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ALTERNATE AIRCRAFT FUELS - PROSPECTS AND OPERATIONAL IMPLICATIONS

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SUMMARY

The results of studies conducted for and by the NASA's Langley Research Center, aimed at assessing the potential use of coal-derived aviation fuels are reported. The studies addressed the prices and thermal efficiencies associated with the production of coal-derived aviation kerosene, liquid methane and liquid hydrogen and the air terminal requirements and subsonic transport performance when utilizing liquid hydrogen. The fuel production studies indicated that liquid methane can be produced at a lower price and with a higher thermal efficiency than aviation kerosene or liquid hydrogen. Ground facilities for liquefaction, storage, distribution and refueling of liquid hydrogen fueled aircraft at airports appear technically feasible. The aircraft studies indicate modest on-board energy savings for hydrogen compared to conventional fuels. Liquid hydrogen was found to be superior to both aviation kerosene and liquid methane from the standpoint of aircraft engine emissions.

INTRODUCTION

Civil transportation accounts for less than 2 percent of the total U.S. energy consumption and about 4 percent of the petroleum energy (1). Figure 1, taken from reference (2), shows the present and potential future fuel consumption of U.S. airlines. The fuel consumption shown by the top curve in figure 1 assumes the use of present technology aircraft and a modest 4-percent (compared to better than 11 percent for the past ten years) annual growth rate (2) in fuel consumption. If a 4-percent annual growth rate in fuel consumption is assumed, air transportation will require 2.5 times as much fuel by the year 2000. Research, aimed at improving the energy efficiency of aircraft, can impact the future fuel demand. The effect on fuel consumption of the implementation of available and potential aircraft technology improvements are shown in figure 1 by the middle and bottom curves respectively. It is evident from figure 1 that even with aircraft technology improvements the fuel consumption of civil air transportation will increase in the future.

In June of 1975 ERDA released an overview of the U.S. energy situation (3), which included a prospectus on the domestic oil situation. Figure 2, reproduced from reference 3, indicates that even with enhanced recovery methods, the production of domestic oil in the U.S. may never surpass that which occurred during 1970 and will constantly decline after the 1980's. This estimate includes already identified resources and estimated undiscovered resources. As the supply of domestic oil declines, competition for that which remains will increase and the question arises, "How should remaining oil resources be utilized?" When addressing this question, it is necessary to look at what other domestic energy resources are available, the fuels or forms of energy which can be produced from these resources, and how these fuels and forms of energy can best be used. In making such evaluation one must consider cost, efficient resource utilization, and environmental aspects must be considered as well.

The NASA is investigating the subject of the use of alternate fuels or aviation fuels derived from energy resources other than naturally occurring crude oil. This paper presents the results obtained thus far of investigations conducted by and for the NASA's Langley Research Center, aimed at assessing the potentials of coal-derived aviation fuels. Coal has been identified (3) as one of the more plentiful remaining U.S. energy resources (an order magnitude greater than crude oil) and was selected as the energy source for this investigation. The fuels considered were synthetic aviation kerosene, liquid methane (LCH_4), and liquid hydrogen (LH_2). Synthetic aviation kerosene was selected for study because the use of such a fuel is likely to cause fewer changes to the present air transportation system than would other fuels. LCH_4 and LH_2 were selected for study because of their high energy content per kilogram (see Table 1). The Langley investigations have included the areas of fuel production, air terminal requirements for aircraft fueling, and the performance characteristics of aircraft designed to utilize alternate fuels. In the fuel production studies the energy requirements associated with the production of each of the three selected fuels have been determined, as have estimates of the fuel prices. In the area of air terminal requirements for alternate fuels only liquid hydrogen has been assessed thus far. Subsonic commercial air transports, designed to utilize liquid hydrogen fuel have been analyzed and their performance characteristics have been compared to aircraft utilizing conventional aviation kerosene. Environmental and safety aspects are discussed, as are key technical and economic issues.

FUEL PRODUCTION

The technology status of coal conversion processes varies considerably. The older, better developed processes tend to require more coal input and produce fuels which are more expensive than the fuels which might be produced by more advanced technology processes currently being developed. Oxygen requirements are a key difference between the older, better-developed processes and the more advanced technology processes. An oxygen plant can require nearly 20 percent of the plant investment and can require 10 percent of the coal input for fuel. Advanced technology processes tend to be aimed at lowering oxygen requirements or the use of air instead of oxygen.

The summary of results reported herein are based upon the findings of fuels production studies conducted for Langley by the Institute of Gas

Technology (IGT) (4, 5) and the Linde Division of Union Carbide (6). A discussion of basic coal gasification precedes brief descriptions of the coal conversion processes considered. Fuel production energy requirements are then discussed, and are followed by a section on fuel prices. More detailed analyses of selected coal conversion processes are included in the Appendix.

Basic Coal Gasification

The ratio of hydrogen atoms to carbon atoms in coal is about 0.8 to 1.0. In aviation kerosene and methane, the ratios of hydrogen atoms to carbon atoms are 2 to 1 and 4 to 1, respectively. Hydrogen, of course, contains only hydrogen atoms. Basically, the purpose of coal gasification is to add hydrogen atoms to the product. In coal gasification, the source of the additional hydrogen is water (as steam). Most of the processes being developed for producing fuels from coal incorporate the same basic steps or modification of the same basic steps shown schematically in Figure 3. After the coal has been milled or crushed to the proper size and then dried, it is introduced into the gasifier, along with steam and air or oxygen. Oxygen is generally preferred over air because nitrogen dilution of the product gas is avoided. In the gasifier, a synthesis or producer gas is generated by the reaction of carbon with steam. This process step is highly endothermic and the required heat energy is supplied by the reaction of part of the coal with oxygen or air. The constituents of the producer gas from the gasifier are noted in Figure 3.

Of the hydrogen which comes out of the gasifier, better than 40 percent comes from the steam. The composition of the producer gas can be controlled to a great extent by controlling the temperature and pressure within the gasifier. High-temperature and low-pressure operation of the gasifier favors the production of a producer gas rich in H_2 and CO. Low-temperature and high-pressure operation of the gasifier favors the production of a producer gas rich in CH_4.

The steps which follow depend upon whether the desired end product is H_2, CH_4, or aviation kerosene. If the end product is to be H_2, the CO shift reacts CO with steam over a catalyst, to make more H_2, and the methanation step which reacts CO with H_2, over a catalyst, to produce CH_4 is used merely as a cleanup step to get rid of any excess CO remaining in the gas. If the end product is to be CH_4, the CO shift is used to produce just enough H_2 for a balanced methanation step, when the remaining CO is reacted with the H_2 over a catalyst to produce more CH_4. If the end product is to be aviation kerosene, the producer gas is purified and reacted over a suitable catalyst to produce a variety of liquid and gaseous products. This type of process is known by the generic term as the Fischer-Tropsch process. Suitable fractions of the liquid products can then be converted to aviation kerosene by further addition of hydrogen.

Liquid hydrocarbon fuels such as aviation kerosene might also be produced by the direct addition of hydrogen to the coal, where the hydrogen is supplied either as a gas or is supplied by a liquid solvent which is rich in hydrogen. The hydrogen is turn is supplied to the solvent by a separate gasifier.

Synthetic Aviation Kerosene Production

The method selected for analysis of the production of aviation kerosene from coal was to modify part of the products of the Consol Synthetic Fuel (CSF) process. The CSF process extracts a de-ashed fuel from the coal that is hydrogenated to desulfurize the fuel and to increase its H_2 content. Hydrogen is added to the coal by an H_2 donor solvent, which is coal derived, and regenerated and recycled within the process. Two of the products of the CSF process are a heavy oil and a high Btu gas. Part of the high Btu gas is converted to H_2 by steam reforming (reaction of CH_4 with steam over a catalyst) and the H_2 is used to hydrocrack and hydrogenate the heavy oil into aviation kerosene. Major by-products of this process are naphtha, sulfur, ammonia, and more high Btu gas.

Methane Production

The two processes selected for producing methane from coal are the HYGAS® process and the CO_2-Acceptor process. Each process represents a somewhat different approach.

HYGAS®.- The HYGAS® process is currently being developed by IGT at a pilot plant in Chicago, Illinois. Basically, two reaction zones are stacked on top of a gasifier. The producer gas from the gasifier rises up through the upper zones and the H_2 from the gas reacts with the coal to produce CH_4. About half of the CH_4 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.

CO_2 Acceptor.- The CO_2-Acceptor process uses no oxygen. The heat required to drive the reaction of steam with coal is provided by the highly exothermic reaction of CO_2 with dolomite (MgO-CaO), which is showered into the gasifier. Part of the CO_2 is supplied by the reaction of the steam with the coal and the rest is supplied by a separate regenerator vessel where CO_2 is driven out of the spent dolomite, by heat. About 37 percent of the CH_4 is formed in the gasifier and the remainder by methanation of the remaining gasifier effluents. No CO shift is required.

Hydrogen Production

Three processes for producing hydrogen from coal were investigated by IGT (4, 5). These processes were the Koppers-Totzek, the U-GAS™, and the Steam-Iron. Each process represents a somewhat different approach.

Koppers-Totzek.- 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 2089 K (3300° F), producing a gas whose composition is about 27 molecular percent H_2 and 51 molecular percent CO. The steps which follow the primary gasification follow basically the same steps as those shown in Figure 3. The Koppers-Totzek process requires about four times as much oxygen as does the HYGAS^{R} process.

U-GAS^{TM}.- The U-GAS^{TM} 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 kN/m^2 (335 psig) and at a temperature of 1311 K (1900° F), producing a gas whose composition is 31 molecular percent H_2 and 43 molecular percent CO. Again the steps which follow the primary gasification follow basically the same steps in Figure 3. The U-GAS^{TM} process requires about three times as much oxygen as the HYGAS® process.

Steam-Iron.- Hydrogen is generated in the Steam-Iron process by reacting iron oxide (ferrous oxide, FeO) with steam and decomposing the steam to produce H_2 and ferrosoferric oxide (Fe_3O_4). The H_2 is removed and the Fe_3O_4 is sent to a reductor where it reacts with a producer gas. The CO and H_2 in the producer gas react with the Fe_3O_4 to produce CO_2, H_2O, and the required FeO. 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; nitrogen cannot contaminate the hydrogen because of the iron oxide barrier. The spend producer gas, having reduced the Fe_3O_4 to FeO still contains some CO and H_2 and can be burned to produce a large electrical by-product.

Fuel Production Energy Consumption

When conventional crude oil is refined into a variety of fuels, including jet fuel, the energy content of the fuels coming out of the refinery can vary from about 88 to 95 percent of the energy input to the refinery, depending upon the type of crude oil being refined and the mix of products coming from the refinery. When fuels are produced from coal, an even lesser percent of the energy in the coal feedstock actually comes out of the plant as useful fuel. IGT (4, 5) assessed the thermal efficiency of producing synthetic aviation fuels from coal (where thermal efficiency is defined as the ratio of the heating value of all products of a particular plant to the heating value of the coal fed to the plant). In the work by IGT, all the energy requirements for the processes were supplied either directly or indirectly by the coal feedstock. Table 2 summarizes the findings of the IGT work with regard to thermal efficiency. As noted on Table 2, the thermal efficiencies are shown, based on the lower or net heating values of all fuel inputs and products. Also shown in Table 2 are the by-products of the various fuel production processes.

The hydrogen and methane production processes have a gas by-product when their gaseous products liquefied. When purifying the gases prior to liquefication, CO and CH_4 are recovered from the H_2 feedstock, and CO and H_2 are recovered from the CH_4 feedstock. In addition the flash-off which occurs when the cryogenic liquids are transferred to storage are recovered. In the case of hydrogen and methane, thermal efficiencies are shown for production of both the gaseous and liquid fuels. The energy requirements for hydrogen liquefaction were determined by Linde (6) to be 104.7 kWh/10^6 Btu of liquid product and the energy requirements for liquefaction of methane were those reported by IGT (4) to be 12.2 kWh/10^6 Btu of liquid product.

Synthetic Aviation Kerosene.- The thermal efficiency of the CSF process itself (prior to hydrocracking and hydrogenation of the heavy oil to produce aviation kerosene) is about 70 percent. After hydrogen has been produced from the high BTU gas product, and used to hydrocrack and hydrogenate the heavy oil from the CSF process to produce a synthetic aviation kerosene, the overall thermal efficiency is 54 percent. The heating value of the by-products of this process amounts to 28 percent of the total output.

Methane.- Of all the fuels and fuel processes investigated, liquid methane produced via the HYGAS® process was found to be the most thermally efficient (64 percent) coal-derived liquid fuel. This stems primarily from the relatively low energy requirement for liquefying methane. The CO_2 Acceptor process is a close second, having a thermal efficiency of 59 percent if the electrical by-product of the process is accounted for as electricity and 63 percent if the electrical by-product is accounted for as the heating value plus the sensible heat of gas which produces the electrical by-product.

Hydrogen.- Of the hydrogen production processes considered, the most thermally efficient process is the Steam-Iron process. The reason for the higher thermal efficiency of the Steam-Iron process is the by-product spent producer gas from the process, as described in a previous section. Depending upon whether the by-product gas (heating value plus sensible heat) or electrical power generated from the gas is credited as the by-product energy, the thermal efficiency of liquid hydrogen produced via the Steam-Iron process is 49 percent or 44 percent. The lower thermal efficiencies associated with producing H_2 gas via the Koppers-Totzek and U-GAS processes can be attributed to a great extent to their large oxygen requirements.

Coal-Derived Fuel Prices

Domestic airlines currently pay about 32 cents per gallon ($2.60/$10^6$ Btu or $2.56/GJ) for aviation kerosene. The price of synthetic fuels will be determined by a number of factors, including the cost of the energy source from which they are produced (coal in the present discussion), the cost of labor and materials required for constructing the plants, and the cost and method of financing the money required to construct the plants.

The Linde study (6) was finished in April of 1975 and the IGT study was finished in June of 1976. Both studies used mid-1974 costs and a private-investor-financing method of calculating the return on the investment. The basic features of the financing method are summarized below:

Project life	25 years
Depreciation	16-year sum of the digits on total plant investment
Capital	100 percent equity
DCF return rate	12 percent
Federal income tax	48 percent
Return on investment during construction	DCF return rate x 1.878* years x total plant investment
Plant stream factor	90 percent

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

The fuel production methods for which fuel prices were estimated by IGT were synthetic aviation kerosene produced from the CSF process products, the HYGAS® process for producing methane, and the U-GAS™ and Steam-Iron processes for producing hydrogen.

A summary is presented in Figure 4 of the prices of coal-derived aviation fuels. Although the prices do not reflect current year dollars, the data is still useful in comparing one fuel/fuel production process against another. The results are shown as fuel price versus the cost of coal. As a point of reference, the Virginia Electric and Power Company now pays about $20-$25 for mine mouth coal. Figure 4 shows that for the processes and fuels considered, liquid methane produced via the HYGAS® process is the least expensive fuel and the price increase due to increased coal cost is less than the other fuel/fuel processes. Liquid hydrogen is the most expensive fuel, with the Steam-Iron process being less expensive than the U-GAS™ process, at least within the range of coal costs considered. Synthetic aviation kerosene (produced from the CSF products) falls between liquid hydrogen and liquid methane.

A further examination of Figure 4 shows the prices of gaseous hydrogen and methane are quite comparable, and at the lower coal costs the gaseous hydrogen is less expensive than is gaseous methane. The reason that the liquid hydrogen prices are so high in comparison to the other two fuels is the cost of liquefying the hydrogen (6). At a $25/ton coal cost more than half of the cost of liquid hydrogen is attributed to liquefaction. Studies are currently underway at Linde to assess the potential for reduction of the cost of hydrogen liquefaction. These studies include an analysis of the addition of a heavy water plant to the liquefaction plant, where the heavy water would be sold as a by-product.

In comparing the prices of LH_2 from the U-GAS^{TM} and Steam-Iron processes, the reader is cautioned that the slopes of the two curves showing the effect of coal cost on LH_2 price are related to the assumption that electrical power costs two cents per kWh. If it assumed that the cost of electricity is governed by the cost of producing electricity in a coal-fired plant and that the coal costs are those shown on the abscissa of Figure 4, the slope of both curves will change, pivoting about the points on the curves which correspond to the LH_2 prices for a coal cost of about $18 per ton. The U-GAS^{TM} LH_2 price curve will steepen somewhat, increasing the LH_2 price for $35 per ton coal by about $0.70/GJ. The slope of the Steam-Iron curves, for both gas and liquid, will decrease because of the value of the large electrical by-product from this process. At a $35 per ton coal cost, the price of LH_2 from the Steam-Iron process would decrease about $0.40/GJ.

The price results presented herein certainly do not put to rest the question of the price of coal-derived fuels. Not until plants are actually constructed and fuels are actually produced will the price picture become more clear.

SYNTHETIC FUELS AT THE AIR TERMINAL

In assessing various aviation fuels, their impact on the air terminal must be considered. Synthetic aviation kerosene would presumably have characteristics sufficiently similar to today's jet fuel that no changes would be required at the airport. The impact of liquid methane on the ground requirements at the air terminal has not yet been assessed. Liquid methane is a cryogenic fuel (112 K) and would require cryogenic storage and transfer facilities. Most major air terminals already have access to natural gas lines and this would certainly facilitate the delivery of methane as a gas to the air terminal.

NASA/Langley - sponsored studies have addressed the impact on the air terminal of the use of liquid hydrogen as an aviation fuel. The Boeing Commercial Airplane Company (7) and the Lockheed-California Company (8) carried out assessments of the impact of the use of LH_2 as a fuel for all wide-body jets at two major airports in the United States (O'Hare International in Chicago, Illinois, and San Francisco International in San Francisco, California, respectively). It was assumed that a supply of gaseous hydrogen was available at the gates of the airports. Boeing and Lockheed were supported by a team of experts in hydrogen liquefaction and storage, airport planning and operation, and airline operations. Both teams, in their analysis of the air terminal complex, determined the size and potential location of hydrogen liquefaction plants and storage facilities. In the studies, subcooled LH_2 was considered to be circulated via pumps through vacuum-insulated pipes from the storage facilities to fueling hydrants, making subcooled LH_2 available continually. The fuel distribution system, including gaseous H_2 boiloff, was confined to a closed loop, permitting no H_2 to escape. There was basically three main lines in the loop. One was used to deliver the LH_2 to the aircraft, one was a backup delivery line, and one was used to collect the boiloff which occurs when the LH_2 was transferred to the aircraft fuel tank. Although the aircraft fuel tanks would always have some LH_2 in them as long as the aircraft is in service, a substantial warming of the fuel tank did occur when the tank is only partially filled. The tank was cooled down by the fuel. The cold boiloff gas was returned to the liquefaction plant for reliquefaction.

Two approaches for getting the LH_2 from the hydrant to the aircraft were iedntified, both of which are shown schematically in Figures 5a and 5b. In Figure 5 a hydrant truck was used to connect the hydrant to the aircraft (8). In figure 5b a boom was extended from the terminal building to the aircraft for fuel transfer.

It was estimated that the necessary liquefaction, storage, and distribution facilities would cost approximately $\$470 \times 10^6$ for O'Hare and $\$340 \times 10^6$ for San Francisco.

The major conclusions of the studies were:

1. Such a conversion would be technically feasible and there were no technical problems which did not lent themselves to straight forward engineering solutions.

2. Sufficient real estate would be available for the necessary liquefaction plant and storage tanks.

3. Relatively conventional ground-support setups and passenger facilities could be used.

4. Turnaround times for LH_2 aircraft are consistent with those of Jet-A aircraft.

SYNTHETIC FUELS IN AIRCRAFT

The subjects of synthetic fuels production and the potential impact of their introduction at the air terminal have been discussed. The next subject is that of determining just how the fuels compare as aircraft fuels. The fuels must be stored onboard the aircraft and delivered to the engines as required. Aviation kerosene is generally housed at an ambient pressure in tanks within the wings and wing box of an aircraft. Onboard storage of LCH_4 or LH_2 is complicated by the fact that they are cryogenic fuels, requiring insulated and pressurized tanks to avoid excessive fuel boiloff. Further, the energy content per liter of LCH_4 and LH_2 is less than that of aviation kerosene (see Table 1) and therefore larger tanks are required to contain these fuels. The NASA/Langley studies have not yet addressed the subject of liquid methane-fueled subsonic aircraft but have addressed liquid hydrogen fueled subsonic aircraft.

LH_2 Fueled Aircraft

The NASA's interest in the use of liquid hydrogen as an aviation fuel stems from several attractive features of the fuel. It has 2 3/4 times the energy of an equal mass of aviation kerosene. It also has wide flammability limits, a high flame speed, and excellent mixing characteristics all of which are factors that help to assure efficient combustion, flame stability in the engines, and help to prevent engine blowouts (9).

The NASA has flown a hydrogen fueled aircraft (10). In 1957 NASA's Lewis Research Center installed an LH_2 tank on the wingtip of a B-57 aircraft and successfully operated one of the aircrafts two engines on hydrogen fuel during cruise. Although the size of the LH_2 tank limited the aircraft to about 20 minutes of cruise on hydrogen fuel, a number of flights were made, demonstrating that a conventional jet engine could be modified to operate on LH_2, and that a workable, safe fuel storage and delivery system was possible.

As part of the Langley effort the question of just how well LH_2 would perform as a fuel for subsonic transport aircraft was addressed in a contract study by the Lockheed California Company (11, 12). The study considered the performance characteristics of both LH_2 and conventional aviation kerosene (Jet-A) fueled aircraft and considered a variety of design ranges and payloads. Both passenger and cargo aircraft were considered in the study. The design range-payload characteristics of the aircraft considered are shown in Table 3. The passenger aircraft which had a 9265-kilometer radius was designed to carry 400 passengers 9265 kilometers, land, takeoff unrefueled, and carry 400 passengers another 9265 kilometers. The maximum nonstop ranges were 19,590 kilometers for the LH_2 aircraft and 19,980 kilometers for the Jet-A aircraft.

LH_2 Fuel Containment.- A variety of approaches for housing the low-density liquid hydrogen were investigated by Lockheed. Three factors made it impractical to house the fuel in the wing. After about six inches of insulation were applied to all sides of a wing tank there was little useful space left for the fuel. Also the fuel tanks, if located in the wing, would tend to be flat and would result in a high ratio of tank surface area to volume of fuel housed, and thereby increase the gross heat transfer to the fuel. In addition, pressurization of the flat-walled tanks to avoid excessive fuel boiloff required additional tanks structural weight and complexity. The most promising concepts were those shown in Figure 6. The configuration in the foreground of Figure 6 housed the LH_2 within the fuselage, whereas the configuration in the background housed the LH_2 in tanks mounted on the wings. The advantages of the configuration with the external wing tanks were that it provided maximum separation of the passengers from the fuel in the event of a crash, the tanks could be sized independently of the fuselage, the tanks could easily be removed for repair, and the configuration provided easier maintenance. The advantages of the configuration with the fuel in the fuselage were its good volumetric efficiency in housing the fuel, it lent itself more easily to protection against engine burst, it provided safer access to servicing vehicles, and its performance was superior to that of the external wing tank version. The drag penalties associated with the wing-mounted tanks caused the performance of such aircraft to be inferior to the configuration with the fuel housed in the fuselage. For that reason, the fuel-in-fuselage configuration is favored.

LH$_2$ Aircraft Mass Characteristics.- Figure 7 shows the onboard fuel masses and gross takeoff masses of the passenger aircraft (11, 12) as a function of design range. The data show that hydrogen's high energy content per kilogram of fuel is reflected in the lower mass of fuel required by the LH$_2$ aircraft, compared to the Jet-A fueled aircraft. Aircraft having longer ranges and/or higher payloads require more fuel. The greater the amount of fuel required to perform the mission, the greater the fuel mass-saving advantages of hydrogen. The lower fuel masses of the LH$_2$ aircraft resulted in lower gross takeoff masses. Although hydrogen's low-energy density per unit volume (one-fourth that of Jet-A) caused additional drag which the airplane's engines had to overcome, less lift had to be generated in order to support the airplane because the LH$_2$ airplane had less mass. Lift is generated at the expense of drag incurred; and overall, the drag increases associated with the low energy per unit volume of LH$_2$ were overshadowed by the fact that less lift was required, smaller wings were required, and thus less total drag was incurred. This shows up in the area of fuel consumption.

Energy Requirements.- Figure 8 shows the relative energy requirements, based on the lower or net fuel heating values, of the LH$_2$ and Jet-A aircraft of the Lockheed study. The energy requirements are presented as the ratio of kilojoules per seat kilometer of the LH$_2$ aircraft to the kilojoules per seat kilometer of Jet-A aircraft, as a function of design range. The energy requirements of the cargo aircraft are shown as a ratio of the LH$_2$-to-Jet-A values for kilojoules per kilogram kilometer. The energy consumption analysis of Figure 8 considers both the onboard energy consumption (exclusive of the energy required to produce the fuels) and the total energy consumption (including the energy required to produce the fuels). Within the range of payloads considered in the Lockheed study, Figure 8 shows that for an airplane having a design range greater than about 4000 kilometers, the LH$_2$ fueled aircraft will use less onboard energy than would its Jet-A fueled counterpart. The greater the range, the greater the fuel savings associated with the LH$_2$ aircraft.

If one chooses to determine how efficiently coal might be utilized as an aircraft fuel, the Lockheed aircraft study results can be combined with the IGT/Linde fuel production studies. Returning to Figure 8, the energy requirements for producing LH$_2$ and aviation kerosene from coal (Table 2) have been combined with the Lockheed aircraft performance data to produce the curve shown on the right of Figure 8. The thermal efficiencies used here are 49 percent for LH$_2$ (Steam-Iron process) and 54 percent for synthetic aviation kerosene. It is assumed herein that coal-derived synthetic aviation kerosene will perform as well in aircraft as conventional aviation kerosene. As more information is gained about the production of this fuel and its properties it may possibly be determined that tradeoffs should be made between fuel production and fuel specifications, perhaps sacrificing some fuel specifications to better accommodate what is practical in the area of fuel production. The dashed curve in Figure 8 indicates that aircraft must have design ranges in excess of 8000 kilometers before coal-derived LH_2 fuel aircraft are more energy efficient than coal-derived aviation kerosene fueled aircraft. Transfer and storage losses are not considered in Figure 8, but as pointed out in Reference 5, such losses should be larger for LH_2 than for aviation kerosene.

The reader is cautioned against making hard decisions based on the curve presented on the right in Figure 8, because of the sensitivity of the results to changes in technology. For instance, a 20 percent decrease in the energy requirements for the liquefaction of the hydrogen would move the total energy curve back over to the 4000-kilometer crossover point. Such a 20-percent improvement potential has already been identified in the Linde study (6).

Critical LH_2 Aircraft Technologies.- Perhaps the two most critical technology items associated with the LH_2 aircraft are that of obtaining a suitable cryogenic insulation system for fuel storage onboard the aircraft and pumps capable of delivering the fuel to the engines in the quantity and state required by the engines.

Insulation: Insulation concepts must be very light, safe, reliable, economically practical, and have a long service life. Insulation concepts developed for use in space generally do not have the useful life required for aircraft application. Insight into the problem of finding a suitable insulation may be gained by examining the approach wherein a foam insulation is bonded to the exterior surface of the fuel tank. If the foam insulation is porous, the gases surrounding the tank will enter the insulation and liquefy, causing cryopumping to occur. If the gas surrounding the tank is air, selective liquefaction of oxygen may occur and an oxygen rich environment in the area surrounding the tanks is a most undesirable situation from the standpoint of safety. NASA-sponsored studies of the broader aspects of hydrogen safety are currently underway. Regardless of what the composition of the gas surrounding the insulation may be, if the gas enters the insulation and liquefies, it may quickly gasify within the insulation when the tank is emptied and warms up, and may cause the insulation to pop off.

Another problem with external foam insulation is the difference between the coefficient of thermal contraction of most foam insulations and that of 2219 aluminum, which is generally regarded as the best material for tank construction. The thermal contraction of most foam insulations is from two to four times that 2219 aluminum. The difference causes high tension stresses in the insulation near the tank wall and compressive stresses in the outer portion of the insulation. Such stresses may lead to structural failure of the insulation.

NASA-sponsored efforts are currently underway to advance the technology status of cryogenic insulation systems for LH_2 aircraft tankage. These efforts involve the testing of available foam insulations and the formulation and testing of additional foam insulations.

Pumps: Engine fuel requirements at climb are 15 times that required for engine flight idle. A pump capable of delivering LH_2 to the engines at all throttle conditions at the desired pressure, without cavitating, and exhibiting a long life and reliability has not yet been developed.

The major NASA/Langley effort during the current year is an engineering analysis of the characteristics of the total fuel system requirements for LH_2 aircraft. The analysis is being conducted for Langley by the Lockheed-California Company and includes consideration of all components of the aircraft fuel system, from the lid on the fuel tank to and including the engines.

ENVIRONMENTAL EMISSIONS

If synthetic aviation kerosene is to have the same thermal physical and chemical properties as conventional jet fuel, the emissions should be the same. If, however, the specifications are changed to better accommodate those which can practically be achieved in synthetic fuel production, the emissions may change. For instance, synthetic aviation kerosene produced via the hydrogenation of coal is high in aromatics. Aromatic content can be decreased by adding further hydrogen but this is expensive in terms of both money and energy. If the specifications for aromatic content are relaxed, engines using such fuels will produce more smoke and more oxides of nitrogen (NO_X).

Liquid methane would make an excellent fuel from the standpoint of emissions. Methane's high ratio of hydrogen-to-carbon atoms and the ease with which it can be vaporized and mixed with combustor air give it excellent combustion characteristics.

Liquid hydrogen appears to be environmentally superior to all other candidate aviation fuels. Hydrogen fueled aircraft would have as their only emission, water vapor and NO_X. Water vapor emissions should be about 2-1/4 times those of Jet-A fueled aircraft. Studies are currently underway at NASA to attempt to determine the effect of water emissions from LH_2 aircraft on the upper atmosphere.

There is every reason to believe that the NO_X emissions of hydrogen-fueled jet engines could be reduced to levels well below that of Jet-A fueled engines. The flame speed associated with the combustion of hydrogen is about 10 times that of hydrocarbon fuels and therefore shorter combustion zones should be permissible in the LH_2 fueled jet engines. Shorter combustion zones mean less dwell time in the combustion zone, and shorter dwell times mean lower NO_X formation (15).

Because of the very low flammability limit of hydrogen when mixed with air (4 percent hydrogen, by volume, for an upward burning flame and 8.5 percent hydrogen for a downward burning flame), there is a potential for further NO_X emissions reductions. If the maximum temperature in the engine can be reduced, the formation of NO_X can be reduced. Lower flame temperatures should be obtainable via lean burning. Currently, jet engines combine about 25 percent of the airflow (fan air excluded) with the fuel in the primary combustor where burning occurs. The remaining three-fourths of the air is then used to dilute the combustion products gases, the combination of the two producing the turbine inlet temperature from whence the power is derived. The lean flammability limit of hydrogen offers the possibility of enlarging the diameter of the primary combustor and allowing more air to be mixed with the fuel and burned in the primary combustion zone (lean burning). As a result of the lean burning, lower temperatures will occur in the primary combustion zone and, thus, lower NO_X formation (order of magnitude) will occur. There will be less air to dilute the combustion products and proper balance of primary combustor and diluent air could be struck to maintain the turbine inlet temperature required to power the aircraft.

CONCLUDING REMARKS

The results of studies conducted for and by the NASA Langley Research Center, and aimed at assessing the potential use of coal-derived aviation fuels have been reported. The studies have considered the production of coal-derived aviation kerosene, liquid methane, and liquid hydrogen. Air terminal requirements and subsonic transport aircraft performance studies have thus far addressed only liquid hydrogen. Within the scope of the studies, the following concluding remarks can be made.

1. If coal is to be the energy resource from which alternate aviation fuels are produced, less coal is required to produce a given amount of energy in the form of liquid methane than is required to produce the same amount of energy in the form of liquid hydrogen or synthetic aviation kerosene. Coal-derived liquid methane will also have a lower price than either of the other two coal-derived fuels.

2. Cryogenic aviation fuels will require special facilities and procedures at the air terminal. It was determined that it is technically feasible to provide hydrogen liquefaction, storage, distribution and fueling facilities at a major air terminal. The time required to refuel a liquid hydrogen fueled aircraft was found to be commensurate with that required to refuel with conventional aviation fuel. Air terminal facilities for refueling just wide-body aircraft would cost on the order of $400 million.

3. Liquid hydrogen fueled subsonic transport aircraft have the potential of consuming less onboard energy than aircraft fueled with conventional aviation kerosene, provided the design range of the aircraft is in excess of 4000 kilometers. As the fuel requirements for design missions increase, so do the potentials for onboard fuel savings via the use of liquid hydrogen fuel. A suitable cryogenic insulation system for housing the liquid hydrogen and pumps for delivering the fuel to the engines are major technology gaps which must be filled.

4. Liquid hydrogen fuel is environmentally superior to both aviation kerosene and liquid methane, having combustion products of only water vapor and oxides of nitrogen and no carbon compounds. Lean burning of hydrogen offers the potential of sizable reductions of oxides of nitrogen.

APPENDIX

This appendix contains a more detailed discussion of selected fuel production processes considered in the main body of the text. The production of synthetic aviation kerosene by the Fischer-Tropsch chemistry and the hydrogenation of coal are discussed as are the properties of their fuel products and their implication with regard to engine performance. Methane production via the HYGAS® and CO_2 Acceptor processes are discussed. Hydrogen production via the Steam-Iron process is discussed.

Synthetic Aviation Kerosene Production

There are two basic methods for converting coal to liquid fuels such as aviation kerosene. One method is known by the generic term as the Fischer-Tropsch process and the other method is through the addition of hydrogen to the coal.

Fischer-Tropsch.- In the Fischer-Tropsch process, coal is essentially completely gasified to a synthesis or producer gas (a gas rich in CO and H_2). 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, and fuel oil. 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 SASOL plant is now being expanded to operate via the Synthol process, which is a modification to the Fischer-Tropsch chemistry. The Synthol process uses a powdered iron catalyst which circulates at high flow rates together with the synthesis gas through the reactor. The improved process and temperature control provided by the Synthol catalyst and reactor design are reported to permit better control of product characteristics (14).

The products from processes designed around the Fischer-Tropsch type chemistry are highly paraffinic and olefinic in nature. Paraffinic and olefinic hydrocarbons have the maximum or near maximum possible hydrogen atoms. If hydrocarbons are low in hydrogen atoms they are known as aromatics. Current jet fuel specifications call for a maximum aromatic content of 20 percent. Fuels with higher aromatic content burn with significantly higher flame radiation, because of higher levels of carbon formed in the flame zone. High radiation levels result in higher combustor liner temperatures and usually reduced liner lifetime. High aromatic content is also conducive to the formation of carbon deposits in the engine, which can cause local hot spots in the combustor and thereby reduce combustor life. In addition, high aromatic content seems to increase smoke formation. Because of the high hydrogen (low aromatic) content of the fuels produced by Fischer-Tropsch type processes, such fuels are of interest because they would meet aromatic content specifications. A disadvantage of such fuels is the relative instability of olefins to gum formation at the high temperatures prevailing in jet engines. The type of olefins produced by the Fischer-Tropsch type chemistry are not of the type (diolefins) which more readily form gums, but none the less, the olefins can be hydrogenated (add hydrogen) to change them to paraffins (14) and thus avoid the formation of gums.

In reference 14, an analysis was reported which described how the Synthol process could possibly be modified to produce aviation kerosene. The process would produce some two dozen products. About 28 percent of the energy product would be aviation kerosene, 14 percent would be gasoline, and 14 percent would be fuel oil. The thermal efficiency quoted for the process was 64 percent. This efficiency is based on the gross or high heating values of the feedstock and products. In terms of lower or net heating values, the thermal efficiency would be about 61 to 62 percent. It should be pointed out that if output of a plant is allowed to include a large number of products, the thermal efficiency is generally higher because it allows the plant to match its products to the products which evolve more efficiently from the various process steps.

Addition of Hydrogen.- This can be accomplished by three different methods - carbonization, direct hydrogenation, and extraction. All three of these processes react hydrogen with coal at elevated temperatures and pressures.

Carbonization: In carbonization, coal is heated in the presence of hydrogen and in the absence of air, causing the coal to decompose and to evolve tar and gas The tar and gas are then treated to yield clean gas and liquid fuels.

Direct Hydrogenation: In direct hydrogenation a coal slurry is reacted (usually with a catalyst) with hydrogen gas at a high pressure (about 85 atmospheres). The material from this process is distilled to yield both gaseous and liquid fuels.

Extraction: In the extraction process the 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 and the solvent then acts as a hydrogen donor during the mixing process. The effluent from the reactor yields a variety of hydrogenated gases and liquids, plus the solvent itself, which is then rehydrogenated and recycled to the reactor.

In all three of these basic hydrogen addition processes, the hydrogen which is required is produced by the gasification of char (devolatized coal) with steam and oxygen. Liquids derived from these three types of processes tend to be quite high in aromatics and if aviation kerosene, capable of meeting the 20 percent aromatics specification, is to be produced from the liquid products, the hydrogen content of the fuels must be increased.

Consol Synthetic Fuel Process.- In the analysis of coal-derived aviation kerosene production done for NASA/Langley by the Institute of Gas Technology (4,5), it was assumed that the feedstock used for the production of aviation kerosene would be produced by the Consol Synthetic Fuel (CSF) process. The

CSF process is representative of the extraction type process. As shown in Figure 9, the CSF process was used to produce naptha, high Btu gas, heavy oil, sulfur, and ammonia. The naptha, sulfur, and ammonia were credited as a by-product. Concerning the nigh Btu gas, 15 percent was accounted for as a by-product; 9 percent was used for power generation, 12 percent was used for plant fuel; and 65 percent was used to manufacture hydrogen for hydrocracking and aromatic hydrogenation of the liquid product in order to produce a kerosene that would meet the 20 percent maximum aromatic content specifications. The hydrogen was manufactured from the high Btu gas via steam reforming or the reaction of CH_4 with steam over a catalyst.

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

Methane Production

HYGAS®- The HYGAS® process is currently being studied by the Institute of Gas Technology under the sponsorship of ERDA and the American Gas Association to determine its potential for producing synthetic natural gas (pipeline natural gas typically contains from 70 to 95 mole percent CH_4). The methane is formed in three conversion zones, which are stacked one on top of the other, with the higher temperature and slightly higher-pressure reactions occurring at the bottom and the lower temperature slightly lower-pressure reactions occurring at the top. There is a continual upflow of the gases from the lower zones to the upper zones. Because the process operates at pressures of 8200 kN/m^2 (1174 psig), the coal is pumped in as a high pressure water-coal slurry. The preheated water-coal slurry is introduced into a vaporizer which is located atop the highest reaction zone. The hot gases from the three zones below the vaporizer are used to vaporize the slurry water. These gases leaving the vaporizer constitute the output of the gasifier. The water vapor from the slurry must, of course, be removed. After the water-coal slurry has been evaporated the dried coal drops to the top reaction zone where, together with recycle char from the middle zone, it is picked up by the effluent gas from the lower zones and the dried coal and char are devolatized. Again, char is merely coal which has had some of its volatiles removed. This process enriches the effluent gases coming up from the lower zones. Of the methane formed in the gasifier, about 9 percent of it is formed in the top zone. The enriched gases from this process go through a cyclone separator before they are used to vaporize the slurry. The char from the separator is divided into recycle feed for the top zone and feed for the middle zone. In the middle zone the char is reacted with gases from the lower zone to produce more methane by the reaction

$$C + 2H_2 \longrightarrow CH_4 \ .$$

Of the methane formed in the gasifier, about 67-percent is formed in the middle reaction zone. The char from the middle zone is reacted with oxygen and steam in the bottom zone to produce the synthesis or producer gas required to supply the hydrogen for the gasification process. Of the methane formed in the gasifier about 24 percent is generated in the bottom gasifier.

The product gas from the top of the gasifier then goes through the basic steps covered in Figure 3, in order to upgrade the gas and increase its methane content. This includes a CO shift step to adjust the H_2/CO ratio from 1.8 in the gasifier effluent to about 3.2 for methanization of CO. Of the total methane produced by the HYGAS® process about 50 percent is produced in the gasifier and 50 percent is produced by methanation.

<u>CO_2 Acceptor</u>.- This process is currently being studied in a large pilot plant at Rapid City, South Dakota, to determine its potential for producing synthetic natural gas. The studies are being sponsored by ERDA and the American Gas Association. The CO_2-Acceptor process derives its name from the fact that the heat required to drive the gasification reaction between coal and steam is supplied by the exothermic reaction of CO_2 with dolomite, Mg O-CaO, which is the acceptor of the CO_2. This reaction is

$$MgO - CaO + CO_2 \longrightarrow MgO - CaCO_3 \quad \text{(exothermic)}$$

The dolomite is supplied to the gasifier by a separate regeneration unit where the reacted dolomite from the gasifier is subjected to heat and the CO_2 is driven out of the dolomite by the following reaction:

$$MgO - CaCO_3 \longrightarrow MgO - CaO + CO_2 \quad \text{(endothermic)}$$

The heat required to drive this regeneration reaction is supplied by burning the residual char (62 percent of the carbon in the coal has already been gasified) from the gasifier, in the bottom of the regenerator, using air as an oxidizer. The regenerated dolomite is returned to the gasifier and the CO_2 is later reclaimed from the regenerator off-gas and is used to supply part of the CO_2 required to react with the dolomite in the gasifier. The additional CO_2 required to react with the dolomite in the gasifier is supplied by the CO_2 generated in the gasification that occurs within the gasifier itself.

About 37 percent of the product methane is actually produced in the gasifier. The balance is produced by methanation of the gasifier effluent. The H_2/CO ratio of the gasifier effluent is sufficient to provide enough H_2 for methanation of both the CO and CO_2 present and therefore no CO shift or CO_2 removal is required.

For each 10^6 Btu (106 Btu = the energy content in 8 gallons of gasoline) of CH_4 produced in the gasifier, about 1090 kilograms (2400 pounds) of dolomite must be circulated through the gasifier. The dolomite loses reactivity as it circulates between the gasifier and the regenerator and the spent dolomite (about 3 percent of the dolomite flow) must be replaced with fresh dolomite. Although dolomite is a naturally occurring substance, the studies being conducted at Rapid City, South Dakota include investigations of methods of reactivating the dolomite.

The regenerator off-gas, which is at a temperature of 1293 K (1867° F) and a pressure of 1115 kN/M^2 (147 psig) contains, besides CO_2, small quantities of CO, H_2 and sulfur compounds. This energy can be recovered in a combined cycle system to produce electrical power as is done in the Steam-Iron process. After internal plant electrical power requirements have been satisfied, a sizable electrical by-product still exists. If, in bookkeeping the by-product electrical power, the power is expressed as equivalent thermal energy the electrical by-product represents 2.5 percent of the heating value of the coal used in the process. If the electrical by-product is represented as the heating value plus the sensible heat of the gas which produces the electrical power, the eletrical power by-product represents 6 percent of the heating value of the coal used in the process.

At this point one might ask oneself the question, "If you have to make at least half of the methane through the methanation reaction, why go to all the trouble of looking at somewhat complicated schemes like the HYGAS® and CO_2 Acceptor processes? Why not use a more simple gasifiers similar to the Koppers-Totzek and U-GAS™ processes and then methanate the gasifiers products to produce methane or use the CO shift conversion to produce hydrogen, depending upon which product is desired?" The more complicated methods are used in an attempt to cut down the cost of the fuel produced. This can be done by two methods: by decreasing plant investment and by decreasing the amount of coal required to produce the fuels. Oxygen requirements are a key factor. The Koppers-Totzek process requires four times as much oxygen as the HYGAS® process. The U-GAS™ process requires about three times as much oxygen as the HYGAS® process. The Steam-Iron process for producing hydrogen and CO_2 Acceptor process uses air in place of oxygen. The investment cost of an oxygen plant can be quite high (about 18 percent of total plant investment for the U-GAS™ process) and the separation of oxygen from air requires energy. In the Koppers-Totzek and U-GAS processes the coal requirements of their oxygen plants amounts to nearly 7 and 10 percent of their total coal requirements, respectively. The higher thermal efficiencies associated with the more sophisticated processes are obvious when Table 2 is examined.

Hydrogen Production

Steam-Iron. The Steam-Iron process has been used commercially to produce hydrogen for years. A schematic of the Steam-Iron process is shown in Figure 10. The hydrogen produced by the Steam-Iron process is not produced in the gasifier but is produced in a separate unit (an oxidizer) where steam is decomposed by reaction with iron oxide as follows:

$$3FeO + H_2O \longrightarrow Fe_3O_4 + H_2$$

Coal is gasified with steam and air to provide a producer gas, the composition of which is shown in Figure 10. The purpose of the producer gas is to supply the CO and H_2 for regeneration of the iron oxide which occurs in a reductor:

$$Fe_3O_4 + CO \longrightarrow 3FeO + CO_2$$

$$Fe_3O_4 + H_2 \longrightarrow 3FeO + H_2O$$

Air can be used in the gasifier instead of oxygen because the hydrogen product gas is not formed in the gasifier, but in the oxidizer, where the iron oxide acts as a barrier against the nitrogen in the air. No CO shift is required in the Steam-Iron process since the product gas is not made directly from the synthesis gas.

Not all the CO and H_2 in the producer gas are expended in reducing the Fe_3O_4 to FeO and the remaining spent producer gas, the composition of which is shown in Figure 10, has a heating value plus sensible heat at 1100 K (1520° F) corresponding to 54 percent of the input coal value. The reductor off-gas is burned in a combustor and expanded 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 by-product gas (heating value plus sensible heat) or electrical power generated from the gas is credited as the by-product energy, the thermal efficiency of liquid hydrogen produced via the Steam-Iron process is 49 percent or 44 percent.

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TABLE 1. - SYNTHETIC AVIATION FUELS PROPERTIES

FUEL	HEAT OF COMBUSTION		BOILING POINT
	kJ/kg	kJ/l	
JET-A	43 200 (1.0)*	33 700 (1.0)*	372 K
LCH_4	50 000 (1.16)*	20 700 (0.62)*	112 K (CRYOGEN)
LH_2	119 900 (2.27)*	8 500 (0.25)*	20 K (CRYOGEN)

(1 kJ/kg = 0.43 Btu/lb)

(1 kJ/l = 3.59 Btu/gal)

* Compared to JET-A

TABLE 2. - THERMAL EFFICIENCY OF PRODUCING SYNTHETIC AVIATION FUELS FROM COAL

(BASED ON NET HEATING VALUE OF ALL FUELS)

Product	Process	By-products	Thermal efficiency, percent	
			Coal to SCF products	Coal to kerosene
Aviation kerosene	Consol Synthetic Fuel (CSF) + hydrocracking+hydrogeneration	Hydrogen liquids Chemicals Gas	70	54

Product	Process	By-products	Thermal efficiency, percent	
			Coal to gas	Coal to liquid
METHANE	CO_2 Acceptor	Chemicals Electricity	63	
		Chemicals Electricity Gas		59
		Chemicals Gas	67	63
	HYGAS®	Chemicals	67	
		Chemicals Gas		64
HYDROGEN	Koppers-Totzek	Chemicals	51	
		Chemicals Gas		38
	U-GAS ™	Chemicals	59	
		Chemicals Gas		42
	Steam-Iron	Electricity	62	
		Electricity Gas		44
		Gas	77	49

TABLE 3. - RANGE CHARACTERISTICS OF AIRCRAFT CONSIDERED IN PERFORMANCE STUDY

RANGE, KILOMETERS	PAYLOAD	
	NO. PASSENGERS	KILOGRAMS
PASSENGER AIRCRAFT		
2 780	130	
5 560	200	
5 560	400	
10 190	400	
9 265 (RADIUS)	400	
CARGO AIRCRAFT		
5 560		56 700
10 190		113 400

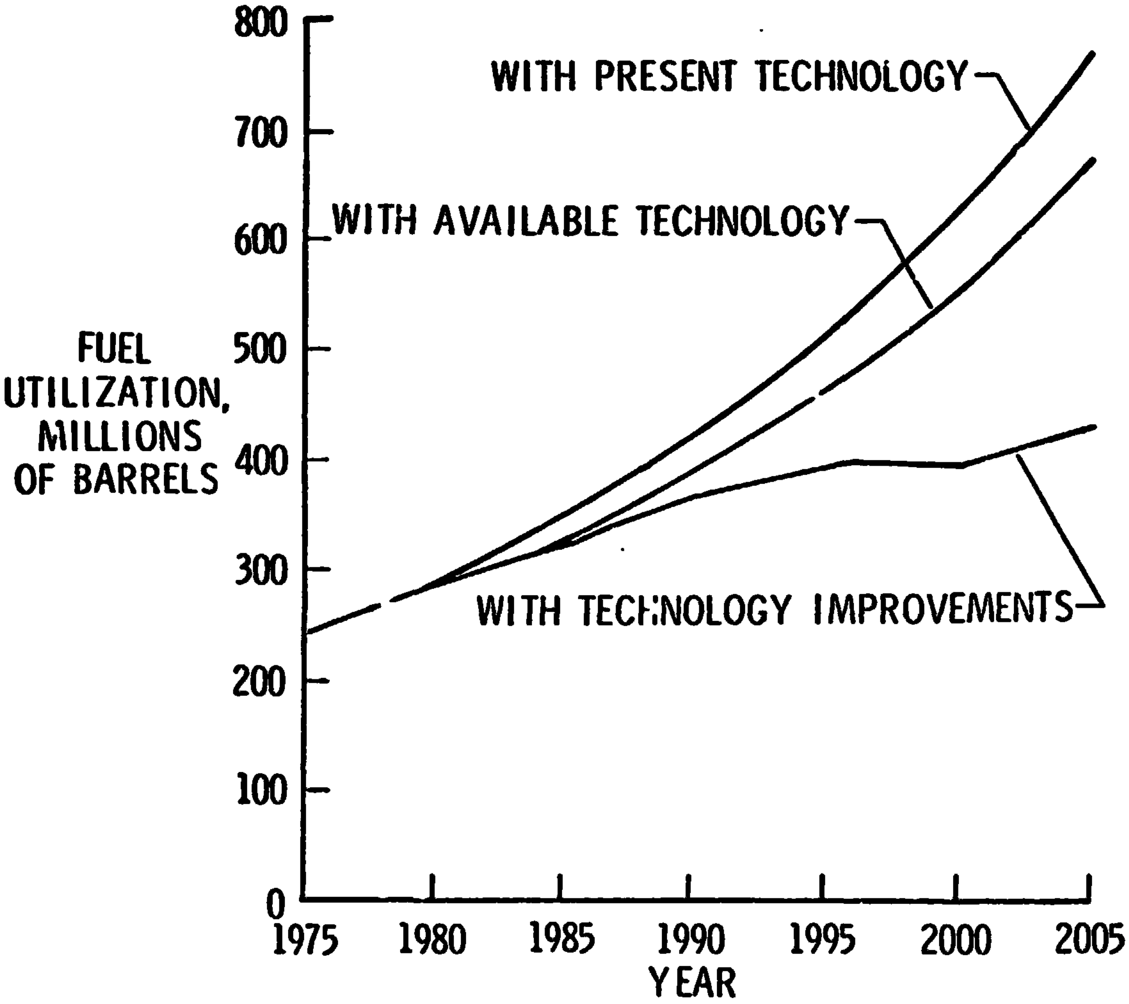


Figure 1. - Forecast of U.S. airline fuel use.

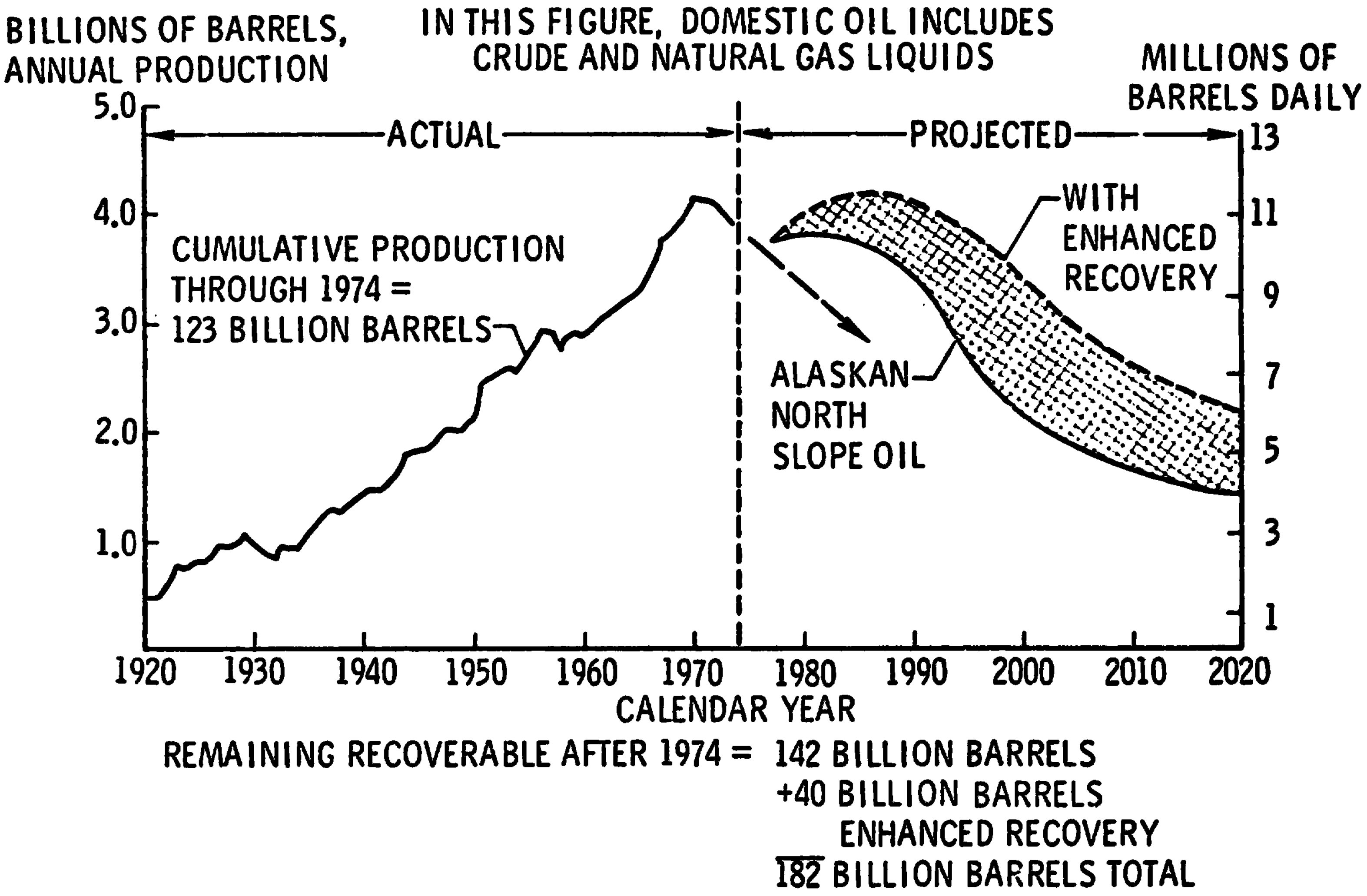


Figure 2. - Projected U.S. domestic oil production.

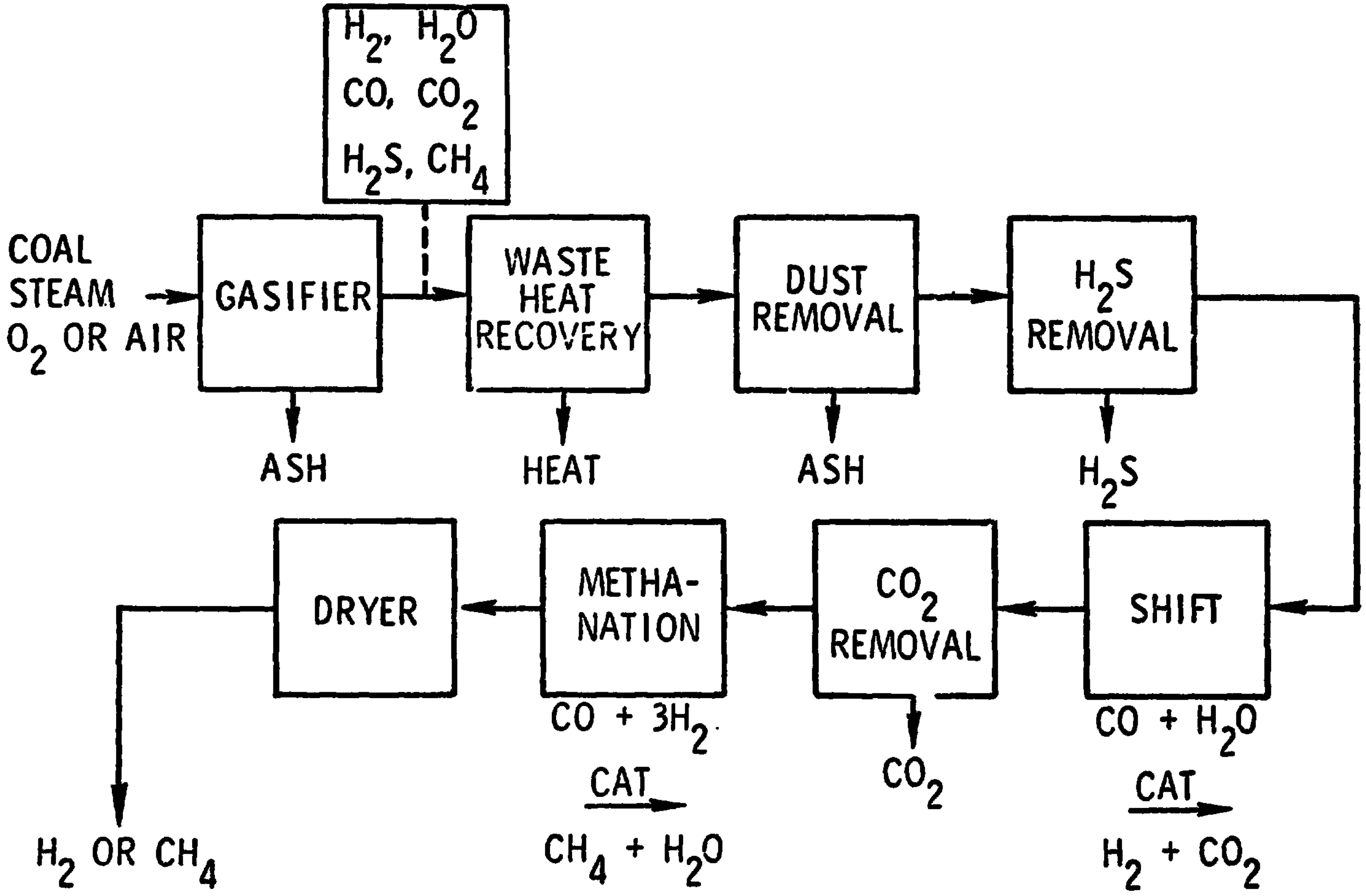


Figure 3. - Schematic of basic process for production of coal-derived fuels.

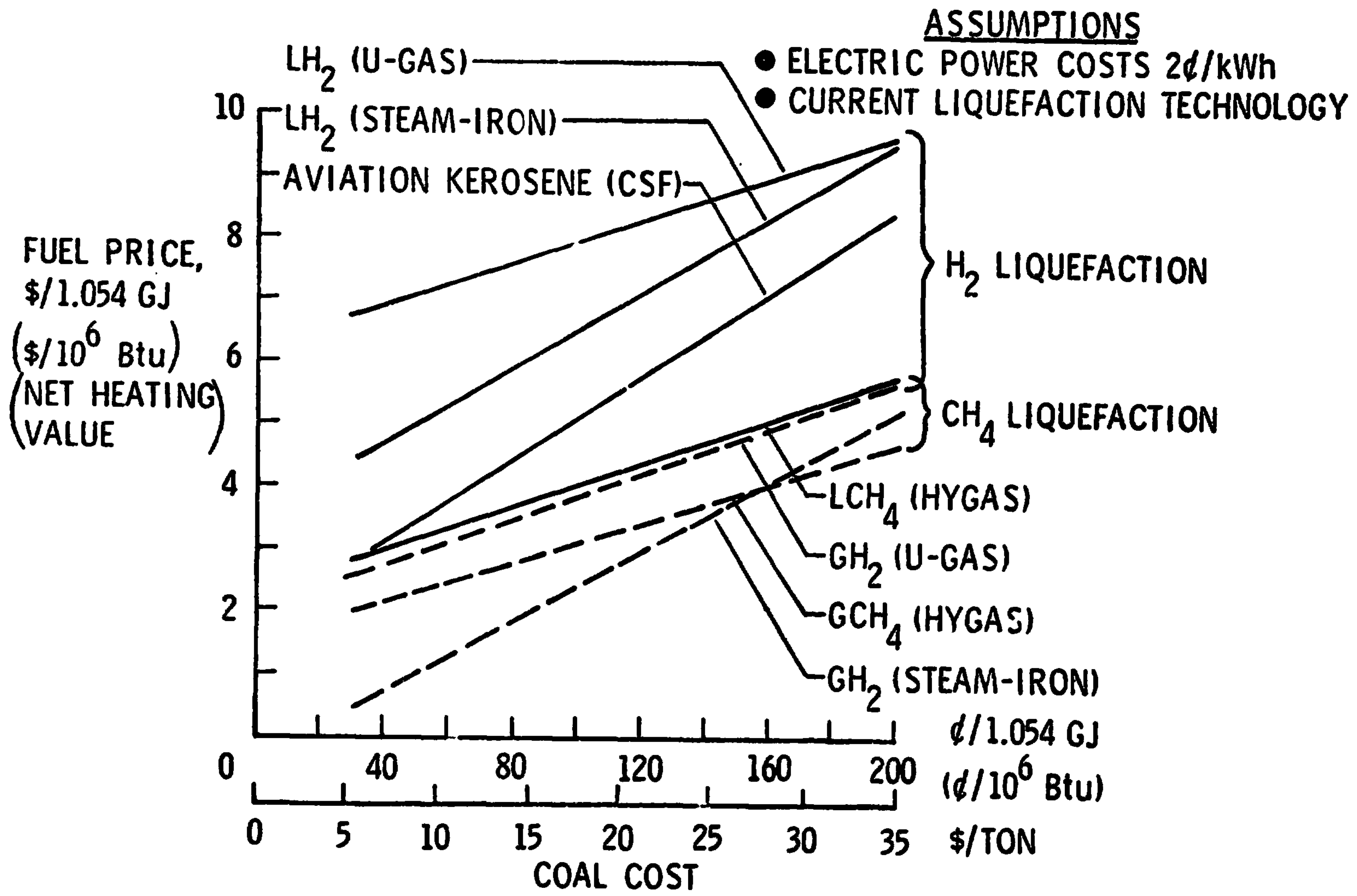


Figure 4. - The price of coal-derived aviation fuels as a function of coal cost.

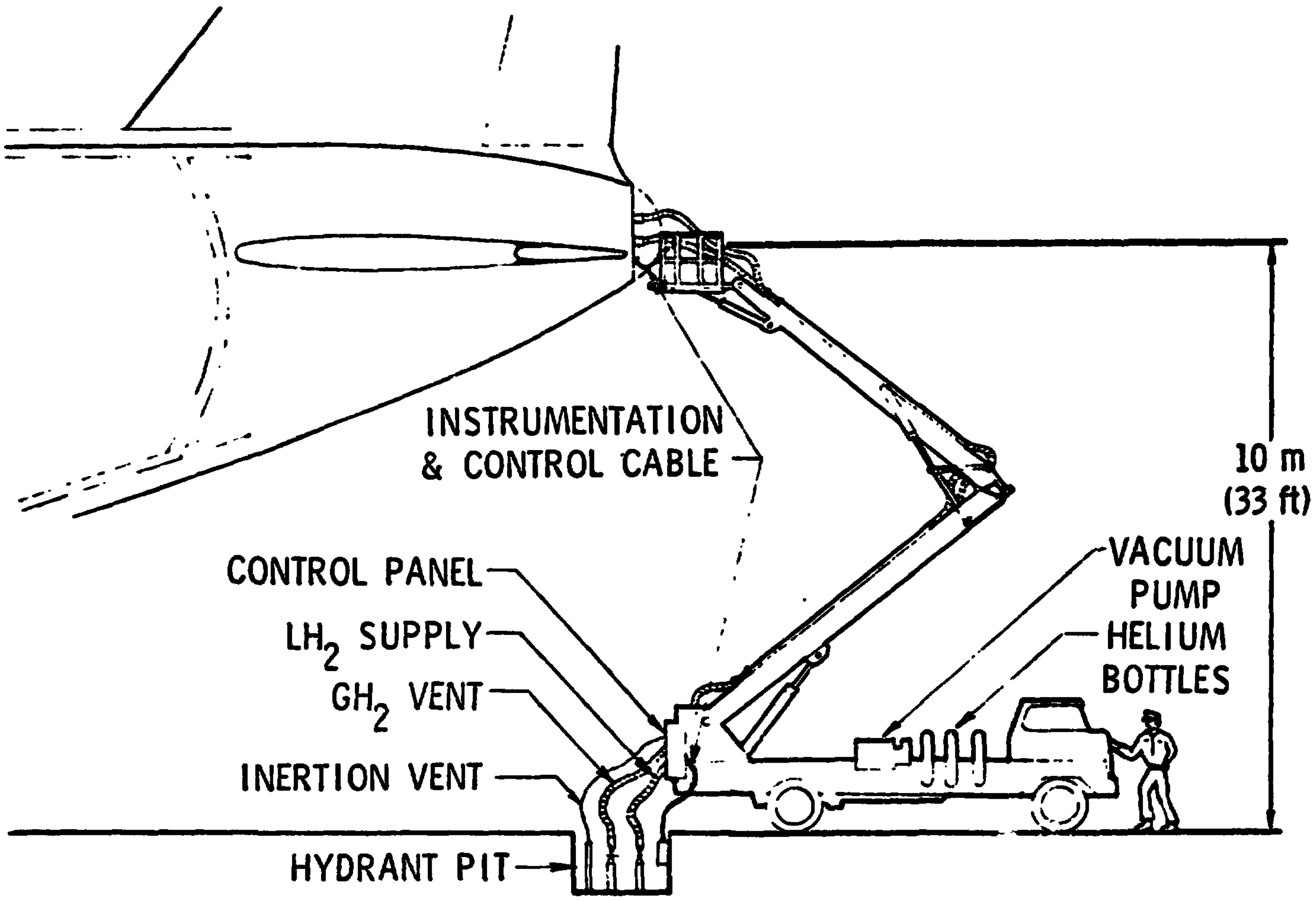


Figure 5a. - LH_2 aircraft fueling via hydrant truck.

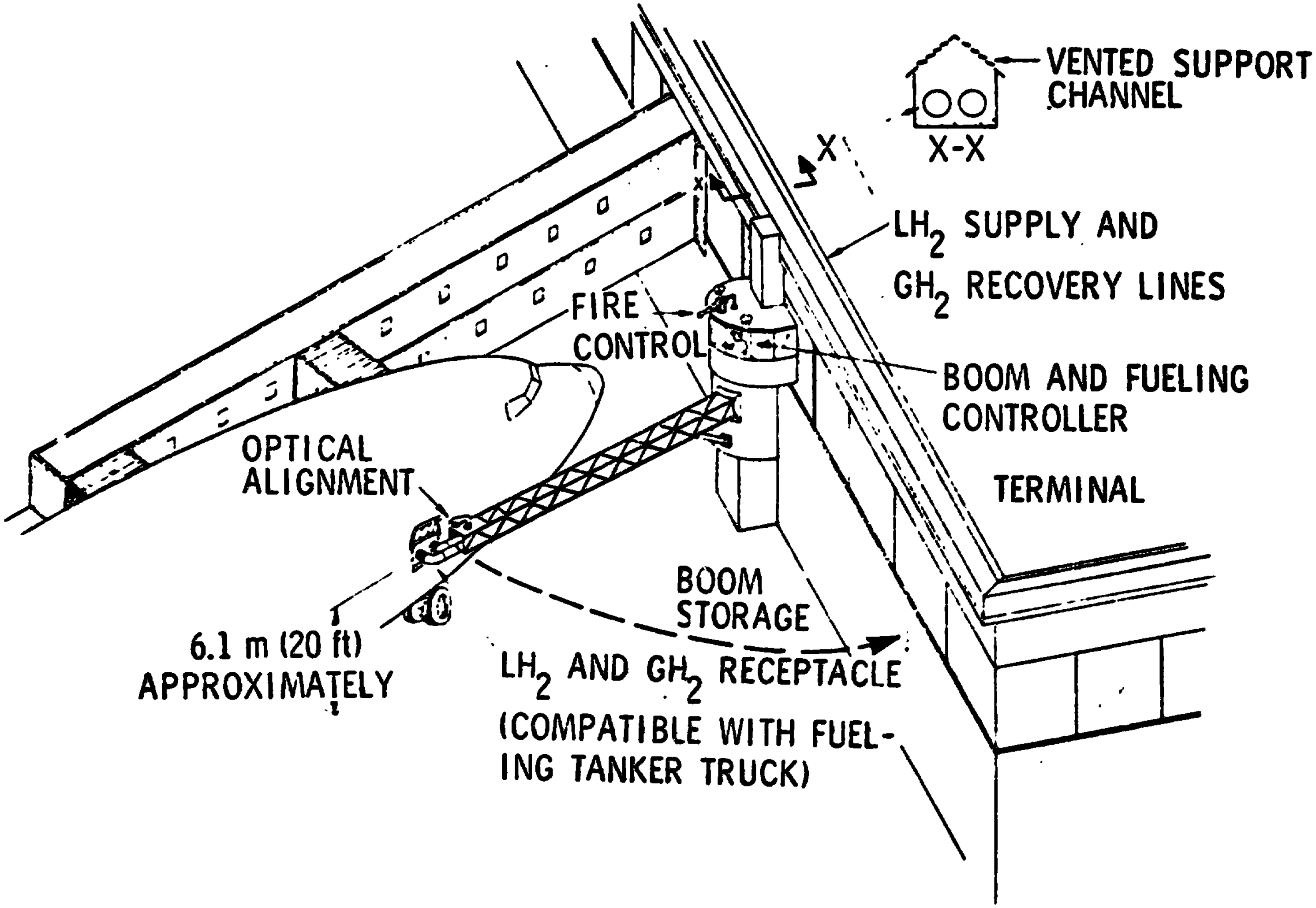


Figure 5b. - LH$_2$ aircraft fueling via terminal boom.

Figure 6. - Two concepts for housing LH_2 aboard aircraft.

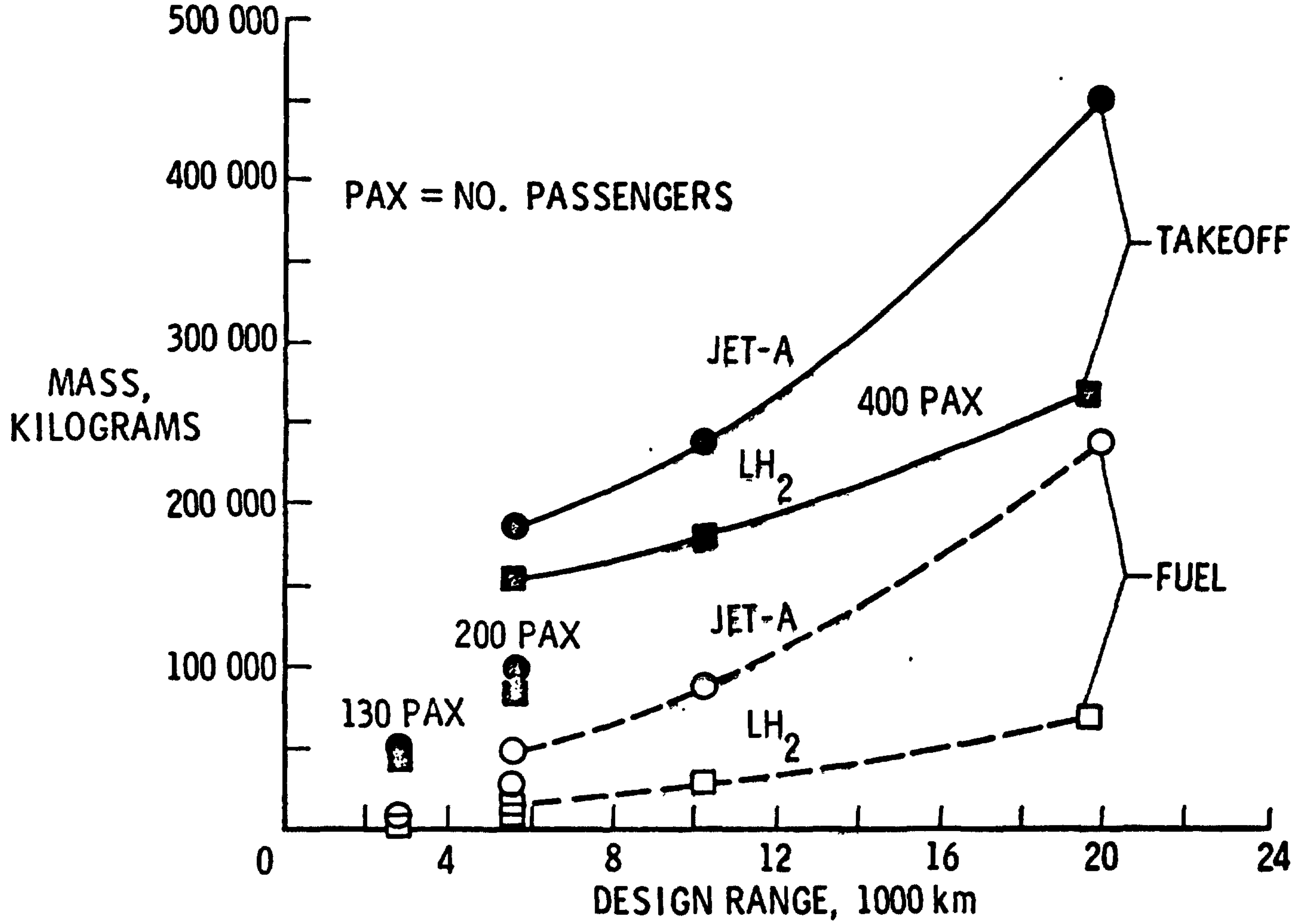


Figure 7. - Mass characteristics of LH_2 and Jet-A passenger transport aircraft.

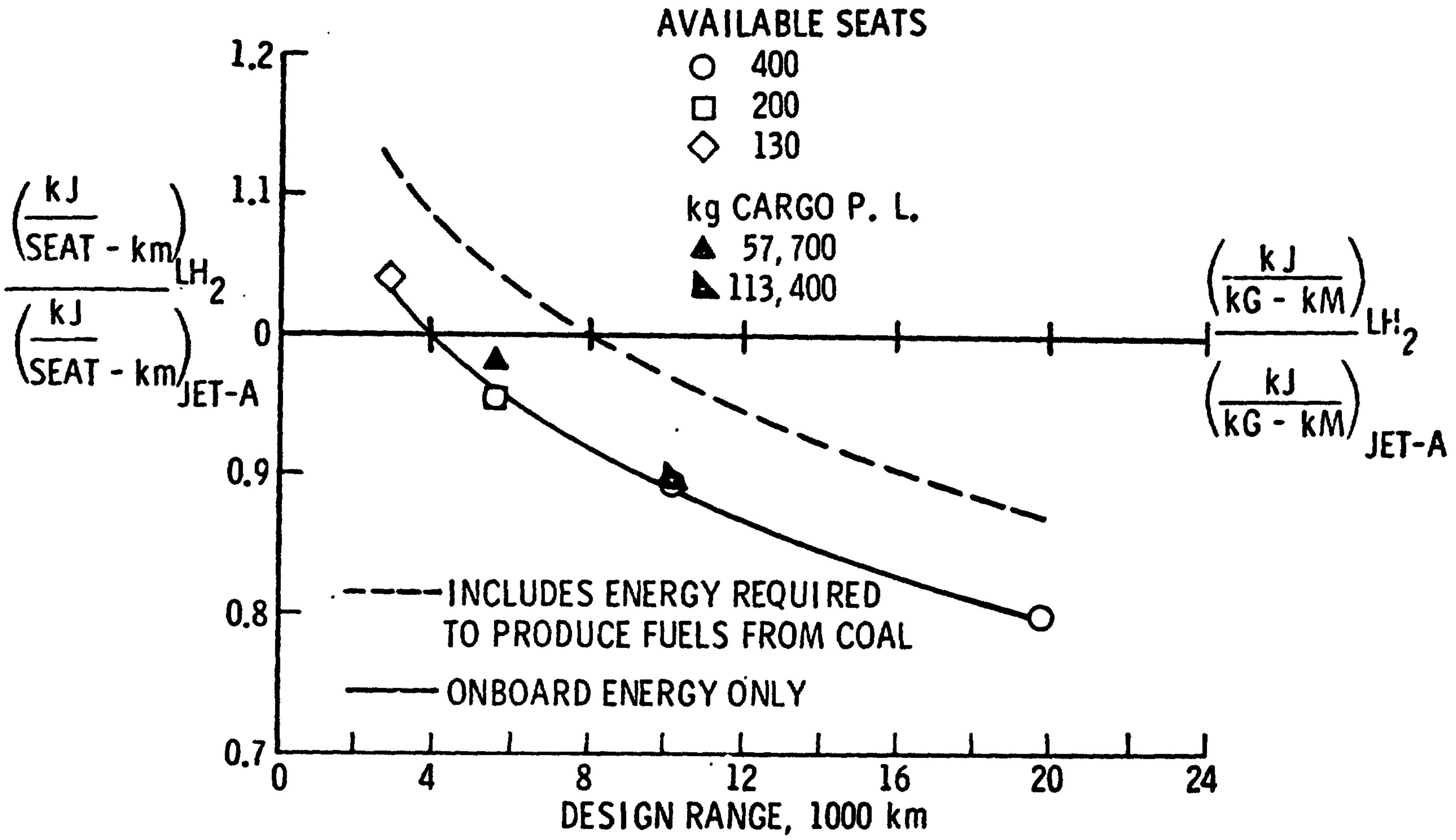
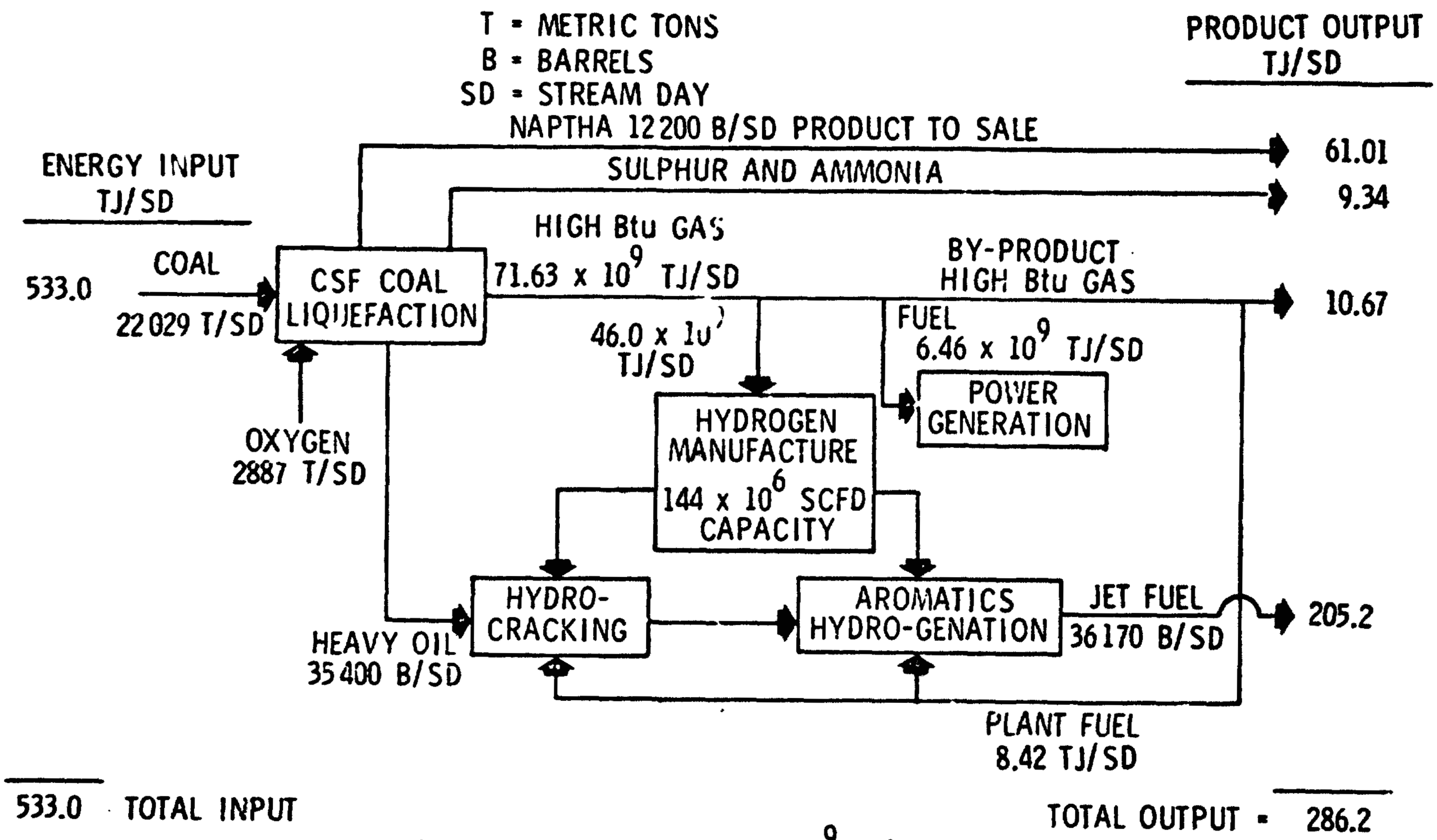


Figure 8. - Relative energy consumption of LH_2 and Jet-A transport aircraft.



$$\text{THERMAL EFFICIENCY} = \frac{286.2 \times 10^9 \text{ TJ/SD}}{533.0 \times 10^9 \text{ TJ/SD}} = .537 \text{ (NET HEATING VALUES)}$$

Figure 9. - Schematic of process for producing aviation kerosene from coal-derived CSF products.

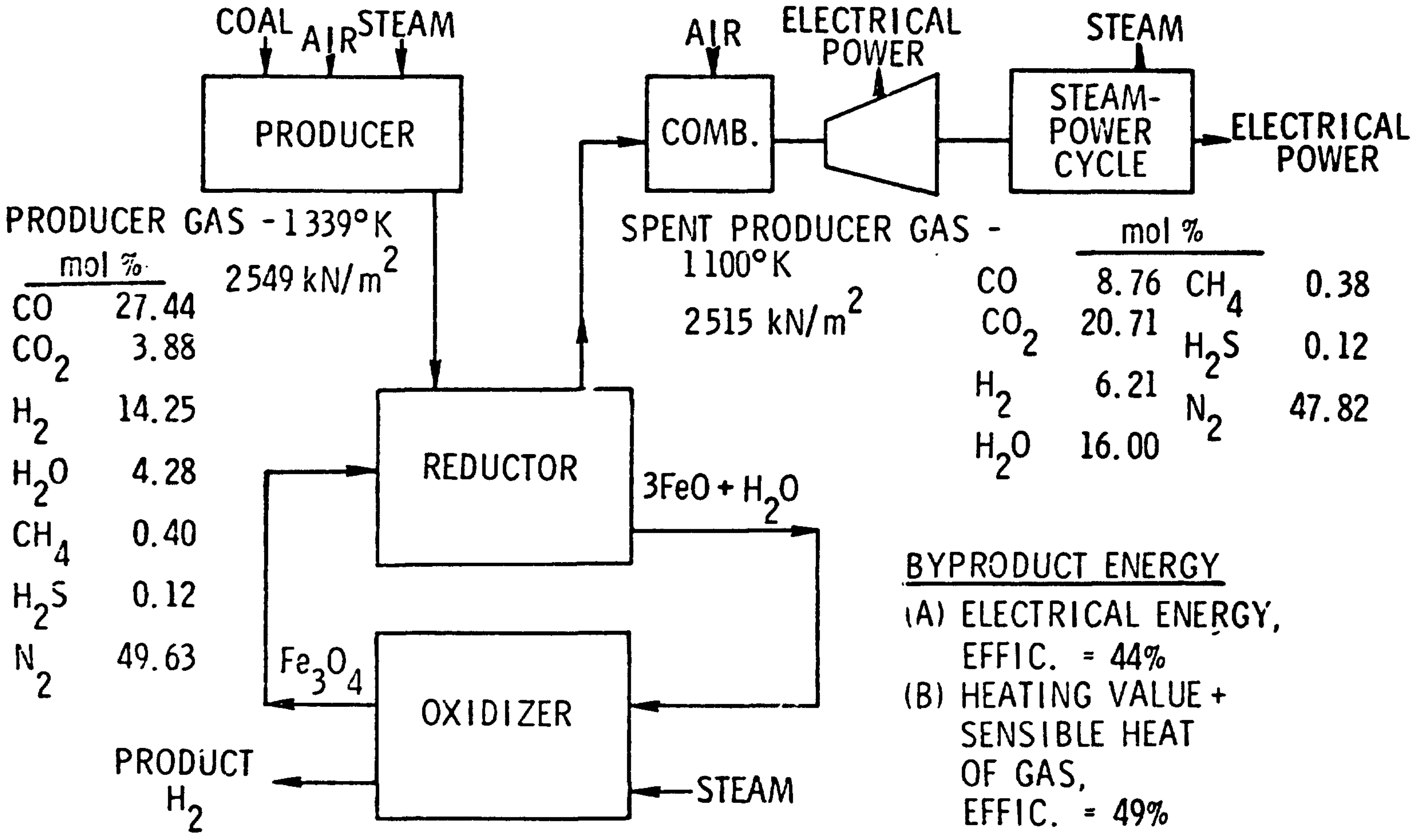


Figure 10. - Schematic of Steam-Iron process for producing hydrogen from coal.

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16. Abstract

The results of studies conducted for and by the NASA's Langley Research Center, aimed at assessing the potential use of coal-derived aviation fuels are reported. The studies addressed the prices and thermal efficiencies associated with the production of coal-derived aviation kerosene, liquid methane and liquid hydrogen and the air terminal requirements and subsonic transport performance when utilizing liquid hydrogen. The fuel production studies indicated that liquid methane can be produced at a lower price and with a higher thermal efficiency than aviation kerosene or liquid hydrogen. Ground facilities for liquefaction, storage, distribution and refueling of liquid hydrogen fueled aircraft at airports appear technically feasible. The aircraft studies indicate modest on-board energy savings for hydrogen compared to conventional fuels. Liquid hydrogen was found to be superior to both aviation kerosene and liquid methane from the standpoint of aircraft engine emissions.

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