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THE USE OF HYDROGEN FOR AIRCRAFT PROPULSION IN VIEW OF THE FUEL CRISIS

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FOREWORD

This paper was initially distributed, under the title "Ramifications of the Fuel Crisis," to attendees of the NASA Research and Technology Advisory Committee on Aeronautical Operating Systems meeting held at the NASA-Ames Research Center on March 7-8, 1973. It was prepared at the request of the Committee Recording Secretary, John H. Enders. Its purpose was to complement Committee discussions concerning the effects of impending fuel shortages on commercial air transportation.

This report is essentially the same as the paper previously distributed. The title has been changed to more accurately reflect its contents. Minor changes have also been made to improve the clarity of this paper.

ABSTRACT

Some factors influencing the technical feasibility of operating a liquid hydrogen-fueled airplane are discussed in light of the projected decrease of fossil fuels. A comparison of available supplies of fossil fuels with their consumption rates indicates impending world-wide shortages of natural gas and oil. Accordingly, coal will be heavily relied upon to meet future energy needs. Ultimately, near the turn of this century, nuclear fuels should become the major source of energy. Other sources of energy, such as wind, tidal, solar, and geothermal, are briefly mentioned.

In view of projected decreases in available petroleum fuels, interest has been generated in exploiting the potential of liquid hydrogen (LH_2) as an aircraft fuel. Cost studies of LH_2 production show it to be more expensive than presently used fuels. Regardless of cost considerations, LH_2 is viewed as an attractive aircraft fuel because of the potential performance benefits it offers. Accompanying these benefits, however, are many new problems associated with aircraft design and operations; for example, problems related to fuel system design and the handling of LH_2 during ground servicing. Some of the factors influencing LH_2 fuel tank design, pumping, heat exchange, and flow regulation are discussed.

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SUMMARY

This report presents results of a preliminary review of the availability of fossil fuels and discusses some factors influencing the technical feasibility of operating a liquid hydrogen-fueled airplane.

A comparison of available supplies of fossil fuels with their consumption rates indicates impending world-wide shortages of natural gas and oil. Coal, which is in abundant supply, will be heavily relied upon to meet future energy needs. Ultimately, near the turn of this century, nuclear fuels should become the major source of energy. Other sources of energy, such as wind, tidal, solar, and geothermal, are briefly mentioned. These are not expected to contribute significantly to the supply of energy in the near future.

In view of projected decreases in available petroleum fuels, interest has been generated in exploiting the potential of liquid hydrogen (LH_2) as an aircraft fuel. Cost studies of LH_2 production show it to be more expensive than presently used fuels. These cost estimates, however, are strongly influenced by the cost of nuclear electric power, which cannot be predicted with any certainty. Regardless of cost considerations, LH_2 is viewed as an attractive aircraft fuel because of the potential performance benefits it offers. Accompanying these benefits, however, are many new problems associated with aircraft design and operations. Of particular importance are problems related to fuel system design and the handling

of LH_2 during ground servicing. This report addresses some of the factors influencing LH_2 fuel tank design, pumping, heat exchange, and flow regulation. Much of this information was obtained from an experimental study of a liquid hydrogen-fueled airplane, which was conducted at the NASA-Lewis Research Center during the mid-1950's.

INTRODUCTION

In past years, the United States has enjoyed abundant use of energy at low cost. But now, as are other industrial nations, we also are being threatened by an energy crisis resulting from a demand for fuel that is outstripping supply. The United States, with only about 6 percent of the world's population, consumes about 35 percent of the world's energy. In the past 100 years, U.S. demand for energy has increased 20 times. Figure 1 illustrates that energy demand in 1985 is projected to be double the amount of energy consumed in 1970.

The energy problem is further aggravated by public resentment of the pollution of our air and water associated with power plants and transportation. New legislation designed to protect our environment has delayed the construction of nuclear reactor power plants and contributed to increased consumption of petroleum fuels. New technological improvements in power production and the use of other pollution safeguards promise to reduce this environmental problem, but this will be costly.

Ground and air transportation industries are primarily concerned about the availability of petroleum fuels at prices that will assure continued viability of these industries. Airline operators have experienced not only price increases in the past two years, but occasionally have also been denied sufficient fuel for normal scheduled operations at east coast facilities. This petroleum shortage occurred because: natural gas shortages forced utilities and industries to switch to oil; new laws against pollution caused utilities to change from high-sulfur coal to oil; high demands for electricity required power companies to use petroleum-fueled turbo-generators; and our wet, cold autumn increased the use of gas and oil for drying crops, such as corn and cotton.

The following review comments on the availability of fossil fuels; other sources of energy, particularly hydrogen; the cost of hydrogen; and the liquid hydrogen (LH_2) airplane.

FOSSIL FUELS

Fossil fuels are thick deposits of organic materials which, under heat and pressure over millions of years, have changed to gas, oil, and coal. Eighty percent of U. S. electricity is produced from them, Ref. 3. These deposits of stored energy once seemed infinite. However, at present and projected rates of consumption, we are beginning to see the "bottom of the barrel".

Natural Gas

Natural gas is our cheapest, cleanest, and most easily extracted fossil fuel. It provides about one-third of our total energy (fig. 1, year 1970) and about one-fourth of our electricity. The world's available reserves and consumption rates are shown in table I. Although the U. S. domestic reserves account for only about 20 percent of the total world supply, we consume 60 percent. At our present rate of production, domestic reserves would be depleted in about 14 years, with the depletion of the remaining world supplies occurring in less than 40 years. The U. S. will become more dependent upon imports from other nations with, of course, increase in cost. The gas industry claims that price increases in gas sales would do much to motivate the industry into finding more domestic reserves. Nevertheless, decreasing dependency will be placed upon natural gas for future energy.

Oil

Total world oil supplies appear no better than reserves of natural gas, as shown in table II. World supplies are expected to be depleted in about 30 years, but other sources (ref. 3) predict oil reserves will last for about 100 years. Although table II indicates that present U. S. reserves will last less than 10 years, we have been successful in finding sufficient new sources of oil to match consumption. These new sources, however, are becoming more difficult to find in North America and we will become more dependent upon imports. We are already importing about 25 percent of our oil and a 50 percent import rate is forecast for about 1980 (fig. 1). This will result in increased costs of oil.

Coal

Coal is the most abundant fossil fuel. United States reserves are estimated to last for several hundred years. Should fossil fuel consumption conform to the pattern projected in the 1950's, Ref. 2, world supplies of fossil fuels would be exhausted in about 900 years, Fig. 2. Although this figure refers to all fossil fuels, the indicated long available time is primarily due to large quantities of coal resources.

Most abundant domestic coal deposits are located in areas far removed from the major coal markets. Economic extraction of this coal is dependent upon strip-mining techniques which are strongly condemned by environmentalists. New federal and state laws, that are responsive to conservationists, restrict strip mining operations to terrain that offers restoration potential. These factors discourage full exploitation of existing resources and result in increasing the cost of coal.

OTHER SOURCES OF ENERGY

The indicated impending shortage of gas and oil and our concern about our environment has stimulated development of new sources of clean energy. Their potential in mitigating the problem is commented upon below.

Nuclear Energy

Over the past 20 years, much effort has been devoted to obtaining power from nuclear reactors. Immediate benefits may be derived from the fission-type reactor with the breeder reactor coming into use near the latter part of this century. Beyond that, fusion-type reactors may become operational.

Fission-type reactor. - This type of reactor derives power from the splitting (fission) of uranium atoms. The rate of constructing fission-type nuclear power plants, as mentioned earlier, has been disappointing. Presently, only 29 plants are in operation, 49 are under construction, and 67 are on order. When all are completed, they should contribute a 30 percent increase to the total U. S. electric power capacity which is about 370 million kilowatts. It now takes from 7 to 9 years lead time to bring a nuclear power plant into operation. This lead time is getting even longer because new environmental standards must be complied with. Strict safeguards must be provided against thermal pollution of lakes and rivers by the large amounts of waste heat produced, as well as radiation leakage from the reactor and its radioactive wastes.

Unfortunately, even this energy source is subject to a fuel shortage. The Atomic Energy Commission (AEC) forecasts the depletion of inexpensive uranium nuclear fuel by the end of this century (ref. 3).

Fast breeder reactor. - This major development of a fission-type reactor, which has strong Presidential support, should ease the nuclear fuel shortage. The liquid metal fast breeder reactor produces more fuel than it consumes. It is also more efficient and thus produces less waste heat. A breeder reactor operates at lower pressure which lessens the danger of radioactive gas leakage. Commercial power from breeder reactors, however, is not expected to be available until after 1985.

Wind Energy

Windmills driving generators would convert wind to electricity. Wind is free and abundant, but unfortunately, unreliable. We are not yet capable of storing large amounts of electricity for use during calm periods.

Tidal Energy

The in and out movement of tides could be used to drive a generator for conversion to electricity. France does operate one such plant (Rance River), but few suitable sites are available in the U. S.

Solar Energy

The greatest energy source, of course, is the sun. The energy that the earth receives from the sun is 100 000 times the world's present electric power capacity. The solar farm, similar to the one near Odeillo in the French Pyrenees, may be a possible approach to harnessing the sun's energy. Another approach involves large orbiting solar collectors and beaming converted energy to earth via microwaves. These approaches, however, are in the distant future.

Hydroelectric Energy

Practically all suitable sites in the U. S. are now being fully utilized.

Geothermal Energy

In the United States, geothermal power is being produced at The Geysers, north of San Francisco. Dr. Robert W. Rex, expert in this field, believes there are sufficient hot water sources in California to produce all of California's present need of electricity by geothermal energy, Ref. 3. New techniques for extracting the heat from the earth with heat pipes may also have appeal, but these developments are not expected to significantly alter the fuel problem in the foreseeable future.

SUMMARY OF ENERGY SOURCES

Figure 1, prepared by the National Petroleum Council graphically summarizes future U. S. energy sources. As previously implied, fossil fuels will continue to be our major source of energy, at least until 1985. Domestic oil production will remain constant, but oil imports will increase.

Gasification of coal to methane will probably also supplement our diminishing gas supplies. Dependence upon nuclear energy will increase. Synthetic crude oil production from shale and synthetic gas production will not significantly affect the fuel problem. Hydroelectric power production will not increase appreciably over present levels.

The increased dependency upon imports, the growing demand for turbine fuels, and the eventual depletion of world oil reserves tend to point toward the necessity of considering fuels, which are not derived from oil, for future aircraft propulsion. Liquid methane and liquid hydrogen (LH_2) have been suggested.

LIQUID METHANE

Both the air transport and ground transportation industries have been studying the use of liquid methane as an attractive fuel (ref. 4). The Lewis Research Center has, for many years, studied the use of liquefied methane as a possible jet fuel for supersonic aircraft and the space shuttle. The results of these studies are reported in the documents listed in the attached Methane Bibliography. Ignoring practical problems associated with the use of liquid methane, commercial supersonic aircraft may derive considerable benefit from methane's higher heating value and cooling capacity as compared to kerosene. However, its availability is also dependent upon fossil fuel processing. If new techniques for producing cheap electricity become a reality, liquid hydrogen, which offers more potential performance benefits than methane, would be a favorable fuel candidate.

LIQUID HYDROGEN

Liquid hydrogen (LH_2) from an energy availability and environmental point of view appears to offer high potential as a jet fuel. However, economic feasibility, associated primarily with cheap electricity, may not be attained until after the year 2000. Use of LH_2 does not appear to demand formidable changes in present aircraft engine design, but substantial changes in fuel system design and fuel handling procedures will be required.

Electrolysis of water by electricity, derived from advanced economical nuclear plants, will probably be the main source of LH_2. In the near future, however, LH_2 production will be dependent upon hydrogen gas extraction from fossil fuels by steam reforming of methane (in natural gas); partial oxidation of coal; and partial oxidation of petroleum.

Cost

Cost estimates for LH_2 shown in table III are constructed from Ref. 5 information. They represent future (1985-2000) costs in 1972 dollars based upon present day technology.

A cost of $\$2.00/10^6$ BTU appears to be a reasonable estimate for LH_2 from steam reformed methane. Costs for LH_2 from partial oxidation of petroleum is also estimated at $\$2.00/10^6$ BTU.

As shortages in natural gas and petroleum develop during the remainder of this centruy, LH_2 production will become dependent upon partial oxidation of coal. Estimated costs of LH_2 via this method may be between \$2.25 and $\$2.50/10^6$ BTU. The initial reaction in this process, however, yields methane. It would, therefore, be wasteful to continue the reaction for the production of hydrogen; particularly, since the depletion of natural gas (essentially methane) will have forced us into using this method in the first place.

The uncertainty in cost of electric power causes uncertainty in estimating accurate costs of LH_2 produced from electrolysis of water. The $\$3.25/10^6$ BTU (ref. 6) cost figure (table III) is based upon breeder reactor power at 2.72 mils per kilowatt hour (kWh). Reference 8 suggests possible electricity costs at 2.6 mils/kWh with a resultant estimate of LH_2 at $\$2.45/10^6$ BTU. Reference 8 also projects a cost of $\$1.41/10^6$ BTU based upon nuclear-generated electricity at 1.6 mils/kWh.

R. R. Hibbard, of the Lewis Research Center, believes that \$3.25 to $\$4.00/10^6$ BTU is a reasonable estimate of LH_2 production costs from the electrolysis method.

All these estimates pertain to liquefying hydrogen at a plant located at or near the airport. The figures do not include the cost of refueling the airplane. Hibbard gives an optimistic cost of $0.50/10^6 BTU for refueling, which should be added to the above estimates. This would cover reliquefaction costs of the captured vented gas generated during cooldown of the aircraft fuel system plus other operating costs.

Summary

Steam reforming of methane and partial oxidation of petroleum would probably be the cheapest source of LH_2 (\$2.50/10^6 BTU, including refueling) during the 1985-2000 era.

As natural gas and oil reach short supply (say the year 2000), LH_2 would be derived from coal at a cost estimate of \$3.00/10^6 BTU, including refueling charges.

Electrolytic LH_2 production would cost between \$3.75 and \$4.50/10^6 BTU (including refueling charges).

Should the breeder reactor make low cost electricity a reality (1.61 mils/kWh), LH_2 costs may be reduced to \$1.90/10^6 BTU (including refueling) by the electrolytic method.

These costs may be compared with 1972 costs of about \$1.00 to \$1.10/10^6 BTU (including refueling charges) for kerosene fuels.

Consideration of LH_2 as an aircraft fuel would not be complete without reference to the availability of another critical element, namely, helium.

HELIUM

Helium is an inert gas that is used: as a refrigerant (liquid helium) to maintain temperatures close to absolute zero; in inert gas-shield arc welding; and for various purposes in our nuclear energy programs. In a LH_2 fueled airplane, helium gas would be used as an inert diluent to purge air from the fuel system and for operating required pneumatic valves and controls.

Availability

Helium is obtained primarily from natural gas found in wells located in Texas, Oklahoma, Arizona, and Kansas. It occurs in concentrations of up to only 2 percent. About 99 percent of the helium recoverable in the free world is obtained from wells found within 250 miles of Amarillo, Texas. Recently, helium has been discovered in natural gas in Russia and in South Africa.

Small quantities of helium may be produced from air, but it requires about 5000 tons of air to produce about 550 cubic feet of helium.

Plants for separating helium from natural gas are operated by the Bureau of Mines. Production figures are shown in table IV (ref. 9). In 1969, the Bureau produced approximately 4.8×10^9 cubic feet which is about 80 times the 1950 production. Large quantities of helium are wasted daily because of the lack of separating plants. Although helium presently appears to be abundantly available, the supply of helium-rich natural gas, as previously discussed is being depleted rapidly.

LIQUID HYDROGEN AIRPLANE

Notwithstanding the poor economic outlook for a LH_2 airplane, implied by the cost considerations previously discussed, it cannot be ignored as a possible solution to a critical fuel problem. In fact, as oil reserves are depleted, the future of aviation transportation may not lie in cost feasibility, but rather in our technical capabilities for finding solutions to the challenging operating problems.

In view of the long lead time available, a very comprehensive, well organized, evolutionary plan may be prepared for attacking the problems associated with scheduled operations of liquid hydrogen-fueled transports.

In the 1950's, the Lewis Research Center expended considerable effort in the study of liquid hydrogen as a propulsive fuel. These efforts led to successful flight testing of a workable liquid hydrogen fuel system on a B-57 airplane (1956 and 1957). One engine of this airplane was operated with hydrogen during cruise at about 50 000 feet. Other flight requirements such as ascent and descent were, however, performed on JP fuel. These investigations affirmed some of the benefits of liquid hydrogen, but more importantly, design and operational problem areas were recognized. Subsequently, research continued toward successful launchings of hydrogen-fueled rockets such as the Centaur. These research activities created the base for present and future development of hydrogen-fueled vehicles. They were unique in that hardware and techniques were developed to accomplish a specific "one-of-a-kind" operation. The point here is that additional research and development is required to establish the technical feasibility of operating commercial air transportation on liquid hydrogen as we operate on JP fuels today. The following discussion reviews some of the results obtained in our liquid hydrogen studies based primarily upon our experiences with the hydrogen-fueled airplane. We will present the potential performance benefits of liquid hydrogen, point to several practical design and operating problems associated with a hydrogen airplane, and offer possible approaches to their solution. (Most of this information may be found in greater detail in ref. 10.)

Performance Benefits

Hydrogen properties, table V, compared to a hydrocarbon fuel point to several potential performance benefits:

1. Hydrogen's heat of combustion is 2.75 times higher than that of jet fuels. The weight of fuel being equal, could permit the hydrogen airplane to fly 2.75 times farther. If the airplane range were kept equal, however, the hydrogen fuel weight required could be less than 40 percent of that of JP fuel.

2. The heat sink (cooling) capacity of hydrogen is much greater than JP. This could be used to cool the aerodynamically heated aircraft structure of high supersonic or hypersonic aircraft. It could also be employed to cool the turbine blades of the engine; thus making it possible to operate at higher turbine inlet temperatures, without overheating the metal blades. This could result in higher engine thrust with some decrease in fuel consumption.

3. Hydrogen can support a flame over a broader range of fuel concentrations than JP fuel, Fig. 3. It is about 10 times easier to ignite with an electric spark, is about 10 times harder to blow out once it is lit, and it burns at a higher velocity than JP fuel. These properties could permit flight at higher altitudes, lessen the danger of flame-out, and permit easier air starts, if a flame-out occurs.

The result of the benefits of items 2 and 3 is an increase in combustion performance, which could effectively shorten the combustor and reduce engine weight.

Deleterious Effects

Other hydrogen properties create disadvantages as follows:

1. The density of liquid hydrogen is only about 9 percent that of JP fuels, table V, and would occupy over 11 times the volume of an equal weight of JP. Even a hydrogen airplane of range equal to a JP airplane would require over 4 times the volume. Finding sufficient internal storage space will be a problem. This could result in weight and payload penalties.

2. Other tank penalties arise because of liquid hydrogen's low boiling temperature (37° R, -423° F). Insulation will be required to minimize fuel losses due to heat transfer. Furthermore, as the airplane ascends to high altitude, the decrease in ambient pressure will permit large amounts of vapor to be flashed off. Closed, high-strength, pressurized and insulated tanks will be required. These would undoubtedly be heavier than the integral fuel storage space now used to accommodate JP fuel.

3. The benefit of high turbine inlet temperatures may have to be compromised because of the undesirable engine noise it tends to create.

4. Liquid hydrogen's low temperature, broad flammability range, and ease of ignition by an electric spark create safety considerations beyond those required for JP use, such as:

(a) Special clothing for maintenance and service personnel

(b) Special tools and ground support equipment

(c) Rigorous training in the hazards of hydrogen

(d) Plumbing design, such as low heat leak piping, fittings, etc.
(e) Location of fuel system components away from potential ignition sources
(f) Development of reliable combustible gas leak detectors and the action to be taken in the event of a leak
(g) Development of extinguishants for hydrogen fires
(h) Development of purging techniques for eliminating air from the fuel system. Air in the system will freeze and consequently provide a combustible mixture.
(i) Development of safe refueling techniques. Tank design will be affected by decisions associated with:
    (1) Refueling the aircraft at the gate;
    (2) Removing tanks and replacing them with full tanks brought in on ground support equipment; or
    (3) Refueling the aircraft at some location remote from the gate

    Regardless of the refueling method used, provisions for capturing tank boiloff vapors will be required at the boarding gate. This gas may be burned at some distant location. or collected for reliquefaction.

Fuel System Problems

Some of the problems associated with aircraft design, engine design, and combustion have been extensively studied over the last two decades. Much of this work is reported in Ref. 10 and the attached Hydrogen Bibliography. This space will be devoted primarily to a discussion of the hydrogen-fueled airplane's fuel system with greatest emphasis placed upon the thermal design of the fuel tank.

A typical LH_2 fuel system is shown schematically in Fig. 4. The system would consist of thermally insulated tanks, fuel pumps, heat exchangers, and flow controls.

Helium would be provided to operate pneumatic valves and provide pressure for hydrogen flow in the event of pump failure or for fuel dumping in the event of an emergency. Helium could also be used for tank inerting. A capability for purging the tank from an external source will be provided. A vent system permitting safe and easy hookup to an external vent would be provided for ground operations.

Fuel tank design considerations. - The thermal design of the liquid hydrogen fuel tank is probably the most critical element of the fuel system. As we have mentioned previously, liquid hydrogen boils at a very low temperature, -423° F. Its low density results in high tank surface area to propellant weight ratio. This combination causes high boiloff losses from uninsulated tanks. During flight, the aircraft engine may consume hydrogen faster than it can be vaporized; however, when the airplane is on the ground and the engines are not operating, heat leak through the tank walls causes the hydrogen to vaporize. This hydrogen must be vented off to prevent excessive buildup of tank pressure. The major considerations involved in tank design are: (1) it must be lightweight; (2) its heat-leak rate should not permit vaporization of fuel faster than it can be consumed by the engine during cruise; and (3) it should be capable of storing fuel on the ground without any losses for a reasonable length of time. Data obtained from experimental tanks and the B-57 flight tank are examined below. These illustrate some of the thermal problems involved in tank design. Detailed information is in Ref. 11.

A typical tank, used for study, is shown in Fig. 5(a). It consists of an inner shell made of either aluminum or stainless steel, a foamed closed-cell insulation, and an outer skin.

Results of boiloff experiments that compare the heat leak performance of the inner shell materials are shown in Fig. 6. At the full tank level, there can be no conduction of heat along the walls of the inner shell, because the temperature throughout the tank is uniform. Therefore, at the full tank condition, the difference in thermal conductivity between aluminum and stainless steel is not an important factor. As the liquid level declines, the thermal conductivity of the material influences the quantity of heat conducted into the liquid, as shown by the slopes of the curves. The heat-leak rate for the low conductivity material, stainless steel, decreased almost in proportion with the decrease in liquid level or wetted area; but the heat-leak rate for the high thermal conductivity material, aluminum, does not decrease as rapidly with a reduction in liquid level. Because of its higher conductivity, aluminum transfers a larger proportion of the heat flowing through the insulation, above the liquid level, down into the liquid.

In tank studies, where the outer skin consisted of a relatively porous shell made of resin-impregnated Fiberglas, the insulation chamber would "breathe" with changes in atmospheric conditions. When liquid hydrogen is put into the inner shell of this type tank, the air in the insulation chamber condenses. As condensation progresses, the pressure in this space is reduced, and more air is drawn in through the porous outer covering. Heat released by the condensation of air causes a more rapid vaporization of the liquid hydrogen in the inner shell. In addition to the increase in heat leak, this phenomenon results in an additional tank weight because of liquid (and probably solid) air in the insulation chamber. An alternative to building the insulation space vacuum-tight so that no air can enter, is to introduce into the chamber a gas such as helium that is non-condensable at these temperatures (fig. 5(b)).

Results of experiments made with an air atmosphere and with a helium atmosphere in the insulation chamber are shown in Fig. 7. With helium in the insulation chamber, heat leak declines with liquid level. With air in the chamber, the initial heat-leak rate was about 30 percent higher than that with helium in the chamber. As the layer of condensed air develops, the rate of further condensation declines and the heat-leak rate curve approaches the helium curve. Since the thermal conductivity of helium is much higher than that of air, the overall thermal conductivity of the insulation will be greater than the thermal conductivity established by standard testing methods. Nevertheless, the heat-leak rate into the tank with helium in its insulation chamber is less than that with condensing air.

In order to derive full benefit of the insulation, air must be precluded from entering the insulation chamber. This suggests that a method be found to seal this chamber (vacuum-tight) without imposing large weight penalties on the tank construction.

While the airplane is on the ground, the loss of hydrogen gas due to heat leak should be avoided. This implies building the inner shell to withstand higher than atmospheric pressure. The tank outlet could then be closed off until heat leak into the tank raises the internal pressure to its design limit. At this time, gaseous hydrogen must be vented off from the tank to restore the pressure to safe values. The time elapsed between tank filling and the first venting off of gaseous hydrogen is called "no-loss" time. For ground operations, it obviously is necessary to have this no-loss time as long as possible.

In this regard, an experiment was performed with a tank similar to the Fig. 5(b) configuration which simulated an airplane waiting to take off. The results, Fig. 8, show an actual pressure rise widely departing from a calculated pressure rise.

A measurement of the temperature profile in the tank explains this discrepancy. One temperature profile is shown in the lower part of Fig. 9. The tank outlet valve was closed at the 7.5 inch liquid level. Heat leaking into the liquid caused its temperature to rise. The corresponding rise in pressure is shown in the upper part of Fig. 9. According to calculations, the pressure should have risen as indicated by the curve marked, calculated. However, actual pressure rise is more rapid.

The temperature profile at the maximum pressure of 39 psia is shown by the solid line in the lower part of Fig. 9. The temperature close to the liquid-gas interface corresponds to an equilibrium vapor pressure of 39 psia, but near the tank bottom the temperature of the liquid corresponds to an equilibrium vapor pressure of only 23.5 psia. This temperature stratification accounts for the discrepancy between the predicted and experimental pressure-time curves.

This undesirable rapid pressure rise can be avoided if temperature stratification is prevented. One way of doing this is to agitate the liquid. When the liquid was agitated, the pressure dropped from 39 psia to almost the calculated pressure; and the resulting temperature profile is nearly uniform, as shown by the circles in the lower part of Fig. 9.

In summary, these experiments indicated that: (1) purging the insulation space with helium gas prevents air condensation in the insulation space but results in an increase in the effective thermal conductivity of the insulation; and (2) temperature stratification of the liquid results in a no-loss time which is less than that based upon calculations with known heat-leak rates.

Those involved with launch vehicles using LH_2 fuel, cognizant of the air condensation problems, have sponsored work on the development of a self-evacuating multilayer insulation system, Ref. 12. A sketch of this system is shown in Fig. 10. This insulation concept consists of a vacuum-tight casing or bag, open cell rigid urethane foam spacers, highly reflective double aluminized mylar radiation shields, and a cryopumpable carbon dioxide (CO_2) gas. Upon cooldown of the inner vessel, the gas in contact with the cold insulation panel condenses to reduce the chamber pressure. The outer panel seal prevents air from entering the chamber. Results of experiments indicated that chamber pressures of 10^{-5} torr could be obtained resulting in heat leaks even less than anticipated. However, failures of the air seal material have occurred upon exposure to near cryogenic temperatures. Before this type of tank can meet the long-life, reusable requirements of an operating aircraft, this problem must be eliminated.

Lockheed Missles and Space Company, Inc. is also pursuing the vacuum jacket insulation concept as described in Ref. 13. In this type of tank, reflective-coated microspheres would be inserted in a compartmentalized insulation chamber, which is sealed by a thin walled outer casing. This insulation chamber would be evacuated to pressures conducive to low heat leak. The outer casing buckling load would be transmitted to the inner vessel wall via contact with the microspheres. The pressurized inner vessel would support this load.

Other concepts have been studied for circumventing the air condensation problem. These involve internal installation of lightweight insulation. In the 1950's, several such attempts were made but with frustrating experiences due to insulation cracking.

More recently, such activities have been renewed. An internal insulation system is described in Ref. 14. Internal insulation would overcome some of the problems associated with external insulation because air condensation may be eliminated and heat leaks through tank supports are reduced. Another benefit is derived, since the outer tank wall would protect the insulation from damage by service personnel.

Some of the problems with internal insulation are associated with: (1) preventing liquid from entering the insulation; (2) engine contamination; and (3) catastrophic thermal failure.

The greatest difficulties, however, are associated with structural integrity of the insulation. Hydrostatic and gas pressure loads and the induced loads by thermal stresses, caused by temperature differences across the insulation, have resulted in mechanical failure of internal insulation systems. New fabrication methods for increasing the strength of the insulation are being studied to overcome the problem, but they result in weight and thermal conductivity penalties.

Liquid hydrogen pumps. - In Lewis' B-57 flight with liquid hydrogen, fuel was transferred to the engine by pressurizing the liquid hydrogen tank. In an operational flight system, a liquid hydrogen pump would be used instead of a pressurized tank. Use of a pump would permit thinner tank wall materials and consequent reduction in fuel storage weight. Results of some of the liquid hydrogen studies, conducted at Lewis, are reported in Refs. 15, 16, 17 and 18.

Pumping hydrogen is aggravated by the low boiling temperature of liquid hydrogen. Difficult cavitation problems have to be dealt with. Techniques for providing hydrogen liquid at the pump inlet suggest burying the pump in the fuel tank or locating it close to the tank. Either method aggravates the liquid hydrogen leakage problem.

Furthermore, the low electric spark energy required for hydrogen ignition makes it undesirable to use electric motors for driving the pump. Vaporized hydrogen gas could be used to drive a turbine connected to the fuel pump. If, however, the pump were installed in the tank bottom, the higher temperature turbine driving gas would add to the thermal problems of the tank.

In JP fueled aircraft, the pump usually provides excessive quantities of fuel. Fuel not consumed by the engine is returned to the tank. In a liquid hydrogen system, return of excess fuel to the tank would further aggravate the tank heat leak problem. It may be necessary, therefore, to design variable speed positive displacement pumps or variable displacement pumps operating at constant speed.

Heat exchanger. - Liquid hydrogen would be converted to the gaseous state through some method of exchanging heat. In supersonic or hypersonic aircraft, the airframe surfaces requiring cooling may serve this purpose. Or a ram air heat exchanger, as used on the Lewis B-57 flights, may be required. Warm-bleed air from the engine may also perform this function.

Hydrogen, in liquid form, would be provided at the inlet of the heat exchanger to obtain the maximum heat transfer performance necessary to keep the heat exchanger size within reasonable dimensions. Sizing the heat exchanger is also complicated by possible formation of ice on the tubes facing the air inlet.

Hydrogen flow regulator. - To the author's knowledge, no studies have been made associated with modulating the flow of hydrogen to an aircraft engine operating over large variances of thrust requirements. The fuel control used in Lewis B-57 flight experiments was dependent upon proportioning hydrogen flow with JP flow, Ref. 10. This arrangement would not be suitable for an operational type liquid hydrogen airplane. As implied in the section discussing pumps, the flow control may be used to modulate pump speed or pump displacement.

CLOSING REMARKS

Our discussion has addressed some aspects of the effect of the "energy crisis" on commercial air transportation.

About the year 2000, oil reserves critical to the aviation industry may not be available in sufficient quantities to satisfy the growth of air transportation.

After the year 2000, electric power obtained from advanced nuclear plants may be available to offer economic feasibility of a LH_2 airplane.

Many problem areas related to an operational liquid hydrogen airplane have already been studied. Some continue to be investigated by researchers in other areas, such as hydrogen-fueled rockets. But continued expansion of research and development efforts will be necessary before the technical feasibility of an operational LH_2 airplane can be demonstrated.

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TABLE I
(from ref. 1)
NATURAL GAS RESERVES AND CONSUMPTION
(10^{15} BTU)

AREA	RESERVES	ANNUAL PRODUCTION	YEARS TO GO
MID EAST	232	0.1	> 2000
AFRICA	165	0.1	> 1500
LATIN AMERICA	66	3	22
NORTH AMERICA*	48	2	24
USA	294	21	14
REST WORLD	570	11	52
TOTALS	1375	37	37

*NORTH AMERICA, EXCLUDING USA

TABLE II
(from ref. 1)
PETROLEUM RESERVES AND CONSUMPTION
(10^{15} BTU)

AREA	RESERVES	ANNUAL PRODUCTION	YEARS TO GO
MID EAST	1750	28	63
AFRICA	350	11	32
LATIN AMERICA	200	11	18
NORTH AMERICA*	40	2	20
USA	200	25	8
REST WORLD	250	20	12
TOTALS	2790	97	29

*NORTH AMERICA EXCLUDING USA

TABLE III

(from Reference 5)

COST OF LIQUID HYDROGEN (1972 DOLLARS)

Source	$\$/10^6$ BTU	Reference
Steam Reform of Methane (Natural Gas)	1.91	6
	2.05	4
	2.00	7
	1.52	8
Partial Oxidation of Petroleum	1.91	6
	2.06	4
Partial Oxidation of Coal	2.25	7
	2.50	5
Electrolysis of Water	3.25	6 (2.72 mils/kWh electricity)
	3.49	4
	2.45	8 (2.6 mils/kWh electricity)
	4.00	7
	1.41	8 (1.6 mils/kWh electricity)

TABLE IV

(from Reference 9)

HELIUM PRODUCTION
(10^3 Cubic Feet)

YEAR	QUANTITY PRODUCED
1950	60,000
1960	475,179
1965	4,385,834
1968	4,854,800
1969	4,752,400

TABLE V

FUEL PROPERTIES

Property	LH_2	JP
Heat of Combustion, BTU/LB	51,571	18,750
Heat Sink,[a] BTU/LB	[b]4900	[c]165-365
Heat Sink, Fraction of Heat of Combustion	0.095	0.0088-0.0195
Density (Liquid), LB/FT^3	4.4	50
Boiling Point (1 Atmosphere), ^{O}R	37	810
Spontaneous Ignition Temperature, ^{O}R	1535	940
Flammability Limit (Lean), Volume % Fuel	4	2
Flammability Limit (Rich), Volume % Fuel	75	9
Minimum Spark Ignition Energy (Stoichiometric, 1 Atmosphere), Millijoules	0.02	0.3

[a]Heat sink is a measure of the cooling capacity of the fluid.

[b]Cooling energy available by permitting temperature rise to 1460^{O} R (1000^{O} F).

[c]Cooling energy available by permitting temperature rise to 835^{O} R-1160^{O} R (375^{O} F-700^{O} F), where fuel degradation occurs.

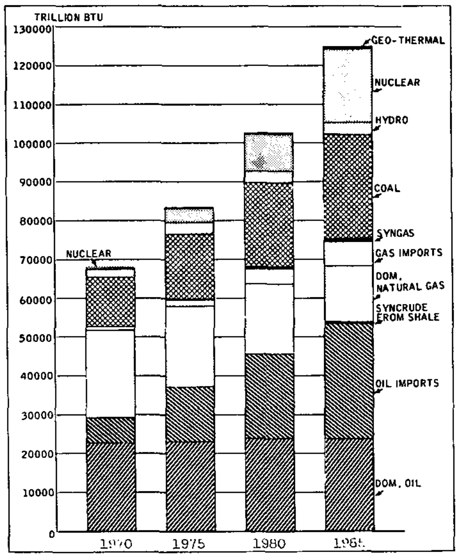

Figure 1. - Contemplated sources of energy for meeting present and projected U. S. demands. (Chart prepared by the National Petroleum Council's Committee on U. S. Energy Outlook for its interim report, U. S. Outlook: An Initial Appraisal 1971-1985, published in 1971.)

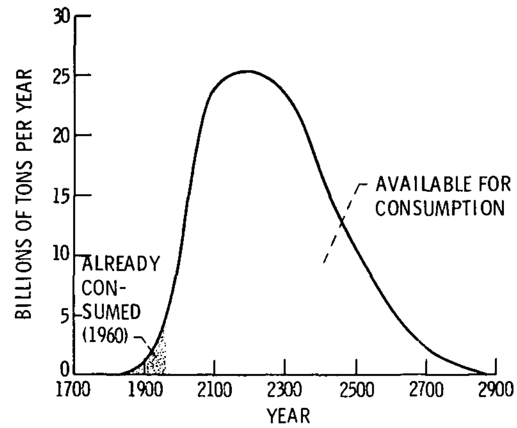

Figure 2. - Possible consumption pattern of fossil fuels (from ref. 2).

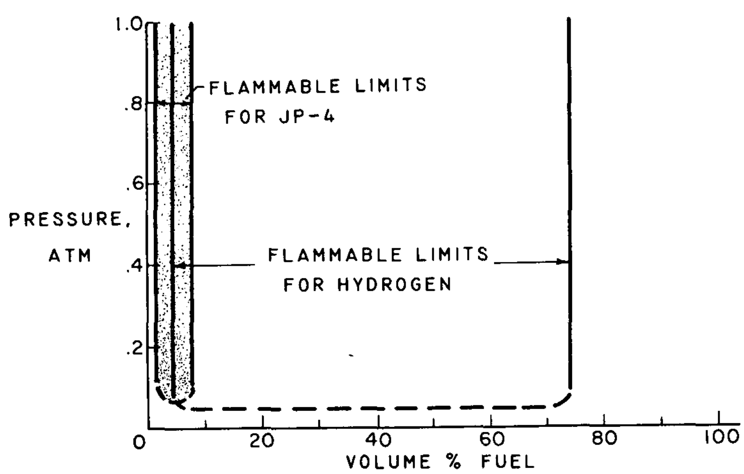

Figure 3. - Flammable range of hydrogen and JP-4 fuel.

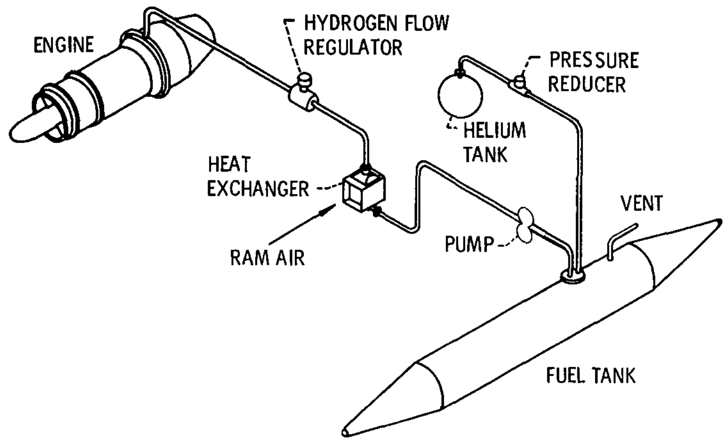

Figure 4. - Hydrogen fuel system.

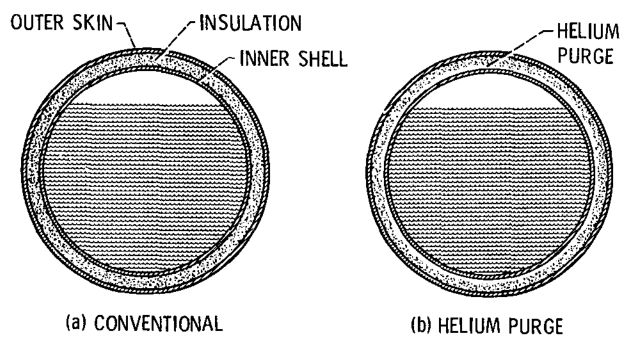

Figure 5. - Cross section of typical insulated tank.

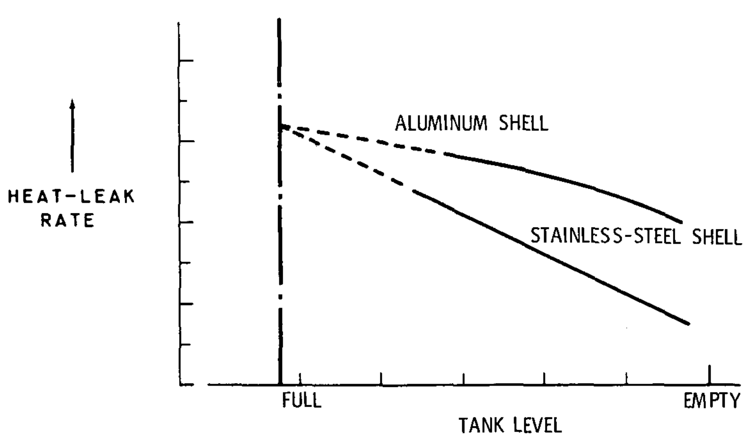

Figure 6. - Effect of liner material on vaporization.

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CS-13663

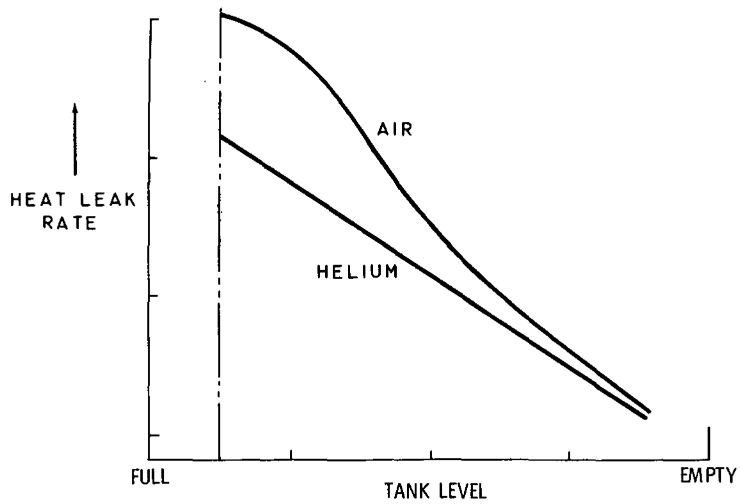

Figure 7. - Effect of atmosphere surrounding insulation on heat-leak rate.

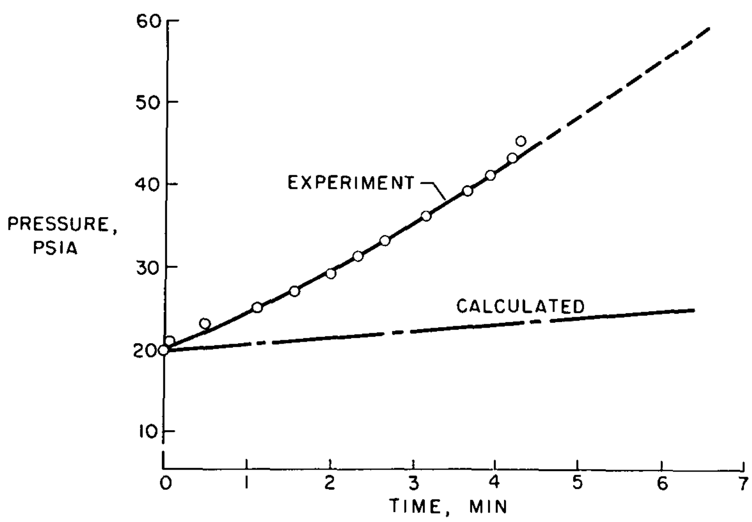

Figure 8. - Pressure-time history for hydrogen in aircraft tank.

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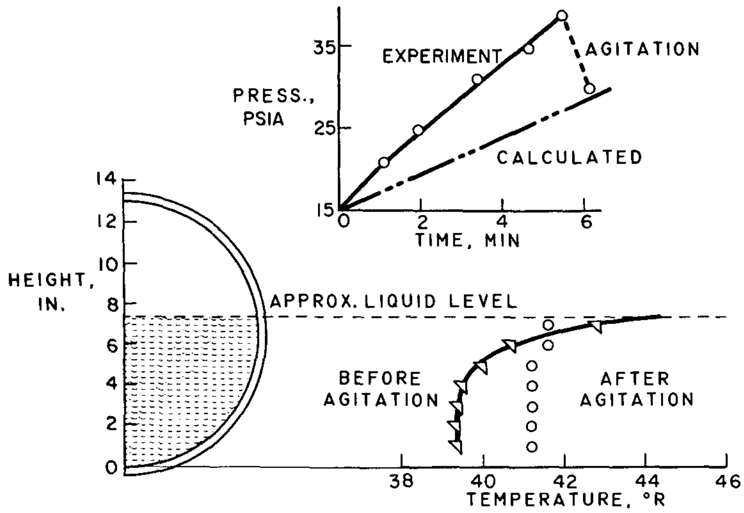

Figure 9. - Temperature profile in liquid hydrogen.

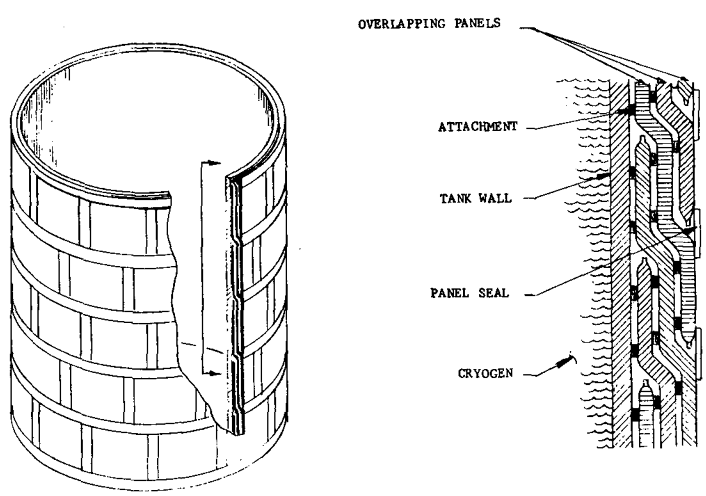

Figure 10. - Self evacuating multilayer insulation (from ref. 12).