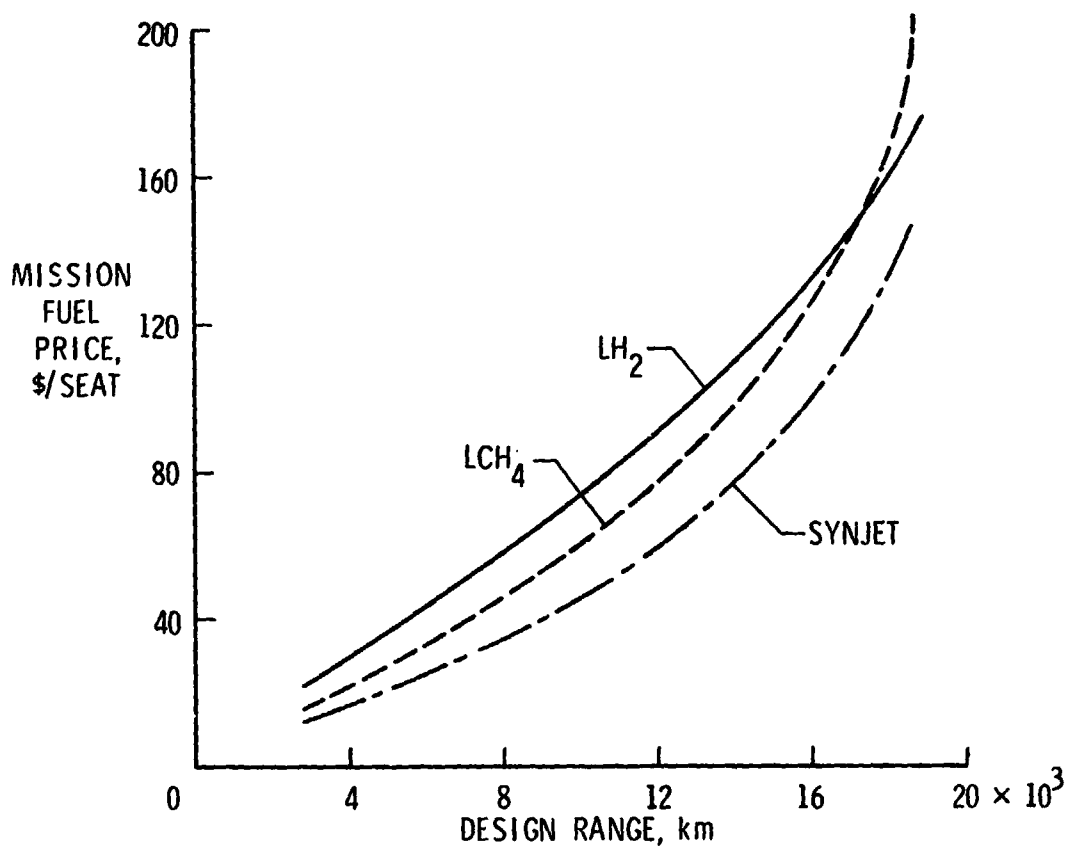


Figure 6. - Mission fuel price per seat for aircraft operations. Assumed fuel price per GJ: $\text{LH}_2 = \$11.58$, $\text{LCH}_4 = \$8.39$, Synjet = $\$6.20$.

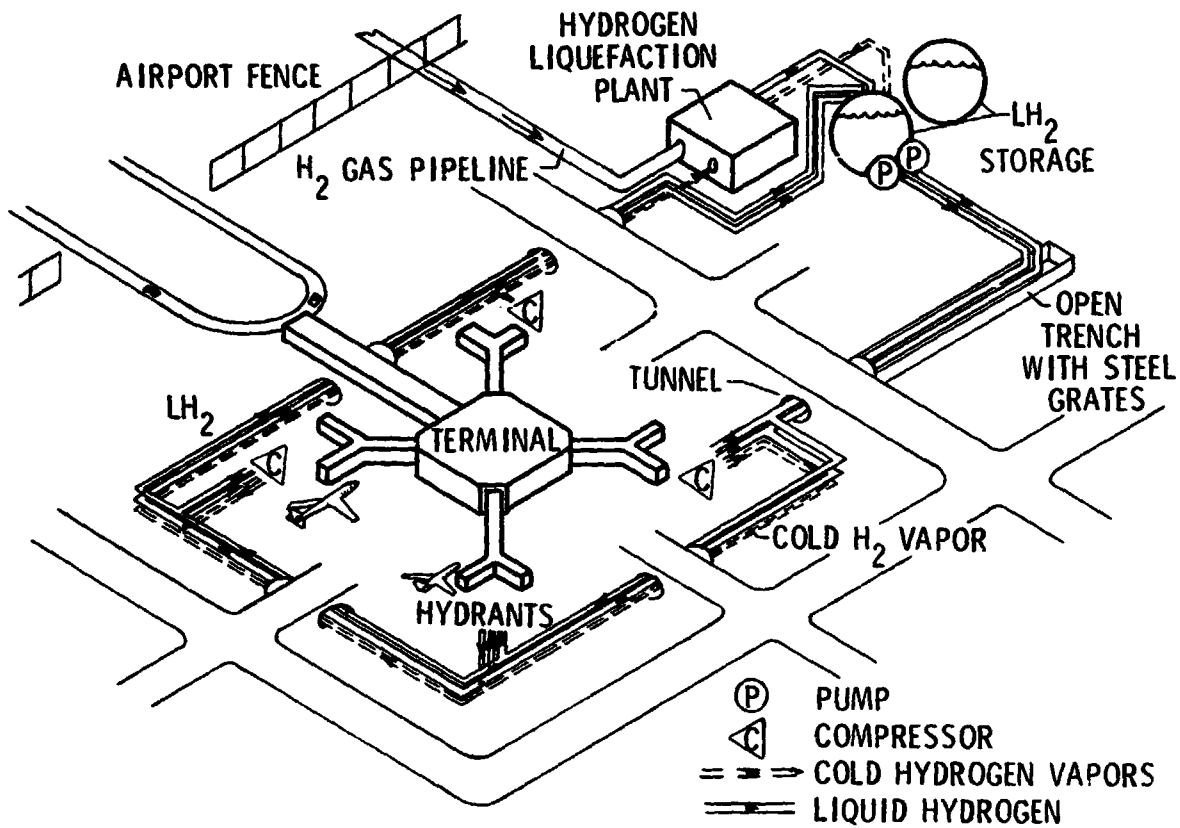


Figure 7.- Schematic arrangement of a hydrogen liquefaction, storage, and distribution system at an airport.

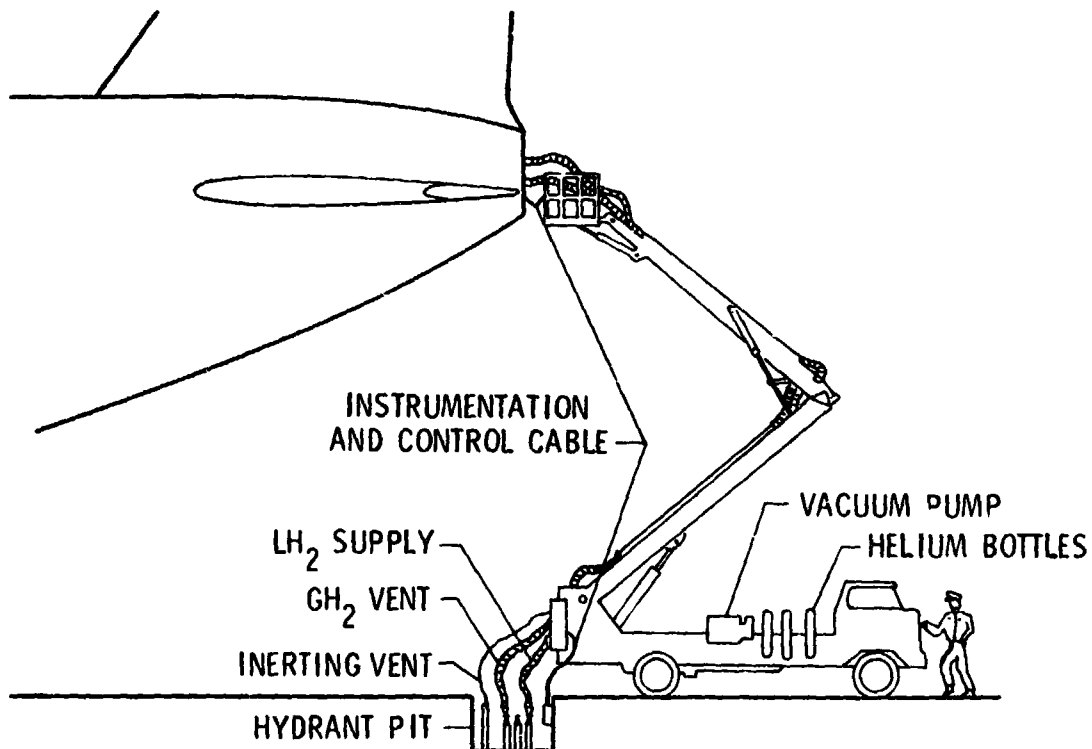


Figure 8.- Fueling of a liquid hydrogen aircraft using a hydrant truck.