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THE LIQUID HYDROGEN OPTION FOR THE SUBSONIC TRANSPORT - A STATUS REPORT

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THE LIQUID HYDROGEN OPTION FOR THE SUBSONIC TRANSPORT - A STATUS REPORT

by

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ABSTRACT

A liquid hydrogen fuel option for subsonic air transports is evolving through NASA studies. In addition to continued air transport design studies, elements of this option include: (1) economical production of hydrogen; (2) efficient liquefaction of hydrogen; (3) materials for long service life LH_2 fuel tanks; (4) insulation materials; (5) LH_2 fuel service and installations at major air terminals; (6) assessment of LH_2 hazards; and (7) the engineering definition of an LH_2 fuel system for a large subsonic passenger air transport. As the one measure in the aircraft fuel conservation program which is independent of hydrocarbon fuels for operation of aircraft, the liquid hydrogen option continues to show promise for the future.

INTRODUCTION

Although the appeal and the potential of liquid hydrogen as an aerospace fuel is firmly established, the use of liquid hydrogen in commercial air transportation is as yet uncertain. It is generally accepted that liquid hydrogen will be the fuel of the future for air transportation. For the future hypersonic transport, cruising within the earth's atmosphere, there is no alternate to liquid hydrogen. Insofar as the next generation of supersonic transports is concerned, the issue of liquid hydrogen as an alternate fuel has been considered, but so far the emphasis of research is on the advanced supersonic transport (AST) using jet fuel. For the subsonic transports, liquid hydrogen is an option to the continued use of aviation fuels derived from natural crude petroleum or to synthetic jet fuels and to liquid methane produced from coal.

Elements of a NASA program to develop liquid hydrogen technology for subsonic commercial air transports assumed to enter service in the 1990 to 1995 time period are listed in Table 1. Since the program's beginning late in 1973, a number of studies were completed. The purpose of the studies and some of the significant results obtained will be presented.

THE HYDROGEN OPTION

In air transportation, a generally expressed view is that hydrogen is the fuel of the future, usually meaning after the start of the 21st century. The fact that this threshold in time will be crossed in less than 23 years is not comforting to the research and development community which recognizes that any new major technical development requires from 10 to 15 years or more to produce a product for commercial use or consumption. This span of years becomes especially meaningful when referenced to the annual production of oil. The actual and projected domestic oil as determined by ERDA (ref. 1) is shown in figure 1. These are data as of the end of 1974.

Alaskan North Slope Oil has not begun to flow in 1976 and it may be 1978 before the pipeline will flow at the expected 318,000M^3 (two million barrels) per day. Similarly, there is as yet no production of oil through enhanced recovery.

Even more disturbing is the relationship of air transport cycle to the projected domestic oil production. This relationship for current and some candidate future air transports is shown in figure 2, and for emphasis is superimposed on the plot generated by ERDA. The air transport cycle is defined here as 5 or more years of research and development (R&D) after project go-ahead; 20 years of useful life after initial entry into commercial service; plus 10 years of production (P) of the basic design.

All of the future airplanes shown in figure 2 were studied and some have had the benefit of substantial periods of supporting research and technology. What is evident from figure 2 is that even if work on these future airplanes were to start in 1977, the prospects of any entering service much before 1990 is dim, and the prospects for using natural crude petroleum for air transportation become increasingly unattractive with the passage of time.

Although a comparatively minor consumer of petroleum energy (about 5 percent in the U.S.) the well being and growth of air transportation depend upon availability of aviation fuels throughout the world (ref. 2). Coal, so frequently cited as the source of alternate fuels, is not available in most parts of the world. The use of indigenous raw materials to produce alternate fuels, then, is an important consideration. The choice of alternate fuel, however, is further conditioned by the requirement, especially for international operations, of universal unanimity on which alternate fuel will serve future worldwide air transportation.

Each of the alternate fuels has major problems. In the case of synthetic fuels, there is no synthetic fuel industry in the Western Hemisphere. Once established, the synthetic crude will be in demand for a variety of products, including fuels for electric power generation, heating, and transportation.

Aviation fuel, a highly refined product at the end of a long chain of refining processes, is not likely to account for much more than the present 5 percent share of a barrel of crude.

Liquid methane has about 16 percent more energy per unit weight than jet fuel. Methane in the form of the less pure pipeline natural gas was tested in jet engines with acceptable results. Natural gas is a relatively common fuel for industrial gas turbines. Methane can be made from coal, vegetation (biomass), and waste products. As a popular, clean-burning fuel, the U.S. or any nation will be hard pressed to supply natural gas, or methane, for its basic needs. Air transportation will be just one of several basic needs and will have to compete with the other needs for its share of the total production of synthetic natural gas.

Liquid hydrogen has 120 kilojoules of energy per gram (51,600 Btu/lb) or about three times the energy per unit weight as jet fuel. For equal volume, LH_2 weighs about one-eleventh as much as jet fuel. Besides being ideal fuel for the gas turbine, hydrogen when made from water by electrolysis is recyclable since the product of combustion of hydrogen is water vapor.

The basic technology of production and use of hydrogen is mature. Hydrogen is produced in large quantities from natural gas for the manufacture of ammonia for fertilizers and from crude petroleum within the refineries where hydrogen is essential to refining processes. In 1973, the energy equivalent of the hydrogen consumed in the U.S. was 1.4 percent out of a total U.S. energy consumption of 70.1×10^6 kilojoules (74×10^{15} Btu) (ref. 3). The total world consumption of hydrogen in 1973 was three times that of the U.S.

Hydrogen is a major constituent of coal and petroleum and large quantities of hydrogen are generated in coal gasification and liquefaction processes. Hydrogen is also essential for the upgrading of fuels derived from natural crude petroleum and in the manufacture and upgrading of synthetic fuels from either coal or oil shale.

The direct use of hydrogen as a fuel is a matter of time and economics. The universal presence of hydrogen in combined form and the serious economic and security implications of continued reliance on finite fossil fuel supplies are escalating research and development by the industrial nations of the world. Each nation is seeking those processes best suited to the nation's resources for the production of hydrogen (ref. 4).

Of the alternate fuels, liquid hydrogen attracted most attention in aviation because of its demonstrated potential as an available, high energy fuel in the U.S. Space Program. Since 1972, studies by the aerospace industry and government organizations (refs. 5, 6, 7, and 8) further substantiated the potential and determined the feasibility of liquid hydrogen for air transportation.

SUBSONIC AIR TRANSPORT DESIGN STUDIES

Studies by the Lockheed Aircraft Corporation for NASA cover a variety of subsonic passenger and cargo transport configurations conceived by the contractor in the initial phases of the study to meet specified payloads, range, and cruise speeds. In addition, jet-fueled airplanes of equal payload and range capabilities and technology were designed to provide a basis of comparison in terms of conservation and direct operating costs. The scope of these studies is shown in Table II. All designs were developed to incorporate 1985 technology and all used the same criteria and guidelines.

The LH_2 air transport configuration selection process required that the designers consider the containment of a volume of liquid fuel about four times that required by a conventional jet transport at a temperature below 20.7^{o}K (-423^{o}F). Of the various concepts considered, the eight shown in figure 3 were defined and analyzed in sufficient depth to permit an appraisal of their performance potential as passenger air transports. Two configurations were selected for more detailed design and analysis. One configuration has internal tanks and in the second, LH_2 is carried externally in pods affixed above the wing. The jet-fueled air transport is of conventional design.

The cargo airplane configurations cover two concepts (figure 4). In the nose loader, the cargo can be loaded from the front when the jaw of the airplane is opened, and off-loaded by a ramp in the aft belly of the airplane. The LH_2 is carried in tanks above the cargo compartment and in the tail cone.

The swing-tail configurations have a hinge system which allows the entire tail section to be rotated in a lateral plane to permit loading and unloading of cargo from the rear. In these designs, the bulk of the fuel is contained in fore and aft tanks in the fuselage.

The conventional jet cargo transport carries fuel within the wings and can be designed either as a nose loader or as a swing-tail configuration.

The principal results of the initial study are given in Table III. The complete results are reported in references 9 and 10.

A follow-on study was made to expand the range spectrum at both ends and in the size of the passenger airplanes (Table IV). Both the fuel-in-fuselage and fuel-in-wing-pod designs were redesigned to carry 200 passengers over a range of 5560 Km (3000 nautical miles), and 130 passengers over a range of 2780 Km (1500 mi.). The 400-passenger fuel-in-fuselage airplane design was also modified to carry the full payload outbound and inbound with a range radius of 5000 nautical miles with no refueling.

Analyses of these designs show first, that like for 10,190 Km (5500 mi.) range, the external tank configuration has no advantage over the internal tank design for medium and short ranges; second, on an energy utilization basis, the LH_2 advantage over jet fuel designs decreases with decrease in airplane size and range with LH_2 holding its advantage down to a range of about 2780 Km

(1500 mi.); and third, that LH_2 provides significant advantages in long range airplanes. For the long range nonrefueling mission, for example, the LH_2 airplane would still be about the size of a Boeing 747. A jet fuel airplane would have a maximum gross takeoff weight about 60 percent greater and would use 20 percent more energy. These results are reported in reference 11.

HYDROGEN LIQUEFACTION TECHNOLOGY

In the 1960's, the U.S. Space Program created a new demand for large scale production of liquid hydrogen. Several plants were built with the largest having a production capacity of 54.4 tonnes (60 tons) per day. By 1973, natural gas was no longer a viable future source for large quantities of hydrogen, and the demand for hydrogen for the Space Program decreased. As a consequence, many of the existing plants were either mothballed or dismantled.

In studies begun in 1973, the price of liquid hydrogen was assumed to be \$2.84 per 10^6 kilojoules (\$3 per million Btu). Now, the price used in studies is double. With about one-half of the cost of liquid hydrogen attributed to the liquefaction process, a study of this energy-intensive process was necessary to determine if the efficiency and concomitantly the economics of the process can be improved. The principal results of a study made by the Linde Division of the Union Carbide Corporation indicate that scaling up process capacity from 27.2 or 54.4 tonnes per day to 227 tonnes (250 tons) per day can be accomplished and that larger capacity can be achieved by modularization of 227 tonnes per day units.

The theoretical work of hydrogen liquefaction is 14.07 kilojoules per gm. With current technology, the energy requirement is 39.05 Kj/gm (16,800 Btu/lb) for a thermodynamic cycle efficiency of 36 percent. The compression equipment accounts for more than half of this inefficiency. Cycle efficiency is expected to improve through advances in technology to about 44 percent in the 1985-1990 time period. The study results, which include areas identified for advancement of liquefaction technology, are reported in reference 12.

To investigate opportunities for improving efficiency and economics identified in the first Linde study, two follow-on studies were made. In the first of the follow-on studies, Linde found that loss of hydrogen due to leakage can be reduced from over 12 percent to less than 5 percent by improved seals and recovery systems on compressors and by the use of valves less prone to leak. Linde also determined that pressurization of the basic coal gasifier, which normally operates at atmospheric pressure, can decrease coal required by 7 percent, improve thermal efficiency by 2 percent, and reduce the cost of liquid hydrogen by 5 percent. These results are described in reference 13 along with other prospects for improvements.

The remaining study examines the merits of addition of a higher molecular weight gas, such as propane, to hydrogen to permit the use of less expensive centrifugal compressors. Also, with liquefaction of large quantities of hydrogen, the one part of deuterium (heavy water) in every 7000 parts of liquid hydrogen introduces an interesting high-market value by-product which can be extracted and sold to decrease the cost of production of liquid hydrogen.

SYNTHETIC FUELS FROM COAL

The need for common base cost and energy data on the conversion of coal to hydrogen led to a study which also included the production of methane and liquid fuels for aircraft. Recognizing that production cost and energy benefits can accrue to synthetic fuels if the coal gasification and liquefaction processes are treated as integrated systems, the Institute of Gas Technology was allowed freedom to exercise judgement in selection of the most promising processes and in conceptual design and arrangement of the process equipment. The plant was sized to produce 237 billion kilojoules/day (250 billion Btu/day) of the main product using 1985 technology. Costs were based on 1974 dollars and private industry financing.

The processes evaluated are shown in Table V. For each process, the amount of coal required to produce 237 billion kilojoules of the main product per day is given along with the input energy value of the coal in terms of higher heating value. The output is similarly given for the main product and for the entire system which includes by-product credits and measures to improve plant efficiency. These data represent a consistent set obtained by following common guidelines and procedures to the extent possible.

Five processes (Table VI) were selected for economic evaluation. The indicators selected to illustrate the economics of the five processes are: (1) total capital requirements; (2) net annual operating cost; (3) annual revenue required; and (4) the 25-year average price of the major product for two prices of coal, one 28.4 cents per million kilojoules (30 cents per million Btu) or \$5.28/ton and the other 56.8 cents/10^6 kilojoules (60 cents/10^6 Btu) or \$10.56/ton.

The data show that the cost of production of alternate fuels is sensitive to process and cost of coal. Also, that the cost of hydrogen produced by the Steam-Iron Process is about the same as methane produced by the HYGAS® Process. The cost of jet fuel component, a partially refined liquid fuel, derived from coal, is about the price paid for fuel by the airlines \$2.46/10^6 KJ (\$2.60/10^6 Btu). The importance of the by-product credit is most evident for the Steam-Iron Process. In this process, which incidentally does not require oxygen as do the other hydrogen and methane processes, large quantities of hot spent producer gas are generated. An analysis on how best to use this waste energy was made by the United Technologies Research Center for IGT. This analysis shows that gas turbine, steam turbine and heat exchanger components can be combined in such a manner that up to 1325 Mw(e) can be generated for an installed capital cost of less than \$200 per Kw. Since only a small portion of this electrical energy is required within the system, the bulk can be sold to the energy market.

The net operating cost shown in Table VI is based on the sale of electricity at one cent per kilowatt-hour. In 1985 and thereafter, the value of electricity is likely to be higher than 1c/Kwhr with an even more favorable effect upon net operations cost and on the cost of producing hydrogen. The results of the IGT study, including the analysis by United Technology Research Center, are presented in reference 14.

Of practical interest is the cost of fuel delivered to the airplane. One cost estimate which takes into account losses due to boiloff as well as the incremental costs of transporting, liquefying, and storing the fuel is given in reference 15. These data were subsequently upgraded in reference 16 to take into account higher coal costs. Currently, for coal at $20 per ton, liquid hydrogen delivered to the airplane is estimated to cost $6.44/10^6 KJ ($6.80/10^6 Btu). The comparable costs of liquid methane and synthetic jet fuel are $5.21 and $3.98 per 10^6 KJ.

INSULATION MATERIALS FOR LH_2 TANKS

Conventional airplane fuel tanks are designed to stringent requirements which take into account the fact that the airplane will take off and land on rough runways, will cruise in turbulent air, will operate in tropic and polar temperatures on the ground and over an equally wide range of temperatures in flight, and will operate over a range of altitudes. A ten-hour day is becoming routine in air transportation, and currently air transports are being designed for a service life of 50,000 flight hours. The tanks and other components will experience thousands of cycles during the life of the airplane. In this long-lived dynamic environment, fuel tanks must not leak.

In modern air transports jet fuel at ambient temperature and small positive pressure is carried in tanks built integral with the wing structure. The reference jet fuel transport of this study, for example, carries 86,400 kg (190,700 lbs) or 108 cubic meters (28,500 gals) of fuel in the wings for the 10,190 Km range.

The change from jet fuel to liquid hydrogen in an air transport is great and requires special design considerations. The foremost is the fact that liquid hydrogen is close to the bottom of the absolute temperature scale; LH_2 boils when the temperature rises above 20°K (-253°C) and freezes below 14°K. To maintain hydrogen fluid requires extremely good insulation and a tank configuration with a ratio of wetted surface area to volume as low as practicable. Tank pressure is low and comparable to conventional jet fuel tanks.

For the 10,190 Km range, the 400-passenger LH_2 transport carries 27,900 kg (61,600 lbs) of fuel - only 32 percent of the weight of fuel carried by the conventional airplane. Fuel volume, however, is another matter. The required tank volume is 393 cubic meters (104,000 gals) as compared to 108 m^3 (28,500 gals), or 364 percent of the jet fuel tank volume. Figure 5 shows the locations of the tanks in the fuselage of the LH_2 airplane. The major tank diameter is about 6.1 m (20 ft).

The thermal protection program is to determine the criteria and select the proper combination of materials which: (1) can satisfy the heat transfer requirements, (2) can be applied in such a manner as to minimize heat shorts or leaks, (3) will survive the operating environment, (4) will have a long service life, and (5) can be inspected, maintained, and repaired as necessary.

Both the Bell Aerospace and Arthur D. Little Company, Inc., are studying closed cell plastic foams. The Bell program surveyed 18 materials and selected 6 foam compositions representing urethanes, polymethacrylimides and polybenzamidiazcles for the initial test program. In this program, test panels of insulation specimen bonded to flat aluminum plates will be thermally cycled 2400 times to simulate the actual flight cycles during the expected life of the airplane fuel tank. The Arthur D. Little program focused on reinforced closed cell foams. The results of these two studies are being factored into the Lockheed LH_2 fuel system study. The Lockheed study also includes hard-vacuum tanks and thermal protection concepts and materials developed for advanced technology space systems.

MATERIAL PROPERTIES IN LH_2 TANK

Liquid hydrogen tanks for air transports are large and comparable in size to tanks in space vehicles. The material which is used successfully in space vehicles is the aluminum alloy 2219-T87, an aerospace material designed for cryogenic usage. The strength and fracture toughness of this material increase with decrease in temperature. At 20°K, the properties of this material are substantially higher than at room temperature. However, the differences in the modes of operation and environment between space vehicles and air transports are great, with structural integrity requirements of air transports more stringent due to the numbers of cycles experienced in daily operation and the economic necessity of long service life of air transports.

In studying tank materials for NASA, the Convair Division of General Dynamics found that though the properties of 2219-T87 were well documented, there were insufficient data for thin gages (nominally 0.050 inch) at 20°K. Additional properties data were generated for strength, toughness, cyclic crack growth and fatigue of the alloy in chemmilled and welded conditions at room temperature and at 20°K. The results reinforce the selection of 2219-T87 and provide preliminary design data. These results are presented in reference 17.

LH_2 HAZARDS

The safety record in handling LH_2 in industry and in the space program is remarkably good. As early as 1956, the use of LH_2 as a fuel was successfully demonstrated in several cruise flights in a twin-engine military jet (B-57) flown from the Cleveland Hopkins International Airport by the then NACA. Flight Propulsion Research Laboratory, now the NASA Lewis Research Center. These years of practical experience tend to mitigate the concern regarding the potential hazards due to spills, fires, and explosions of hydrogen. As limited as was the research in the 1950's on the hazards of LH_2 spills, fires and explosions, this research provided the data for the design of LH_2 airplanes, engines and rocket motors, and for large industrial facilities to liquefy gaseous hydrogen and store and distribute liquid hydrogen for the space program and other uses. As noted in reference 18, the largest test spill was one of 20.8 cubic meters (5500 gals). Two spills were of $1.89 m^3$ (500 gals) and a number of smaller spills of 189 liters (50 gals) or less. Much larger quantities of LH_2 are involved in and in support of the future LH_2 air transports. None of the data available was considered applicable to the analyses of the consequences of the rupture of a large storage tank or the rupture of large tanks in the airplane as in a hard crash landing. These early considerations led to a study for NASA Langley by Mount Auburn Research Associates in collaboration with Factory Mutual Research Corporation. However, the calculated properties of hydrogen gas clouds generated from large spills, and their subsequent dispersal are suspect because the analytical models used were developed from small spill data. The applicability of such models to much larger spills remains to be established.

AIRPORT REQUIREMENTS

An early concern (ref. 19) in the use of liquid hydrogen in air transportation was the impact on the airport and on airline ground operations. A preliminary assessment of this concern was obtained in two studies of two major U.S. airports in which the current and predicted widebody traffic was used to simulate LH_2 air transport operations at these airports in the 1990 to 1995 time period. The study by Boeing Commercial Airplane Company dealt with operations at the Chicago O'Hare International Airport and that by the Lockheed-California Company at the San Francisco International Airport.

In these studies, it was assumed that pipeline hydrogen gas was available at the airport boundaries. The object then was to determine whether or not a hydrogen liquefaction facility of size sufficient to meet the traffic requirements of the current widebody traffic could be designed and built within the airport boundaries. The attendant considerations were whether or not LH_2 could be stored on the airport and also how were the airplanes to be fueled. Compatibility of LH_2 with the conventional jet fuel and aviation gasoline facilities required to serve the larger traffic of conventional aircraft was another consideration.

The findings of the two study teams are summarized as follows: Boeing - "All potential technical problems identified in the study lend themselves to straightforward engineering solutions." Lockheed - "... It is entirely feasible and practicable to provide LH_2 facilities and equipment at San Francisco International Airport to accommodate long-haul commercial transport air traffic starting 1995-2000."

A major contribution of these studies is the closed fueling cycle which both study teams developed independently as the solution to safety, fuel economy, energy conservation, and practical airline ground operations. Refueling time, for instance, can be about the same as for conventional transports. Figures 6 and 7 illustrate two different approaches to fueling LH_2 air transports. Results of these two studies are given in references 20 and 21.

STRATOSPHERIC EMISSIONS

A model developed by The Aerospace Corporation can be used to calculate upper atmosphere temperatures due to water vapor and NO_X. A 3-dimensional model developed by George Washington University permits an analysis of causal phenomena on the changes in the stratosphere. Published results from these studies are not yet available.

LH_2 FUEL SYSTEMS FOR SUBSONIC TRANSPORTS

In the LH_2 air transport, some conversion of liquid to gaseous hydrogen in the fuel system is necessary but for the most part, great care must be exercised in the design of the entire fuel system to minimize the flow of outside heat into the system. The thermal protection system must be balanced between energy loss and the practical side of airline operations, including inspection, maintenance and repair. An insight into the nature and magnitude of the LH_2 fuel system problem is given in reference 22.

A study by Lockheed-California Company is underway to define in engineering detail an LH_2 fuel system and the additional research and technology required to bring the technologies to a state of readiness for future industry application. The 400-passenger, 10,190 Km range subsonic transport is used as the reference configuration for the LH_2 fuel system. A variety of engine cycles and operating conditions will be considered to determine the prospects for further improving the energy efficiency of the propulsion system by capitalizing on the most favorable properties of hydrogen both as a fuel and as a coolant. Several LH_2 fuel tank thermal protection systems concepts will be analyzed to determine the best combinations of materials and system elements in terms of safety, energy conservation and economy of operation. The initial design requirements for wide-range operation, long service life pumps, fuel control and management subsystems, and other important subsystems and accessories will be determined. When completed, this study will provide a base for the initial design, development and test of hardware in ground test systems, and eventually in flight.

CONCLUDING REMARKS

These studies examined in engineering detail the processes for converting coal to hydrogen and other alternate fuels, and hydrogen gas into liquid. A principal finding is that the price of alternate fuels, including liquid hydrogen, is about two or three times that of jet fuel. Large volumes of LH_2, like any high energy fuels, are a potential hazard and must be treated accordingly. The installation of LH_2 fuel complexes at major air terminals to provide fuel to air transports is well within the feasibility of engineering knowledge. Moreover, the solution of vent gas (boiloff) dispersal from the airplane while on the ground, even during refueling, assures that the routine airline ground services can be carried out in essentially the same time and manner as with jet fuel transports.

The first look at cost of LH_2 fuel installations at two of the largest airports in the world show that the costs are of the same magnitude as current cost of major airport modifications, and perhaps less than the plant investment cost of a 237 billion kilojoules (250 billion Btu) per day coal gasification plant. Very few airports in the world would require such large fuel complexes.

The first generation LH_2 subsonic commercial air transport is likely to be a possible follow-on to the Boeing 747. Compared to its jet fuel counterpart, the LH_2 transport for the same payload and range, will have a much lower take-off gross weight, and consequently, smaller wings, less powerful engines and lighter landing gear. It will also require less onboard energy to fly the same mission.

A subsonic LH_2 transport can be built in the price range of a jet fuel transport. There are pockets of deficiency in the technology, but none which cannot be resolved with proper investment in research and development.

The current study of LH_2 fuel systems will define the principal remaining technical areas in the design of the air transport. When completed, the program will have provided much of the foundation for the liquid hydrogen option for future commercial air transports.

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Table I. - LH_2 Technology Research Areas

Start Date	Research Areas	Status
Feb. 1974	Subsonic Air Transport Design Studies	Completed
July 1974	Hydrogen Liquefaction Technology	Completed
Oct. 1974	Synthetic Fuels from Coal	Completed
May 1975	Insulation Materials for LH_2 Tanks	In Progress
June 1975	Material Properties for LH_2 Tanks	Completed
July 1975	LH_2 Hazards	Completed
Sept. 1975	Airport Requirements	Completed
June 1975	Stratospheric Emissions	In Progress
Sept. 1976	LH_2 Fuel Systems for Subsonic Transports	In Progress

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TABLE II. - SUBSONIC AIR TRANSPORT DESIGN STUDIES

SCOPE

SPEED MACH NO.	RANGE KM	FUEL	SERVICE	PAYLOAD	DESIGN CONCEPTS
0.80 .85 .90	5,560 (3,000 N.MI.) 10,190 (5,500 N.MI.)	LH_2	PASSENGER	400 PASS. 600 " 800 "	FUEL-IN-FUSELAGE (4)
				400 "	FUEL-IN-WING PODS (2)
				400 "	FUEL-IN-WING (2)
			CARGO	*125,000 LBS 250,000 "	NOSE LOADER
				125,000 " 250,000 "	SWING TAIL
		JP	PASSENGER	400 PASS.	CONVENTIONAL
			CARGO	125,000 LBS. 250,000 "	CONVENTIONAL-LOW WING CONVENTIONAL-HIGH WING

*125,000 LBS = 56,700 KG; 250,000 LBS = 113,400 KG

TABLE III. - SUBSONIC AIR TRANSPORT DESIGN STUDIES

PRINCIPAL RESULTS

COMPARED TO JET A AIRPLANES OF SAME RANGE, PAYLOAD AND ADVANCED TECHNOLOGY

THE LH_2 AIRPLANES ARE:

LIGHTER
QUIETER
GENERATE LESS ENGINE EXHAUST POLLUTION
CAN USE SHORTER RUNWAYS
USE LESS ONBOARD ENERGY
HAVE SMALLER WINGS BUT LARGER FUSELAGES

SOMEWHAT COSTLIER

A PREMIUM CAN BE PAID FOR LH_2 FUEL BECAUSE OTHER ELEMENTS OF DOC FAVOR THE LH_2 AIRPLANES

OVERALL FLIGHT (ENERGY) EFFICIENCY IMPROVES WITH INCREASE IN SIZE OF AIRPLANE

THE INTERNAL TANK DESIGN IS DECISIVELY ADVANTAGEOUS OVER EXTERNAL TANK DESIGN

TABLE IV. - SUBSONIC AIR TRANSPORT DESIGN STUDIES

SCOPE (EXTENDED)

SPEED MACH NO.	RANGE KM	FUEL	SERVICE	PAYLOAD	DESIGN CONCEPTS
0.80 .85 .90	2,780 (1,500 N.MI.)	LH_2 JP	PASSENGER	130 PASS.	FUEL-IN-FUSELAGE FUEL-IN-WING PODS
	5,560 (3,000 N.MI.)			200 PASS.	FUEL-IN FUSELAGE FUEL-IN WING PODS
	9,260 RADIUS (5,000 N.MI.) NO REFUELING			400 PASS.	FUEL-IN-FUSELAGE

Table V. - COAL CONVERSION TO SYNTHETIC FUELS INPUT, OUTPUT AND OVERALL EFFICIENCIES

SYNTHETIC FUELS & PROCESSES	INPUT		OUTPUT		OVERALL EFFICIENCIES	
	QUANTITY	HIGHER HEATING VALUE*	MAIN PRODUCT	SYSTEM	MAIN PRODUCT	SYSTEM
	TONNES/DAY (TONS/DAY)	10^9 KILOJOULES/DAY (10^9 BTU/DAY)	10^9 KILOJOULES/DAY (10^9 BTU/DAY)		PERCENT	
Hydrogen						
Koppers-Totzek	22,700 (25,012)	465.0 (440.5)	264.0 (250.3)	265.0 (251.1)	56.8	57.0
U-Gas	19,440 (21,443)	398.0 (377.7)	264.0 (250.2)	264.5 (250.9)	66.2	66.4
Steam-Iron	28,850 (31,853)	592.0 (561.0)	264.0 (250.2)	365.0 (350.9)	44.6	62.8
Methane						
HYGAS®	17,700 (19,580)	364.0 (344.8)	255.0 (241.5)	269.0 (255.1)	70.0	74.0
CO_2 Acceptor	20,200 (22,239)	413.0 (391.7)	264.5 (250.7)	278.0 (262.9)	64.0	67.1
Jet Fuel Component (CSF Coal Liquefaction)						
Refinery Import Gasoline	22,000 (24,283)	555.0 (525.5)	311.5 294.3)	394.0 (373.6)	45.8	60.9
Hydrocracking	22,000 (24,283)	555.0 (525.5)	205.5 (194.5)	292.5 (277.2)	37.0	52.7

* Hydrogen and Methane - Western Coal (20,450 joules/gram or 8,800 BTU 1b)
Jet Fuel Component - Eastern Coal (25,100 joules/gram or 10,800 BTU/1b)

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Table VI. - COAL CONVERSION TO SYNTHETIC FUELS

ECONOMICS

SYNTHETIC FUELS & PROCESSES	TOTAL CAPITAL REQUIREMENTS	NET OPERATING COST	ANNUAL REVENUE REQUIRED	MAJOR PRODUCT PRICE 25-Year Average	
				PRICE OF COAL*	
				$\$0.28/10^6$ KJ	$\$0.56/10^6$ KJ
	MILLION DOLLARS			$\$10^6$ KJ ($\$/10^6$ BTU)	
Hydrogen					
U-GAS	539.79	75.043	178.095	2.05 (2.17)	2.51 (2.65)
Steam-Iron	532.58	10.444	131.189	1.51 (1.60)	2.16 (2.28)
Methane					
HYGAS®	435.92	57.395	150.657	1.67 (1.77)	2.10 (2.22)
Jet Fuel Component (CSF Coal Liquefaction)					
Refinery Import Gasoline	616.55	150.046	268.312	2.09 (2.21)	2.63 (2.78)
Hydrocracking	656.57	112.051	237.517	2.72 (2.87)	3.52 (3.72)

*$\$0.28/10^6$ KJ = $\$0.30/10^6$ BTU = \$5.28/Ton (Western) or \$6.48/Ton (Eastern)

$\$0.56/10^6$ KJ = $\$0.60/10^6$ BTU = \$10.56/Ton (Western) or \$12.96/Ton (Eastern)

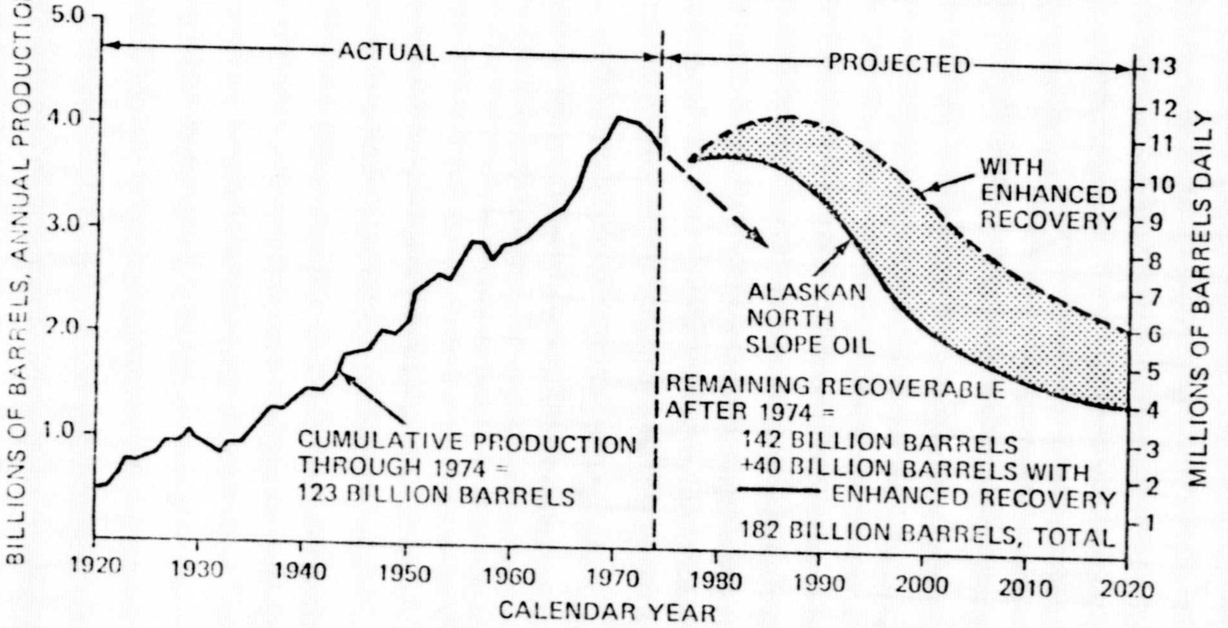
IN THIS FIGURE, DOMESTIC OIL INCLUDES CRUDE AND NATURAL GAS LIQUIDS

Figure 1. Projected Domestic Oil Production

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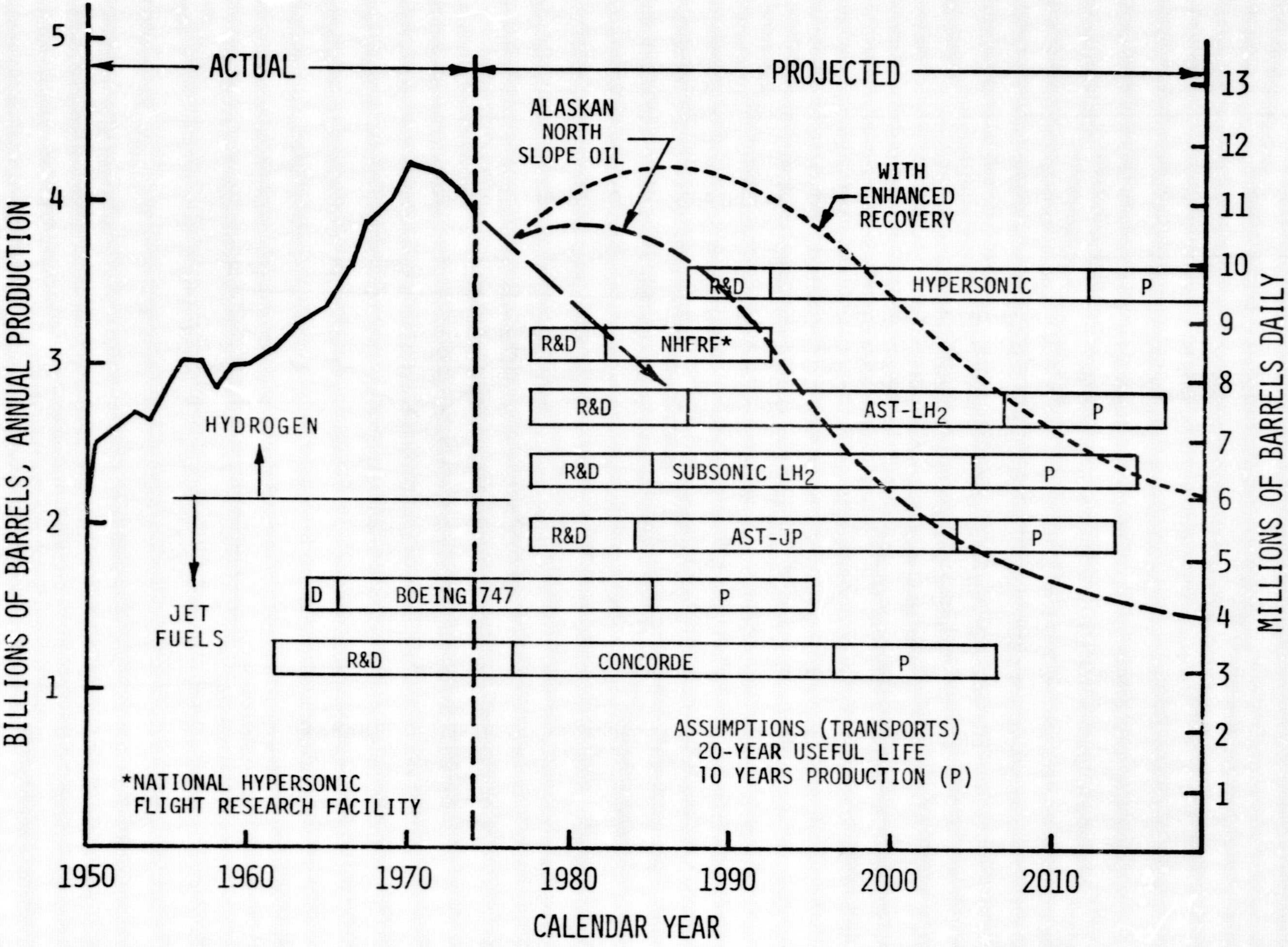

FIGURE 2. - AIR TRANSPORT LIFE CYCLE AND PROJECTED DOMESTIC OIL PRODUCTION

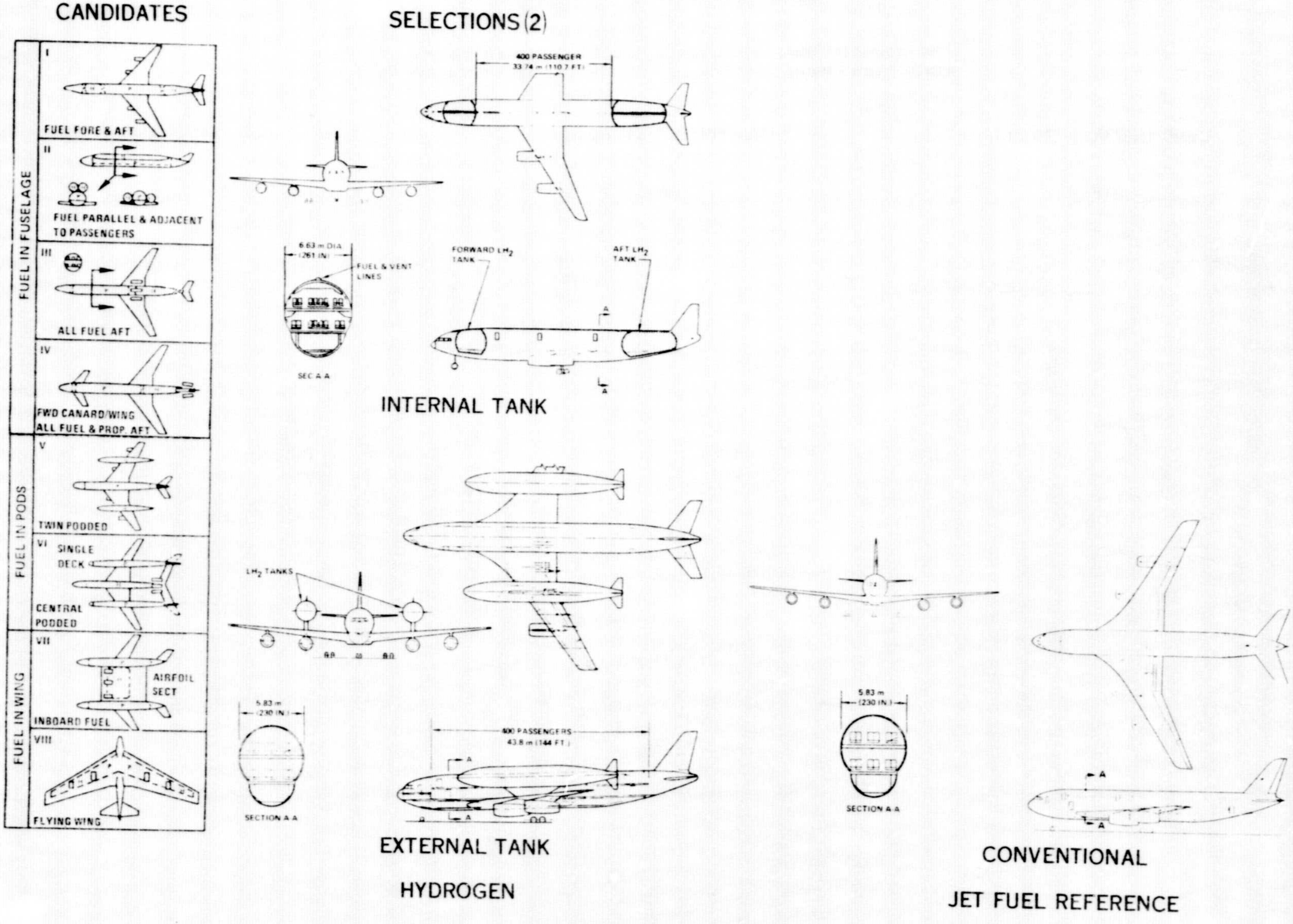

Figure 3.- LH_2 and jet fuel reference configurations for 400-passenger air transports

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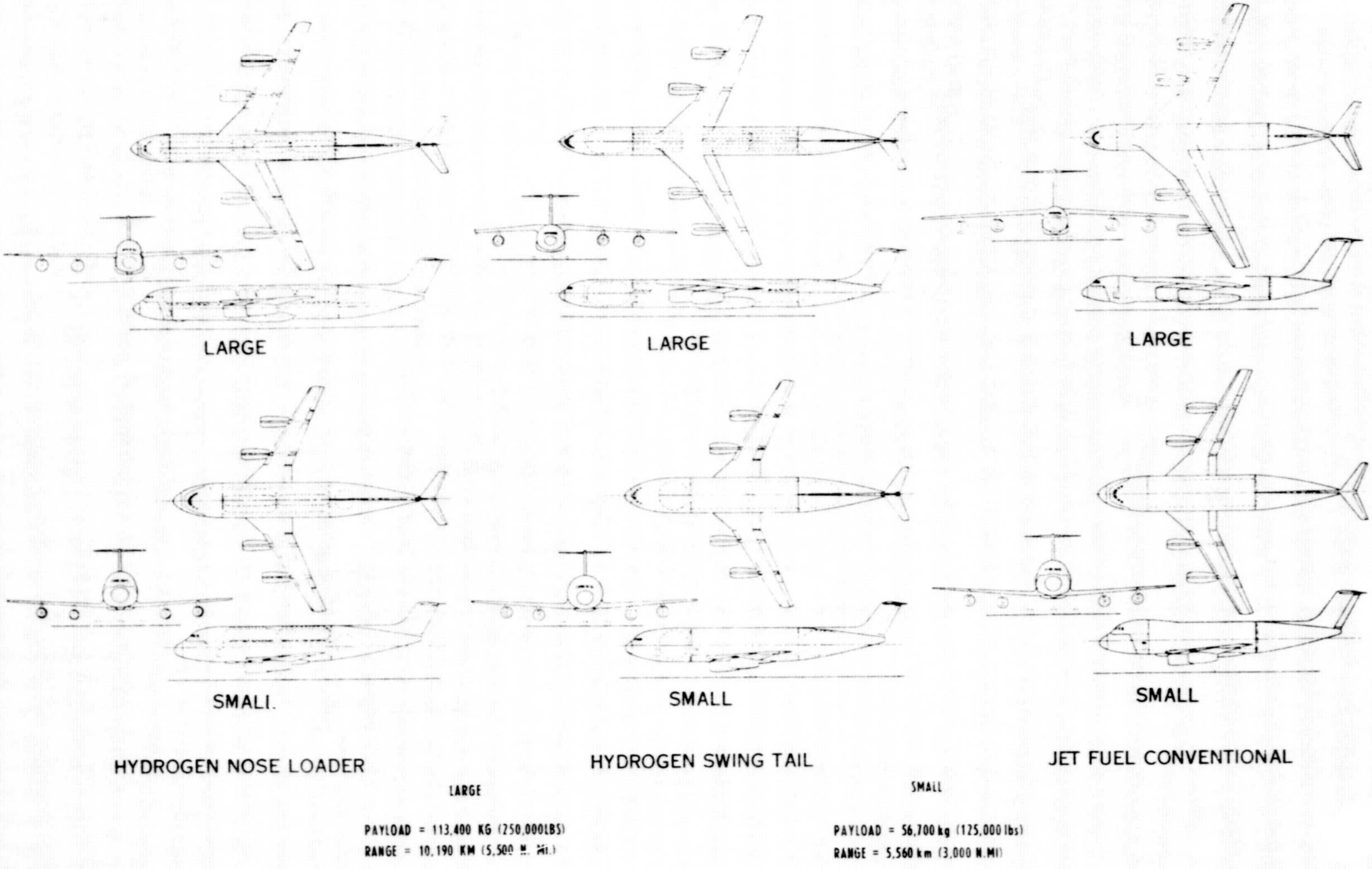

Figure 4.- Selected LH_2 and jet fuel reference large and small air transport cargo configurations

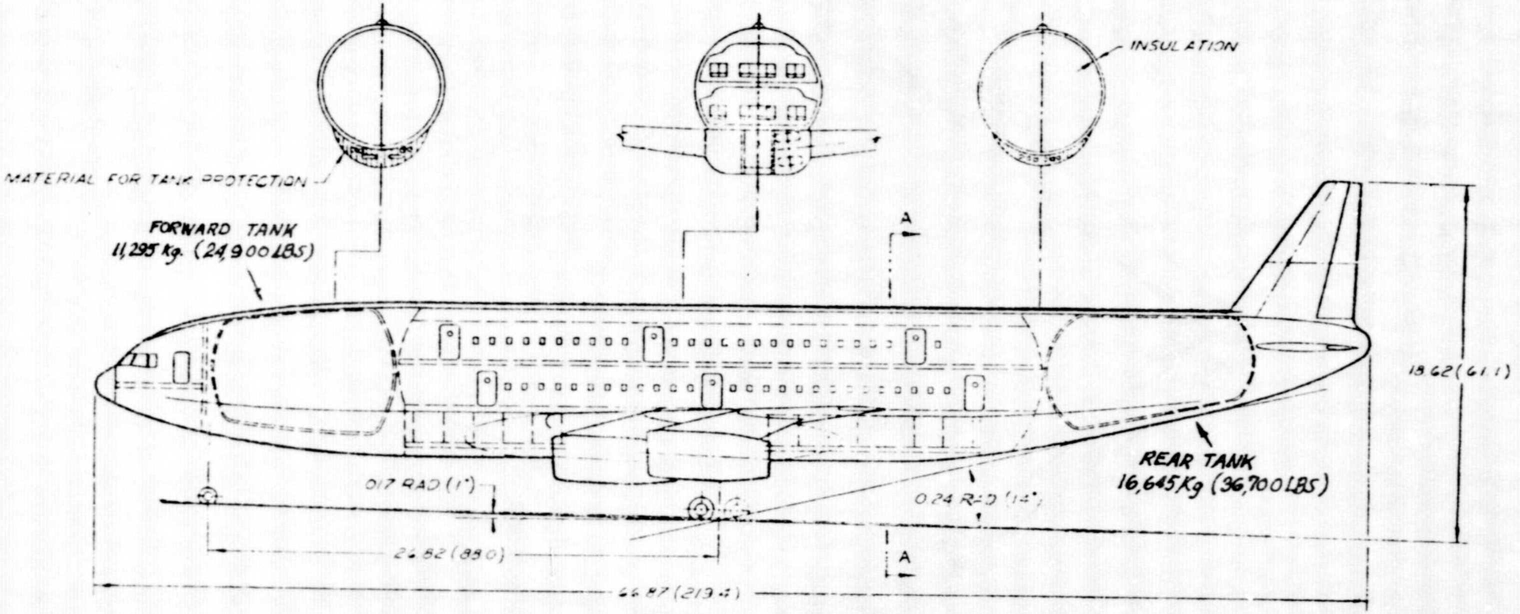

FIGURE 5. - LH_2 TANKS AND 400-PASSENGER COMPARTMENT, 10,190 KM (5,500 N.MI.) RANGE SUBSONIC FUEL-IN-FUSELAGE AIR TRANSPORT.

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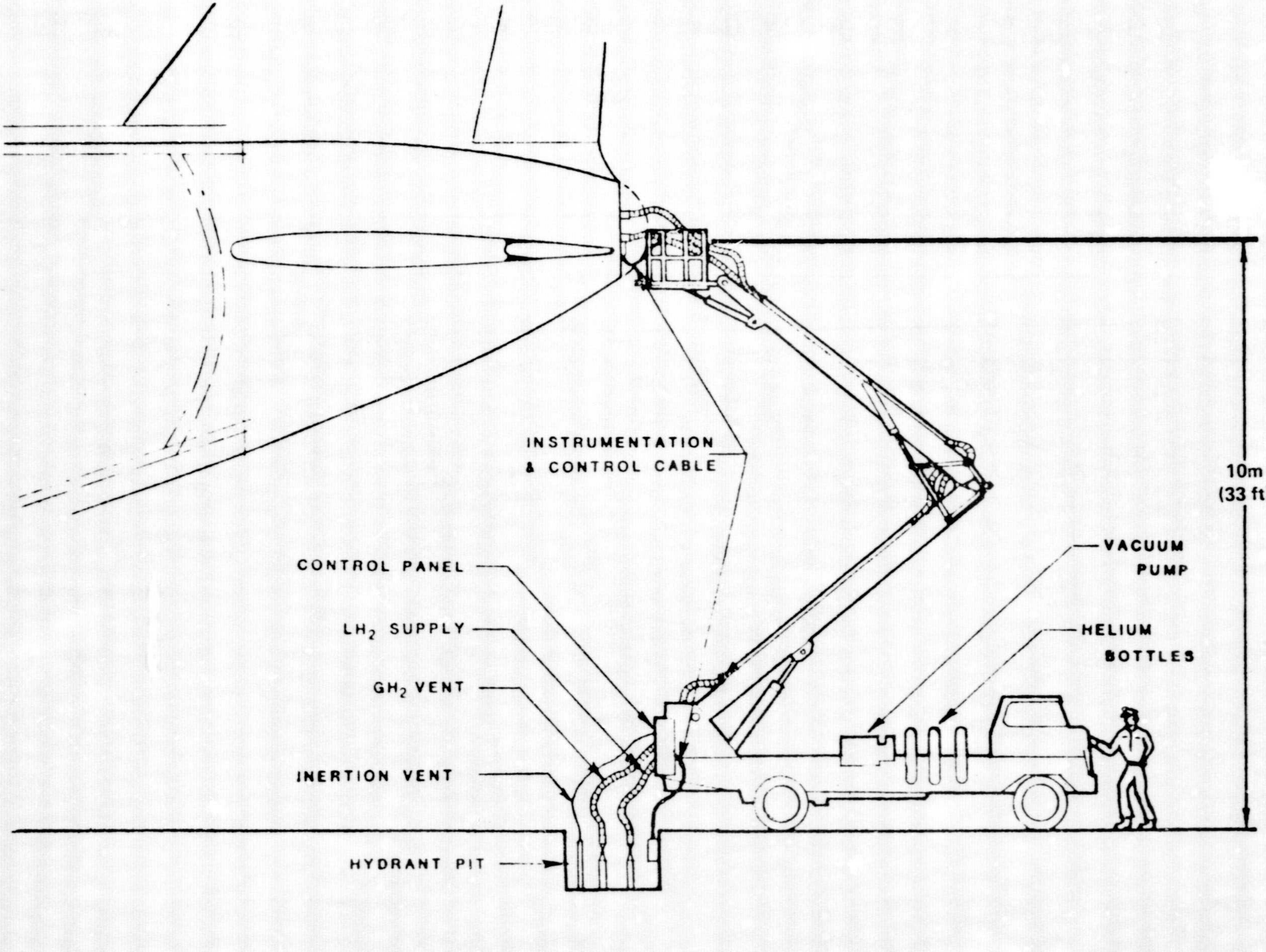

FIGURE 6. - LH_2 HYDRANT-TRUCK FUELING CONCEPT.

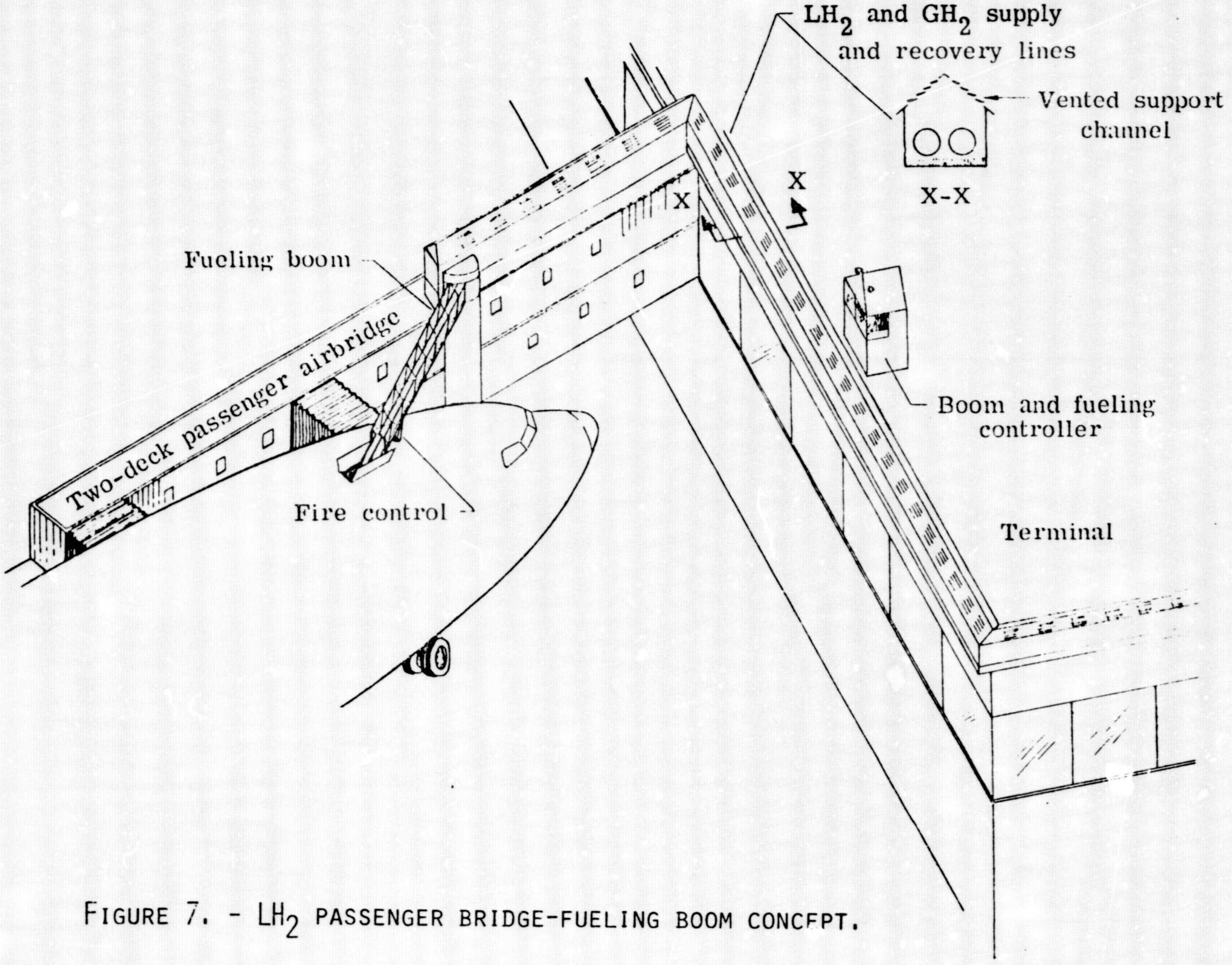

FIGURE 7. - LH_2 PASSENGER BRIDGE-FUELING BOOM CONCEPT.

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16. Abstract

A liquid hydrogen fuel option for subsonic air transports is evolving through NASA studies. In addition to continued air transport design studies, elements of this option include: (1) economical production of hydrogen; (2) efficient liquefaction of hydrogen; (3) materials for long service life LH_2 fuel tanks; (4) insulation materials; (5) LH_2 fuel service and installations at major air terminals; (6) assessment of LH_2 hazards; and (7) the engineering definition of an LH_2 fuel system for a large subsonic passenger air transport. As the one measure in the aircraft fuel conservation program which is independent of hydrocarbon fuels for operation of aircraft, the liquid hydrogen option continues to show promise for the future.

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