NASA CR-
132558

VOLUME I

SUMMARY REPORT:
STUDY OF THE APPLICATION OF HYDROGEN FUEL TO LONG-RANGE SUBSONIC TRANSPORT AIRCRAFT

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JANUARY 1975

Prepared under Contract NAS 1-12972

for
LANGLEY RESEARCH CENTER
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

by
LOCKHEED-CALIFORNIA COMPANY
AND
LOCKHEED-GEORGIA COMPANY

DIVISIONS OF LOCKHEED AIRCRAFT CORPORATION

1. REPORT NO. NASA CR-132558

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE VOLUME I
SUMMARY REPORT: Study of the Application of Hydrogen Fuel to Long Range Subsonic Transport Aircraft

5. REPORT DATE January 1975

6. PERFORMING ORG CODE

7. AUTHOR(S)
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Lange, R.H. and Moore, J.W.

8. PERFORMING ORG REPORT NO. LR-26752-1

9. PERFORMING ORGANIZATION NAME AND ADDRESS
LOCKHEED-CALIFORNIA COMPANY
P.O. BOX 551
BURBANK, CALIFORNIA 91520
AND
LOCKHEED-GEORGIA CO.
MARIETTA, GEORGIA 30063

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO. NAS 1-12972

12. SPONSORING AGENCY NAME AND ADDRESS
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

13. TYPE OF REPORT AND PERIOD COVERED Contractor Final Report; Feb-Oct, 1974

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This study was performed to investigate the feasibility, practicability, and potential advantages/disadvantages of using liquid hydrogen as fuel in long range, subsonic transport aircraft of advanced design. Both passenger and cargo-type aircraft were investigated. To provide a valid basis for comparison, conventional hydrocarbon (Jet A) fueled aircraft were designed to perform identical missions using the same advanced technology and meeting the same operational constraints.

The liquid hydrogen and Jet A fueled aircraft were compared on the basis of weight, size, energy utilization, cost, noise, emissions, safety, and operational characteristics. A program of technology development was formulated.

17. KEY WORDS (SUGGESTED BY AUTHOR(S))
hydrogen, subsonic transport aircraft, Jet A, cryogenic insulation, alternate fuel, exhaust emissions, noise, safety, energy utilization

18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIF. (OF THIS REPORT) Unclassified

20. SECURITY CLASSIF. (OF THIS PAGE) Unclassified

21. NO. OF PAGES 48

22. PRICE*

FOREWORD

Volume I is a summary of the "Study of the Application of Hydrogen Fuel to Long Range Subsonic Transport Aircraft." The work was performed under Contract NAS 1-12972 for NASA-Langley Research Center, Hampton, Virginia, during the nine month period, February through October 1974. This summary report outlines the methodology, presents the results and conclusions, and lists items recommended for further investigation and development. Details of the study are presented in Volume II, the contract final report, NASA CR-132559 dated January 1975.

The work was divided according to vehicle category: (1) passenger/cargo mission aircraft; and (2) all-cargo mission aircraft. The study was performed by the Advanced Design organizations of the Lockheed-California Company, Burbank (passenger/cargo missions), and the Lockheed-Georgia Company, Marietta (cargo-missions). Prime responsibility for contract execution rested with the California Company under the direction of G. Daniel Brewer as study manager. Robert E. Morris was project engineer for passenger aircraft. Deputy study manager for cargo mission aircraft analysis was R. H. Lange in Georgia. J. W. Moore served as project engineer for cargo aircraft.

Mr. C. T. D'Aiutolo of the Aeronautical Systems Division of NASA-Langley Research Center, was the technical monitor for the contract.

SUMMARY

This study examined the feasibility of using liquid hydrogen as fuel in advanced designs of long range, subsonic transport aircraft, and assessed the potential advantages. Both passenger and cargo-type aircraft were investigated. Passenger aircraft were designed to perform all combinations of the following matrix of primary mission requirements:

PAYLOAD	36,300 kg (88,000 lb) = 400 Passengers + cargo
RANGES	5,560 km (3,000 nmi) and 10,190 km (5,500 nmi)
CRUISE SPEEDS	Mach 0.80, 0.85, and 0.90

In addition, 600 and 800 passenger capacity aircraft were designed for Mach 0.85 cruise speed and for both ranges.

Cargo aircraft designs were studied to perform the following missions:

	Mission 1	Mission 2
PAYLOAD	56,700 kg (125,000 lb)	113,400 kg (250,000 lb)
RANGE	5,560 km (3,000 nmi)	10,190 kg (5,500 nmi)
CRUISE SPEED	Mach 0.85	Mach 0.85

To serve as a basis for comparison, reference aircraft fueled with conventional hydrocarbon (Jet A) were designed to identical ground rules and for the same missions, except that the passenger airplane requirements were limited to only one speed, Mach 0.85.

Due to the low density, high energy content, and cryogenic temperature of liquid hydrogen (LH_2) it was anticipated that optimum designs of LH_2 fueled aircraft might require unusual design configurations to gain maximum advantage from its use. This was found not to be the case. Although many unusual configurations were explored, the designs of LH_2 fueled aircraft selected as preferred configurations for both the passenger and cargo applications are conventional in appearance. Unusual design concepts which were investigated proved to be inferior.

In every case the hydrogen fueled aircraft, which were selected using minimum direct operating cost as the primary criterion, were found to be lighter, quieter, able to operate from shorter runways, require smaller engines, minimize pollution of the environment, and expend less energy in performing their design missions, relative to equivalent designs fueled with Jet A. In addition, the hydrogen aircraft are physically smaller in span, height, and wing area, but have larger fuselages.

The purchase price estimated for the LH_2 aircraft was somewhat higher than that of the reference designs. This was due to a high value accorded the hydrogen-peculiar items, for which there is insufficient data to establish a truly meaningful cost basis.

Direct operating costs of the hydrogen aircraft are significantly lower than that of their Jet A fueled counterparts if the fuels cost the same per unit of energy.

An evaluation of operations, maintenance, and safety aspects of the hydrogen fueled aircraft revealed no significant features that would seriously affect airline-type turn-around schedules, compared to current practice with Jet A fuel. Equipment to perform operations like refueling will be different, but neither the number of personnel involved nor the elapsed time required should be adversely affected.

The examination of larger payloads (600 and 800 passengers) indicated an increasing flight efficiency for the larger aircraft. As payload increased, both direct operating cost and block fuel fraction (expressed as a percentage of gross weight) decreased.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 INTRODUCTION

Growing concern for the problem of providing adequate supplies of petroleum-derived fuels to meet U.S. demand, and recognition of the inevitable price that must be paid for our ever increasing dependence on foreign supplies, has led the NASA to a broad study effort to review energy trends and to evaluate the possibilities of alternate fuels for transport aircraft. The availability and cost of petroleum-derived fuel for commercial transport aircraft will continue to become less and less attractive in coming years. Shortages will continue to develop in the future, both because of international political and economic pressures, and as a result of depletion of natural resources. Ultimately, and it is simply a question of "how soon," rather than "if," an alternate fuel must be developed.

It is generally agreed that the alternate fuel will be either synthetic kerosene, manufactured from coal, oil shale, or tar sands, or it will be liquid hydrogen. Hydrogen can be made from a combination of coal and water, or from water alone, using any of several processes and a wide variety of possible energy sources. The choice between synthetic kerosene and liquid hydrogen will be made based on considerations of cost, emissions, energy, noise, practicability, and long range world-wide availability. The present study was performed to:

- Assess the feasibility and potential advantages of using liquid hydrogen (LH_2) as fuel in long range, subsonic transport aircraft (both passenger and cargo types).
- Identify the problems and technology requirements peculiar to such aircraft.
- Outline a program for development of necessary technology on a timely basis.

2.0 STUDY SCOPE

Advanced design transport aircraft were studied for both passenger and cargo-carrying missions. Guidelines for the study are listed in Table 1. The matrix of design requirements for the aircraft is shown in Table 2. To provide a basis for a valid comparison of physical, performance, and economic parameters of the LH_2-fueled designs with conventionally fueled aircraft, reference passenger transport designs using Jet A fuel were established for one cruise speed (Mach 0.85), 400 passenger capacity, and for both ranges. In addition, Jet A-fueled reference aircraft were designed for both of the cargo missions. Special care was taken to assure that the reference aircraft were designed to the same standards as the aircraft they were to be compared with in each case.

All passenger aircraft were designed and evaluated at Lockheed-California Company and all cargo aircraft at Lockheed-Georgia Company. A large number of candidate aircraft configurations of both types were conceived and subjected to a critical qualitative evaluation. The two configurations given the highest ratings for each type of payload were selected for more detailed study and analysis.

Design studies were conducted to determine appropriate characteristics for the hydrogen-related systems required on board the aircraft. These studies included consideration of material, structural, and thermodynamic requirements of the cryogenic fuel tanks, their structural support systems, thermal protection systems, and for the fuel system. Operations and maintenance procedures and requirements were considered in the design of these components and systems.

Computer decks were generated to parametrically represent the performance, size, and weight of advanced design, quiet turbofan engines using technology forecast to be available after 1985, consistent with initial aircraft operational capability in 1990-95. Decks were generated for engines designed for both fuels, liquid hydrogen (LH_2) and Jet A.

Similarly, aerodynamic, weight and cost data were generated in parametric form to represent use of advanced technolgies.

TABLE 1. BASIC GUIDELINES

Fuel: Liquid Hydrogen (assumed available at airport for this study)

Initial Operational Capability: 1990-95

Advanced Aircraft Technologies:

- Supercritical aerodynamics
- Composite materials
- Active controls
- Terminal area features

Advanced Engines: Contractor-derived performance for both LH_2 and Jet A fueled turbofans

Noise Goal: 5.18 km^2 (2 sq. mi.) area for 90 EPNdB contour (sum of takeoff + approach)

Emission Limit Goals:

• Ground Idle	CO	14 gm/kg. fuel burned
	HC	2 gm/kg. fuel burned
• Takeoff Power	NO_x	13 gm/kg. fuel burned
	Smoke	SAE 1179 Number 25

Landing and Takeoff: 2410 m (8000 ft.) runway, 32.2°C (90°F) day, 304.8 m (1000 ft.) alt.

Direct Operating Cost:

- 1967 ATA equations (international basis)
- 1973 dollars
- 350 aircraft production base
- Baseline fuel costs

  LH_2 = \$3/1.054 GJ (\$3/10^6 Btu = 15.48¢/lb.)

  Jet A = \$2/1.054 GJ (\$2/10^6 Btu = 24.8¢/gal. = 3.68¢/lb.)

TABLE 2. REQUIRED AIRCRAFT DESIGNS

LIQUID HYDROGEN FUELED	
Passenger Aircraft	
Payload	400 PAX + cargo = 36,300 kg (88,000 lb)
Range	5560 km (3000 nmi); 10,190 km (5500 nmi)
Cruise speed	Mach 0.80; 0.85; 0.90
Configurations	Select 2 for analysis
Payload	600 PAX + cargo; 800 PAX + cargo
Range	5560 km (3000 nmi); 10,190 km (5500 nmi)
Cruise speed	Mach 0.85
Configuration	Preferred configuration from analysis of 400 PAX aircraft
Cargo Aircraft	
Mission 1	56,700 kg (125,000 lb) payload, 5560 km (3000 nmi) range, M 0.85 cruise speed
Mission 2	113,400 kg (250,000 lb) payload, 10,190 km (5500 nmi) range, M 0.85 cruise speed
Configurations	Select 2 for analysis
JET A FUELED	
Reference Aircraft	
One Mach 0.85 design for each 400 PAX and cargo payload/range combination.	

With baseline component characteristics established and expressed in parametric form, parametric vehicle studies were then carried out to determine performance capability, weight, cost, and significant design tradeoffs for both LH_2-fueled and Jet-A-fueled aircraft representing the full range of variables specified for evaluation. The results were analyzed to determine the most satisfactory design of each candidate aircraft configuration for each design range and payload. The LH_2

fueled aircraft designs thus selected were then compared with each other for the purpose of choosing a preferred configuration. After additional design refinement the selected LH_2 configuration was then critically compared with the reference (Jet A) aircraft in a "benefits evaluation."

The characteristics of LH_2 fueled passenger aircraft sized to carry larger payloads were also determined. Aircraft designs capable of carrying 600 and 800 passengers were established based on the selected configuration to determine the influence of size on aircraft operating characteristics and economics.

Finally, a research and technology development program was formulated based on critical technology requirements identified during the study.

3.0 STUDY RESULTS

3.1 HYDROGEN RELATED TECHNOLOGY

One of the purposes of this study was to explore the problems and possibilities related to use of liquid hydrogen (LH_2) as the fuel for commercial transport aircraft. In an exploratory investigation such as this it was necessary to examine the requirements of hydrogen-related structure and equipment in order to establish criteria for estimating hardware weights and costs, and to determine acceptable procedures which could be used as a basis for estimating operating costs.

3.1.1 Fuel System

The aircraft designs of this study were predicated on the basis that hydrogen is stored on-board in liquid form at a nominal absolute pressure of 145 kPa (21 psia), which corresponds to an equilibrium temperature of -251.6°C (-421.3°F). To maintain the hydrogen at this cryogenic condition for extended periods without unacceptable loss due to boil-off, the tanks must be carefully insulated. Fuel lines and valves which carry the LH_2 to the engines also require insulation.

A conceptual diagram of the elements of an aircraft LH_2 fuel system is shown in Figure 1. Nominal pressures and temperatures are shown on the diagram for each of the significant conditions which exist as the cryogenic fluid moves through the system from tank to engine combustion chamber. Tank-mounted, submerged pumps boost the pressure from the tank level to 241 kPa (35 psia) for delivery through the feed system as a sub-cooled liquid to high pressure pumps mounted in each engine nacelle. There the pressure is raised to approximately 5,160 kPa (750 psi) where, as a gas, it passes through a heat exchanger and picks up heat from a secondary coolant, e.g., a mixture of sodium and potassium (NaK), which has been used to cool the engine high pressure turbine stages. At about this same point, another heat exchanger, this one using a less exotic fluid as an intermediate coolant (e.g., a water-glycol mix), can be employed to cool the air bled from the compressor to pressurize the passenger and crew compartments, thus eliminating the need for conventional mechanical refrigeration equipment for an environmental control system (ECS). Accounting for the pressure drop through the heat exchangers, engine control valves, and fuel injection system, the fuel reacts in the engine combustion chamber at the design pressure of 3580 kPa (520 psi).

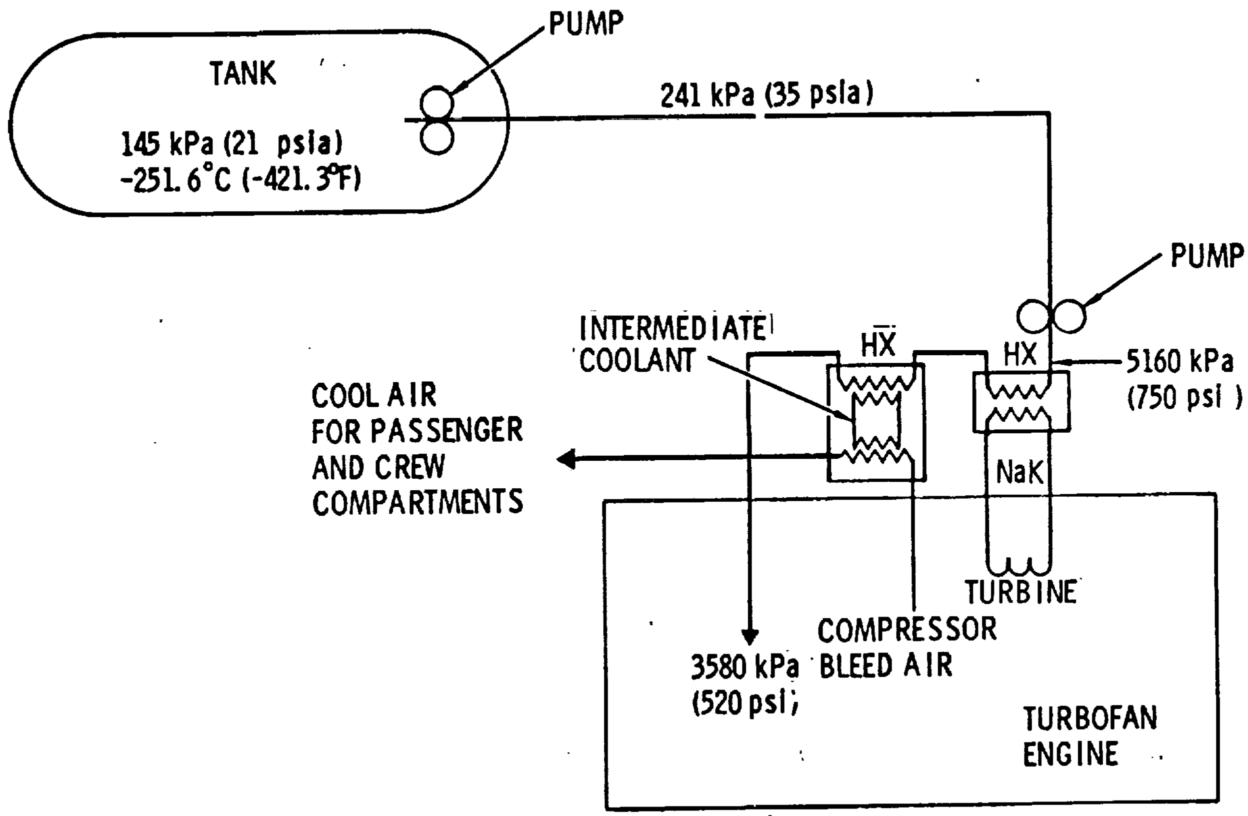


Figure 1. Hydrogen Fuel System Elements

As mentioned, the fuel tanks are carefully insulated to minimize loss of hydrogen by boil-off and to prevent frost buildup on the external surfaces of the aircraft. During service, some liquid hydrogen will be kept in the tanks at all times to maintain the system at cryogenic temperature, thus avoiding subjecting the tank structure and the support system to extreme and repetitious temperature cycling, and eliminating the requirement for expensive and time-consuming chill-down and/or purge operations. Gaseous hydrogen, vented from the aircraft tanks to avoid exceeding design pressure during out-of-service periods, would generally be recovered and reliquified, or it could be used to fuel ground service power units.

For extended out-of-service periods, e.g., when some type of major maintenance not related to the tank or insulation system is required on the airplane, the tanks would be defueled and purged with nitrogen but maintained at a pressure slightly greater than ambient. This would be expected to occur not more than perhaps two or three times per year.

When the tanks themselves, or their insulation system, require inspection or repair, after being defueled and purged with nitrogen the tanks would be vented to the atmosphere to provide safe entry by maintenance personnel. During the early service life of the aircraft, it is expected that the regulating agencies might demand frequent tank and insulation inspections to assure continued flight worthiness and to gain service knowledge. In routine commercial airline service, after cryogenic tank integrity is well established, this kind of inspection would be considered to be in the same category as that required for aircraft primary structure, i.e., normally performed at intervals of 8,000 to 10,000 hour of operation, or roughly every two or two and one-half years.

Operational procedures for LH_2 fueled aircraft are conceived as being not radically different from current practices. The equipment would be different, of course, but the manpower and the elapsed time per function should be virtually the same. For example, during a routine fueling process, estimated to require about 30 minutes for normal turn-around, cabin attendants can perform housekeeping chores, cargo can be loaded, and food service stowed. Upon completion of these services, the people can board and the flight would then be ready for takeoff. With properly designed equipment and scheduling of operations there is no obvious reason a hydrogen-fueled airplane should require more time for turn-around than conventional jet-fueled aircraft.

3.1.2 Tank and Insulation System

Design of tanks to contain liquid hydrogen efficiently in the subject aircraft is recognized as one of the critical technical challenges. Two basic types of tank designs were considered: integral, where the tank serves both as the container of the fuel and also carries the fuselage structural loads; and non-integral, in which case the tank merely contains the fuel and a separate structure is provided to resist fuselage axial, bending, and shear loads.

Based on a previous analysis of the differences between integral and non-integral cryogenic tanks (Ref. 5), it was decided that the integral type tanks would be used wherever feasible in the present conceptual design study. It is emphasized, however, that this was an arbitrary choice and is a subject which deserves significant design and development attention. Design conditions for subsonic aircraft are significantly different than those for supersonic aircraft (Ref. 5), so it does not necessarily follow that the type of tank design preferred for one application would necessarily be best for the other. In addition, there are many other potentially attractive tank design concepts which should also be evaluated.

A parametric design analysis was performed to determine the thickness of foam insulation which should be applied to the outside of the hydrogen tanks of the subject aircraft to provide the degree of thermal protection desired for least weight and/or cost. The point design study was carried out for a 10,190 km (5500 nmi) range, Mach 0.85, 400 passenger airplane. The result is shown in Figure 2, a plot which reflects consideration of the economic aspects of the problem. Airplane cost, amortized over 15 years and based on use an average of 3285 hours per year over that period, is plotted in terms of cost per flight hour as a function of insulation thickness, along with cost of block fuel and cost of hydrogen lost through boil-off during flight as well as on the ground. The minimum cost indicated by the top line, the cumulative effect of all factors, occurs at an insulation thickness of about 165 mm (6.5 in.). These results were obtained on the basis of no recovery of boiled-off hydrogen on the ground, i.e., as if vent gases were simply allowed to escape. In comparison, the minimum point in the second curve from the top which includes only the in-flight boil-off, or in effect assumes 100 percent recovery of ground boil-off, occurs at about 140 mm (5.5 in.) of insulation thickness. Based on these results, a nominal thickness of 152 mm (6 in.) of foam insulation was selected to serve as a basis for performance and cost evaluations of the aircraft in this study. The difference between these curves shows that recovery of ground boil-off hydrogen can make a difference of about $68 per flight hour based on a cost of LH_2 of $3 per 1.054 GJ (million Btu's), the baseline cost specified for use in this study, and neglecting any cost for recovery or reliquefaction.

3.1.3 Engines

In order to provide a most nearly equitable basis for comparing aircraft performance using both LH_2 and Jet A fuel, propulsion data was generated to parametrically represent quiet, high performance turbofan engines based on advanced component technology. A summary of the characteristics of the base size engines for both fuels at sea level static, standard day conditions is presented in Table 3.

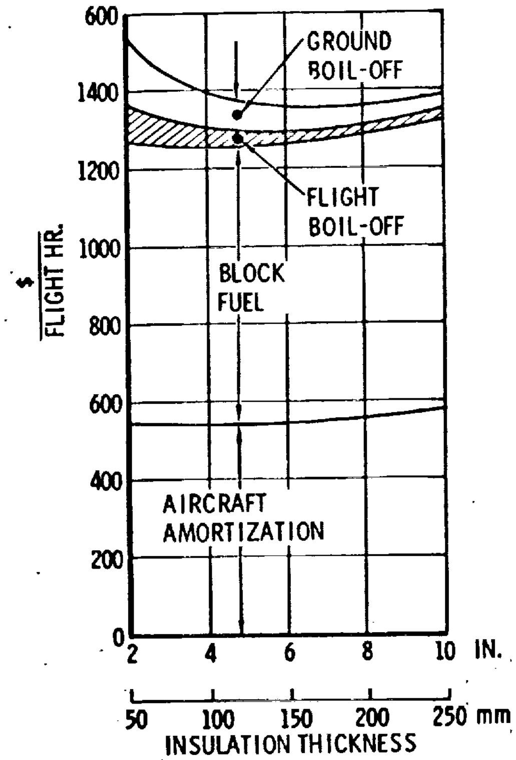


Figure 2. Economic Selection of Insulation Thickness

Consistent with the noise goal stated in the basic guidelines, engines using both fuels were designed to operate at noise limits 20 decibels (dB) below the FAR Part 36 specification during takeoff. Accordingly, the nacelle design incorporates acoustic lining on the fan duct walls, as well as on the surfaces of a splitter ring extending the full length of the duct. A variable geometry inlet was used to suppress forward radiation of compressor noise. The fan has no inlet guide vanes and the turbine was designed with appropriate rotor/stator spacing relationships and treatment so that turbine noise would not be a factor.

Installed cruise performance of both the Jet A-fueled and LH_2-fueled turbofan engines derived for this study is shown in Figure 3. For reference, the performance of a current technology turbofan engine, the Pratt and Whitney Aircraft JT9D, is also shown. The quieted, advanced design Jet A-fueled 1985 state-of-the-art engine has approximately 13 percent lower cruise SFC than does the current engine. The SFC difference between the advanced design Jet A and LH_2-fueled engines is primarily due to the higher gravimetric heating value of liquid hydrogen.

TABLE 3. CHARACTERISTICS OF DERIVED TURBOFAN ENGINES

[ENGINE DESIGN POINT DATA
SEA LEVEL STATIC - STANDARD DAY]

	LH_2	JET A
Turbine Inlet Temperature °K (°R)	1690 (3040)	1690 (3040)
Overall Pressure Ratio	35	35
Bypass Ratio	12.95	10.90
Fan Stages	1	1
Fan Pressure Ratio	1.51	1.51
Fan Face Mach No.	0.56	0.56
Hub/Tip Ratio	0.35	0.35
Compressor Pressure Ratio	23.3	23.3
H.P. Turbine Stages	2	2
H.P. Turbine Pressure Ratio	3.9	4.6
Cooling Air percent	0	5
L.P. Turbine Stages	4	4
L.P. Turbine Pressure Ratio	7.4	6.2
Installed Performance		
Thrust/Weight	3.7	3.7
SFC $\frac{kg}{hr}$/daN $\left[\left(\frac{lb}{hr}\right)/lb\right]$	0.096 (0.094)	0.286 (0.281)

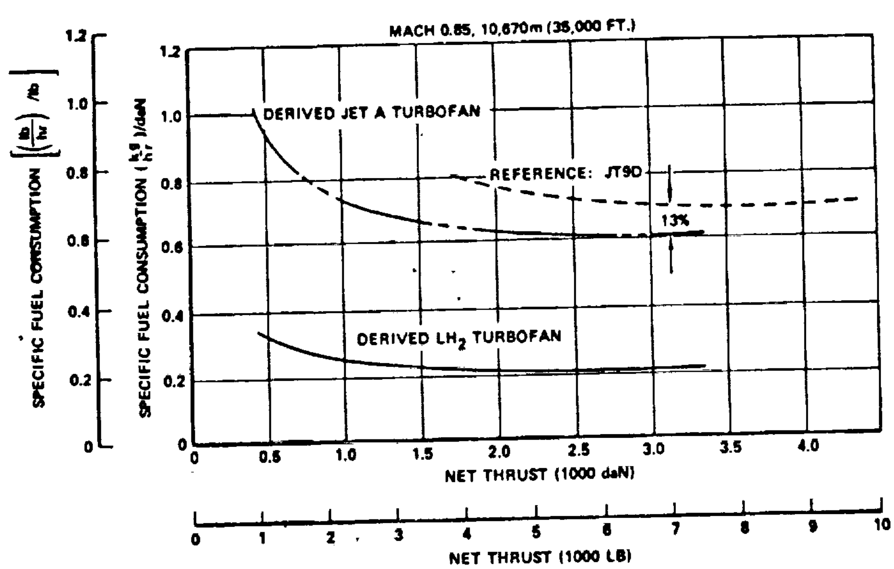


Figure 3. Cruise Performance of Turbofan Engines

3.2 PASSENGER AIRCRAFT

This program to investigate the potential of using liquid hydrogen as fuel for commercial transport aircraft was viewed as an opportunity to explore many different design configurations to see which offered maximum advantage for efficient containment of the low density, very energetic, cryogenic liquid. Compared with conventional hydrocarbon (Jet A) aircraft fuel on an energy per unit weight basis, LH_2 is higher by a factor of 2.8; however, on the basis of energy per unit volume, LH_2 is lower by a factor of 3.78. In other words it takes 3.78 times more volume to contain the weight of LH_2 to produce a given impulse, compared with the volume required for the 2.8 times more weight of Jet A which will produce the same impulse.

3.2.1 Configuration Concepts

With this in mind, plus consideration of the desirability of achieving maximum separation of passengers from the fuel for safety reasons, a broad range of airplane configuration concepts was explored. The design possibilities were categorized as follows:

- Fuel in fuselage
- Fuel in pods
- Fuel in wing

Representative examples of designs in each of these categories are illustrated in Figure 4, along with brief comments concerning reasons for their acceptance or rejection. The result of these considerations was a conclusion that the characteristics of LH_2 were not so peculiar that conventional aerodynamics and structural design practices could be violated with impunity.

The two airplane design concepts selected for detail consideration are illustrated in Figures 5 and 6. Externally, there is little to distinguish the configuration of the internal tank arrangement shown in Figure 5 from current, conventionally-fueled, wide-body transports. Internally, the arrangement is unique. The passengers are located in the central portion of the fuselage in a double-deck arrangement with the fuel tanks located forward and aft. The fuel tanks occupy the full usable cross-section of the fuselage. As a result, there is no provision for physical access between the passenger compartment and the flight station. The

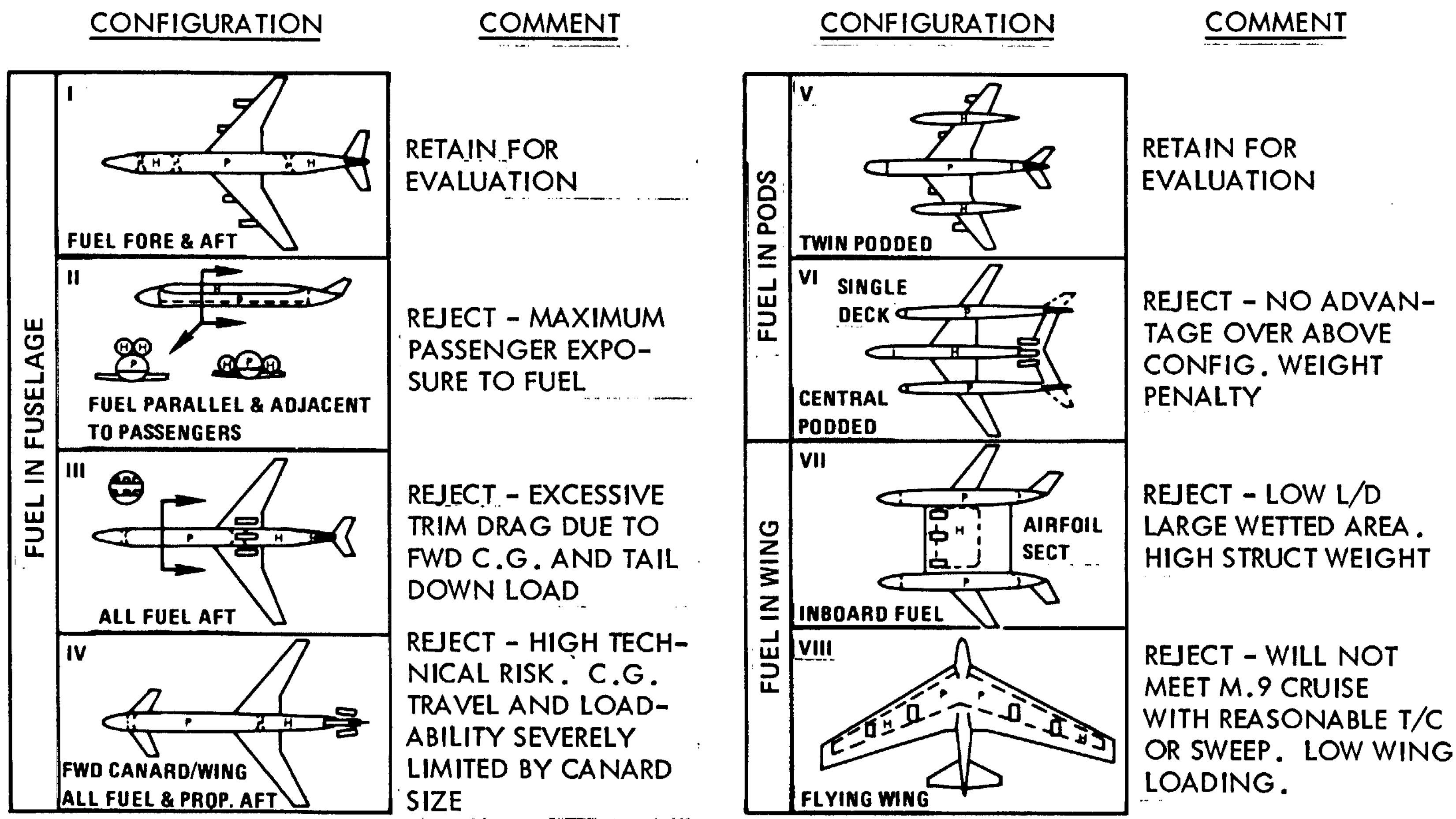


Figure 4. Candidate Configurations of LH_2 Passenger Aircraft

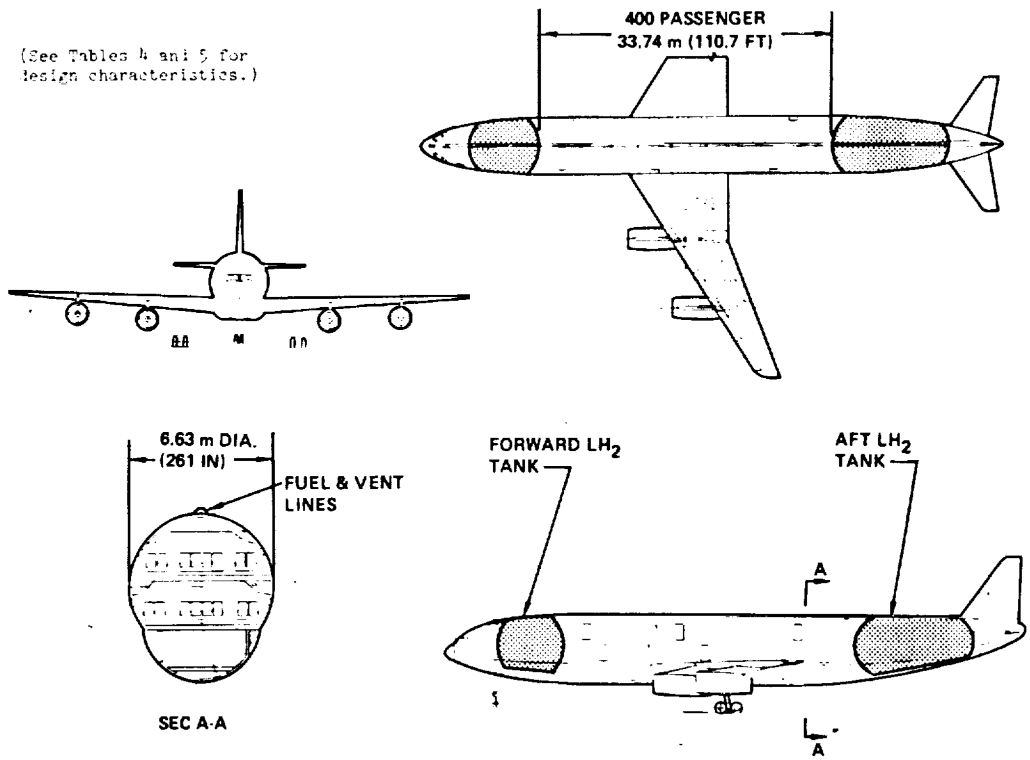


Figure 5. LH_2 Passenger Aircraft - Internal Tank Configuration

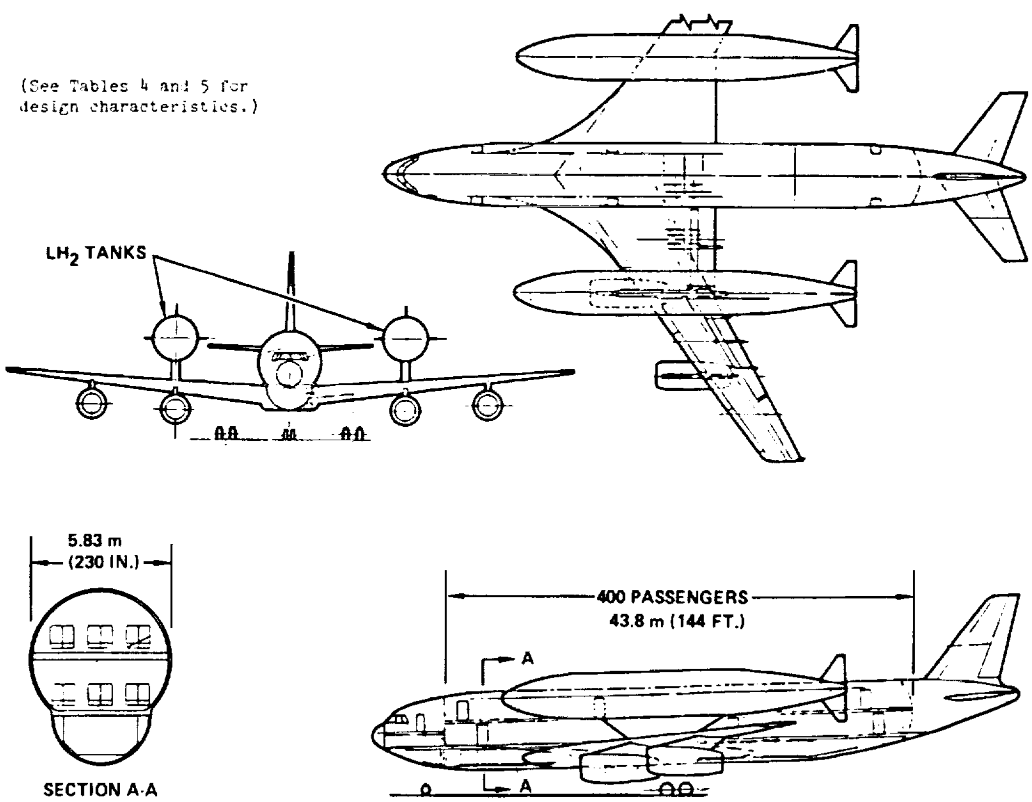


Figure 6. LH_2 Passenger Aircraft - External Tank Configuration

passengers are seated in a 2-4-2 arrangement on both decks for a total of 16 seats per row. Cargo is carried in space provided below the passenger compartment. Total payload weight for the 400 passenger design is 88,000 pounds.

The external tank configuration illustrated in Figure 6 carries the passengers in a comparable arrangement except that the fuselage diameter is somewhat smaller so the passengers are seated in a 2-2-2 arrangement for a total of 12 per seat row. This preserves the fineness ratio (length to diameter ratio) of the fuselage for aerodynamic advantage. All of the liquid hydrogen fuel is carried in the external tanks mounted on pylons above the wing. This configuration was originally proposed to provide an evaluation of potential advantages thought to exist for that configuration in safety, operations, and maintenance. It was recognized that there would be a performance penalty associated with carrying large, externally-mounted tanks, but it was felt that the accessibility of the tanks for inspection and repair, plus the safety associated with minimum hazard from effects of leaks, in addition to achieving maximum separation of passengers from fuel, might offer compensating advantages. Analysis did not confirm that these potential advantages were substantial enough to outweight the performance superiority of the more conventional internal tank configuration.

A comparison of several key design and performance parameters for these two design concepts of LH_2-fueled aircraft is presented in Tables 4 and 5 for the 5560 km (3000 nmi) range aircraft, and the 10,190 km (5500 nmi) range aircraft, respectively. In only three of the fifteen parameters listed is the internal tank design found to have a rating not as favorable as the external tank configuration. However, the last three items in the tables are the most significant. In each of these, energy utilization, airplane price, and direct operating cost, the internal tank configuration is the obvious choice by a large margin.

The candidate internal and external tank LH_2 aircraft designs were compared and evaluated on the basis of operation, maintenance, and safety considerations, in addition to the performance characteristics. From an operations point of view, it was concluded the internal tank design was preferred. Considering maintenance aspects, the external tank configuration could be seen to offer definite advantages. In safety, there was little basis for a clear cut decision in selecting a preferred design configuration except that the magnitude of the task of providing the required protection against engine burst for the external tank configuration made the internal tank approach more feasible and therefore more attractive.

TABLE 4. DESIGN COMPARISON: INTERNAL VS EXTERNAL TANK LH_2 AIRCRAFT

[400 PAX; 5560 km (3000 nmi); M = 0.85]

	SI	CUSTOMARY	EXTERNAL TANKS SI	EXTERNAL TANKS CUSTOMARY	INTERNAL TANKS SI	INTERNAL TANKS CUSTOMARY	FACTOR (EXT/INT)
Gross Weight	kg	lb	159,800	352,300	153,500	338,500	1.04
Fuel Weight	kg	lb	18,500	40,700	16,300	36,000	1.13
Operating Empty Weight	kg	lb	101,400	223,600	97,300	214,500	1.04
Wing Area	m^2	ft^2	294	3170	286	3077	1.03
Span	m	ft	48.7	160	50.6	166	0.96
Fuselage Length	m	ft	60	197	64	210	0.94
FAR T.O. Field Length	m	ft	1536	5040	1788	5860	0.86
FAR Landing Field Length	m	ft	1760	5780	1770	5810	0.99
L/D (Cruise)	-	-	13.1	13.1	15.2	15.2	0.86
SFC (Cruise)	$\frac{kg}{hr}/daN$	$\left(\frac{lb}{hr}\right)/lb$	.203	.200	.203	.200	-
Thrust per Engine	N	lb	135,000	30,390	111,000	24,960	1.22
Energy Utilization	$\frac{kJ}{seat\ km}$	$\frac{Btu}{seat\ nmi}$	1793	1430	1498	1196	1.20
Airplane Price	$\$10^6$	$\$10^6$	25.0	25.0	23.6	23.6	1.06
DOC*	$\frac{¢}{seat\ km}$	$\frac{¢}{seat\ nmi}$	.612	1.134	.554	1.026	1.11

*LH_2 Fuel Cost = \$3/1.054 GJ = \$3/10^6 BTU = 15.48 ¢/lb

TABLE 5. DESIGN COMPARISON: INTERNAL VS EXTERNAL TANK LH_2 AIRCRAFT

[400 PAX; 10,190 km (5500 nmi); M = 0.85]

	SI	CUSTOMARY	EXTERNAL TANKS		INTERNAL TANKS		FACTOR (EXT/INT)
			SI	CUSTOMARY	SI	CUSTOMARY	
Gross Weight	kg	lb	198,100	436,800	177,700	391,700	1.12
Fuel Weight	kg	lb	36,700	81,000	27,900	61,600	1.31
Operating Empty Weight	kg	lb	121,300	267,800	109,900	242,100	1.11
Wing Area	m^2	ft^2	338	3640	312	3360	1.08
Span	m	ft	52.1	171	53	174	0.98
Fuselage Length	m	ft	60	197	66.8	219	0.90
FAR T.O. Field Length	m	ft	1610	5290	1900	6240	0.85
FAR Landing Field Length	m	ft	1770	5810	1770	5810	-
L/D (Cruise)	-	-	13.4	13.4	16.1	16.1	0.83
SFC (Cruise)	$\frac{kg}{hr}/daN$	$\left(\frac{lb}{hr}\right)/lb$	.202	.199	.202	.199	-
Thrust per Engine	N	lb	172,100	38,760	127,500	28,690	1.35
Energy Utilization	$\frac{kJ}{seat\ km}$	$\frac{Btu}{seat\ nmi}$	2050	1634	1550	1239	1.32
Airplane Price	$\$10^6$	$\$10^6$	30.2	30.2	26.9	26.9	1.12
DOC*	$\frac{¢}{seat\ km}$	$\frac{¢}{seat\ nmi}$	.688	1.277	.576	1.079	1.18

*LH_2 Fuel Cost = \$3/1.054 GJ = \$3/10^6 BTU = 15.48 ¢/lb

The following is a summary of the conclusions reached regarding the two design concepts in each of the more significant areas of consideration:

Characteristics	Preferred Tank Arrangement
Operations	Internal
Maintenance	External
Safety	Internal
Weight	Internal
Size	External
Energy utilization	Internal
Price	Internal
Direct Operating Cost	Internal

Accordingly, the internal tank design concept for LH_2-fueled passenger aircraft was selected for further analysis and subsequent comparison with reference Jet A aircraft.

3.2.2 Benefits Evaluation

A parametric design study was conducted to provide reference (Jet A-fueled) aircraft for direct comparison with the subject LH_2-fueled aircraft. Particular care was taken to assure that the competitive aircraft were designed to carry the same payload, the same distance, at the same cruise speed, and to operate with the same set of design constraints and requirements as their counterparts.

The general arrangement of the Jet A aircraft is shown in Figure 7. The fuselage arrangement is the same as that used for the external tank hydrogen vehicle. All fuel is contained in the wing box structure resulting in some structural load relief for this wing compared to the hydrogen version.

Table 6 is a compilation of vehicle data for aircraft designed to use each fuel and to transport 400 passengers 5560 km (3000 nmi) at Mach 0.85 cruise speed. Table 7 is comparable data for aircraft designed for the longer 10,190 km (5500 nmi range. Note that the specifications for the LH_2 aircraft presented in Table 6 differ slightly from the values given for the internal tank airplane in Table 4. The differences are due to an adjustment in the amount of reserve fuel carried in the 5560 km (3000 nmi) range mission and to a final iteration of the design.

TABLE 6. COMPARISON OF FINAL DESIGNS: LH_2 VS JET A PASSENGER AIRCRAFT

[400 PAX; 5560 km (3000 nmi): M = 0.85]

	SI	CUSTOMARY	LH_2 SI	LH_2 CUSTOMARY	JET A SI	JET A CUSTOMARY	FACTOR (JET A/LH_2)
Takeoff Gross Weight	kg	lb	152,000	335,200	183,200	404,300	1.21
Operating Empty Weight	kg	lb	96,500	212,900	95,500	210,600	.99
Block Fuel Weight	kg	lb	12,700	28,000	37,400	82,400	2.95
Total Fuel Weight	kg	lb	15,600	34,300	47,800	105,700	3.08
Wing Area	m^2	ft^2	283	3,047	301	3,235	1.06
Wing Loading, Takeoff	kg/m^2	lb/ft^2	537	110	610	125	1.14
Landing	kg/m^2	lb/ft^2	488	100	488	100	1.0
Span	m	ft	50.5	165.6	52	170.6	1.03
Fuselage Length	m	ft	64	210	60	197	.94
Lift/Drag (Cruise)			14.86	14.86	16.66	16.66	1.12
Specific Fuel Consumption (Cruise)	$\frac{kg}{hr}/daN$	$\left(\frac{lb}{hr}\right)/lb$	.203	0.200	.592	0.582	2.91
Thrust per Engine (SLS)	N	lb	110,000	24,720	114,500	25,770	1.04
Thrust/Weight (SLS)	N/kg	-	2.90	.295	2.51	0.255	.87
FAR T.O. Distance	m	ft	1,790	5,860	2,437	7,980	1.36
FAR Landing Distance	m	ft	1,770	5,804	1,760	5,760	.99
Approach Speed (EAS)	m/s	knots	69.5	135	69	134	.99
Weight Fractions	percent	percent					
Fuel			10.2	10.2	26.2	26.2	2.57
Payload			26.3	26.3	21.8	21.8	.83
Structure			31.7	31.4	27.8	27.8	.89
Propulsion			10.7	10.7	6.7	6.4	.60
Equipment and Operating Items			21.7	21.4	17.8	17.8	.83
Energy Utilization	$\frac{kJ}{seat\ km}$	$\frac{Btu}{seat\ nmi}$	1,510	1,204	1,580	1,260	1.05

TABLE 7. COMPARISON OF FINAL DESIGNS: LH_2 VS JET A PASSENGER AIRCRAFT

[400 PAX; 10,190 km (5500 nmi); M = 0.85]

	SI	CUSTOMARY	LH_2		JET A		FACTOR (JET A/LH_2)
			SI	CUSTOMARY	SI	CUSTOMARY	
Takeoff Gross Weight	kg	lb	177,800	391,700	237,200	523,200	1.34
Operating Empty Weight	kg	lb	110,000	242,100	110,800	244,400	1.01
Block Fuel Weight	kg	lb	24,000	52,900	75,000	165,500	3.13
Total Fuel Weight	kg	lb	27,900	61,600	86,500	190,800	3.10
Wing Area	m^2	ft^2	313	3,363	389	4,186	1.24
Wing Loading, Takeoff	kg/m^2	lb/ft^2	569	116.5	610	125	1.07
Landing	kg/m^2	lb/ft^2	493	101	518	106	1.05
Span	m	ft	53	174	59.2	194.1	1.12
Fuselage Length	m	ft	66.7	219	60	197	.90
Lift/Drag (Cruise)			16.07	16.07	17.91	17.91	1.12
Specific Fuel Consumption (Cruise)	$\frac{kg}{hr} / daN$	$\left(\frac{lb}{hr}\right) / lb$	.203	0.199	.590	0.581	2.92
Thrust per Engine (SLS)	N	lb	127,700	28,700	145,400	32,700	1.14
Thrust/Weight (SLS)	N/kg	-	2.88	0.293	2.45	0.25	.85
FAR T.O. Distance	m	ft	1,900	6,240	2,435	7,990	1.28
FAR Landing Distance	m	ft	1,770	5,810	1,590	5,210	.90
Approach Speed (EAS)	m/s	knots	69.5	135	63.7	124	.92
Weight Fractions	percent	percent					
Fuel			15.7	15.7	36.5	36.5	2.23
Payload			22.5	22.5	16.8	16.8	.75
Structure			30.7	30.7	26.0	26.0	.85
Propulsion			12.3	12.3	6.4	6.4	.52
Equipment and Operating Items			18.8	18.8	14.3	14.3	.76
Energy Utilization	$\frac{kJ}{seat\ km}$	$\frac{Btu}{seat\ nmi}$	1,550	1,239	1,735	1,384	1.12

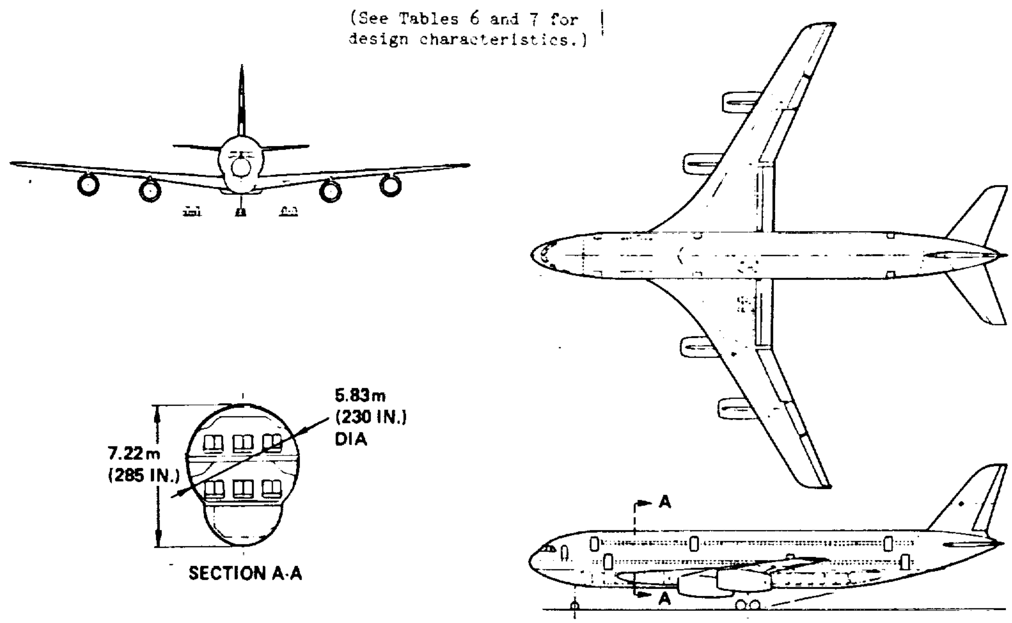


Figure 7. Jet A Passenger Aircraft - General Arrangement

The liquid hydrogen fueled airplanes are seen to offer significant advantage in almost every category of comparison at both ranges. The penalties occasioned by the density and temperature of liquid hydrogen, reflected in the values shown for Lift/Drag, are more than overcome by the tremendous advantage of the heating value of the fuel, cf., values listed for specific fuel consumption. The LH_2 aircraft are lighter, require smaller wings but larger fuselages, use smaller engines, can take off in shorter distances, and use less energy per seat mile in performing their missions. It will be noted, however, that the advantage is decreased at the shorter range. This follows because the fundamental advantage gained from using hydrogen stems from substituting a high energy fuel for a relatively lower energy fuel. Those design missions which require a large amount of fuel automatically offer the maximum payoff for using hydrogen.

Table 8 is a summary of costs calculated for the subject aircraft. The LH_2 aircraft are seen to cost more, both to develop and to produce, than their Jet A counterparts. It is not surprising that development costs for the hydrogen fuel versions run higher than those for their Jet A counterparts because of the new

TABLE 8. COST COMPARISON: LH_2 VS JET A PASSENGER AIRCRAFT

		AIRCRAFT			
Range	km	5,570		10,200	
Fuel		LH_2	JET A	LH_2	JET A
Costs	$\$10^6$				
Development					
Airframe		594.2	566.0	669.5	692.5
Engine		408.0	350.9	455.0	416.6
Total		1002.2	916.9	1124.	1109.1
Production					
Airframe		17.33	17.14	20.10	19.86
Engine		3.07	2.66	3.50	3.29
Avionics		0.50	0.50	0.50	0.50
R & D Amortization*		2.51	2.32	2.82	2.81
Total		23.41	22.62	26.92	26.46

*Based on 350 aircraft and 2000 engines

technology involved. Production costs of the LH_2 aircraft are higher because of costs estimated for hydrogen-related equipment such as tanks, insulation, fuel system, and engines. Such items were arbitrarily assigned a high value because they represent little-known technology and because their production is acknowledged to involve operations of greater complexity than the corresponding Jet A components. A more accurate and realistic assessment of the cost of such items can be made after some technology development has occurred and more is known about preferred designs of the hydrogen-related systems and components.

Production costs of both the LH_2 and the Jet A advanced design aircraft are considerably higher per unit of operating empty weight (OEW) than current aircraft. For example, the short range hydrogen design is \$242/kg (\$110/lb) of OEW, and the corresponding Jet A-fueled aircraft of advanced design is \$238/kg (\$108/lb). The sales price of current widebody transport aircraft, e.g., L-1011 and DC-10, is approximately \$183/kg (\$83/lb) of OEW.

A comparison of direct operating cost as a function of fuel prices is shown in Figure 8 for the 10,190 km (5500 nmi) range passenger aircraft. To provide perspective for the significance of the relative positions and slopes of the two lines in the figure, prices paid for Jet A by U.S. domestic and international air carriers in September, 1974 (Reference 6), are indicated on the graph. Similarly, recent estimates from two sources (References 3 and 7) of the potential cost of providing liquid hydrogen to airports are shown. As indicated by the broken line, an additional increment of 44¢/1.054 GJ (44¢/10^6 BTU's) can be paid for liquid hydrogen and still provide a direct operating cost equivalent to that calculated for the Jet A fueled aircraft. For the shorter range, 5560 km (3000 nmi) passenger aircraft, this price differential reduces to 21.5¢/1.054 GJ.

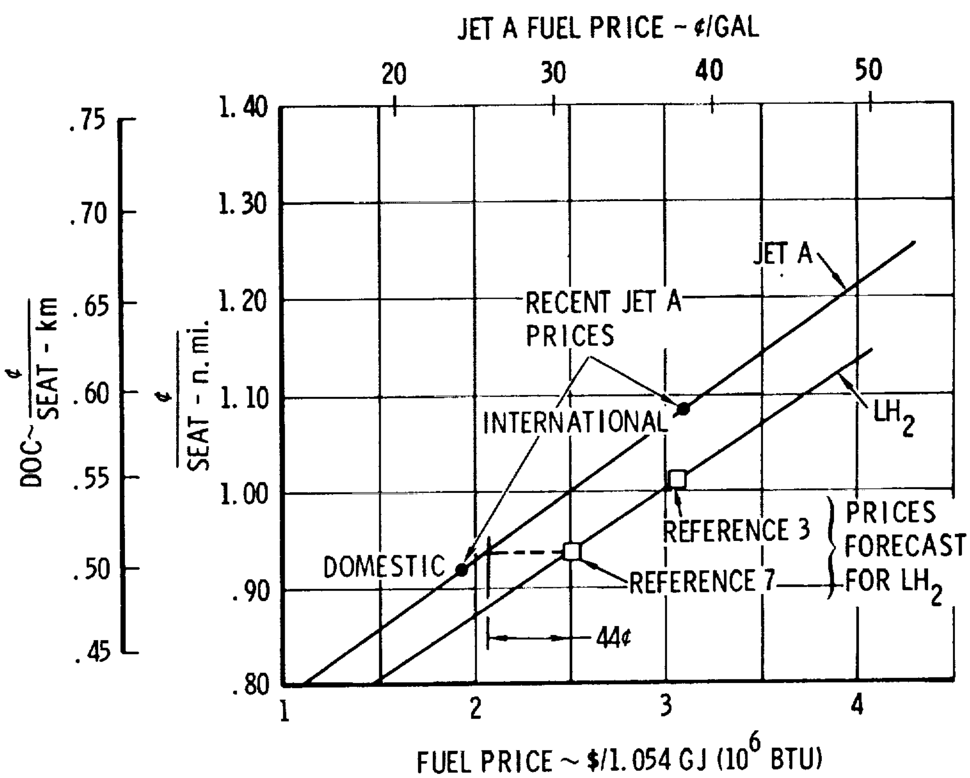


Figure 8. Direct Operating Cost vs Fuel Price
(Long Range Passenger Aircraft)

The results of noise calculations for the subject passenger transport aircraft are presented in Table 9. All aircraft were designed to be 20 db quieter in the sideline noise level than the FAR Part 36 specification, regardless of the fuel used. The different noise level reductions calculated for flyover and approach reflect the effect of other design parameters, e.g., thrust-to-weight ratio (T/W) and lift-to-drag ratio (L/D), on noise characteristics of the respective aircraft. The LH_2-fueled aircraft are slightly noisier than their Jet A-fueled counterparts during approach. This stems from a combination of features; the LH_2 aircraft have smaller engines, they have lower lift/drag ratios, and their weight at landing is approximately equal to that of the corresponding Jet A airplane. As a result, during final approach the LH_2 aircraft are required to operate their engines at a more advanced throttle setting to maintain a 3-degree glide slope, thereby producing more engine noise.

TABLE 9. NOISE COMPARISON: LH_2 VS JET A PASSENGER AIRCRAFT

AIRCRAFT	NOISE LEVELS (EPNdB)			AREA OF 90 EPNdB CONTOUR	
	FLYOVER	SIDELINE	APPROACH	km^2	sq. mi.
5560 km (3000 nmi)					
LH_2	88.1 (103.8)	86.4 (106.3)	97.9 (106.3)	9.8	3.8
JET A	92.7 (105.1)	86.4 (106.9)	96.6 (106.9)	10.6	4.1
10,190 km (5500 nmi)					
LH_2	89.2 (104.9)	87.2 (106.8)	98.4 (106.8)	11.1	4.3
JET A	94.2 (107)	87.8 (107.6)	96.7 (107.6)	12.2	4.7
L-1011 (CERTIFICATION TESTS)	96.0 (105.6)	95.0 (107)	102.8 (107)	17.1	6.6
( ) = FAR PART 36 LIMITS					

The areas at the airport which would be subjected to noise levels greater than 90 EPNdB are also listed. The LH_2 aircraft at both design ranges show smaller areas thus affected. For comparative reference, noise levels for the Lockheed L-1011 wide-bodied aircraft measured during FAA certification tests are listed.

Goals for allowable emission of noxious products from the engines are shown in Table 10, along with estimated emission levels for advanced design engines fueled with Jet A and LH_2. The level of emissions of carbon monoxide (CO), unburned hydrocarbon (UHC), smoke, and oxides of nitrogen (NO_x) shown for the Jet A engines was obtained from work reported by Pratt & Whitney Aircraft (Reference 8), General Electric Co., (Reference 9), and NASA-Lewis Research Center (Reference 10 and 11). Since liquid hydrogen fuel contains no carbon, there will be no emission of CO, UHC or smoke. There is strong likelihood that NO_x emissions from LH_2 fueled engines can be significantly reduced below that forecast for engines burning Jet A fuel, based on equivalent technology. The statement of NO_x emissions from the LH_2 engine is expressed in terms of grams per kilogram of fuel burned divided by 2.8 (the ratio of heats of combustion of the two fuels), to reflect the fuel flow rate for

TABLE 10. EMISSIONS COMPARISON: LH_2 VS JET A AIRCRAFT

EMISSION PRODUCT	ENGINE CONDITION	ESTIMATED EMISSION LEVEL (g/kg FUEL)		
		GOAL	JET A	LH_2
CO	IDLE	14	30	0
UNBURNED HC	IDLE	2	4	0
SMOKE	TAKEOFF	25*	15*	0
NO_X	TAKEOFF	13	12	≤12**
H_2O	CRUISE		41.9 LB/N.MI.†	82.4 LB/N.MI.†
ODORS	GROUND OPERATIONS		OBJECTIONABLE	NONE

*SAE 1179 SMOKE NUMBER

**$g \Big/ \left(\frac{\text{kg FUEL}}{2.8}\right)$

†FOR THE 10,190 km (5500 n mi) RANGE AIRCRAFT

approximately equal thrust levels from both engines. Water vapor from the hydrogen fueled airplane is nearly twice the amount produced by the Jet A design; however, it is still only a trace amount compared to moisture normally present in the atmosphere.

Finally, considering the comparative safety of LH_2 and Jet A fuels in aircraft, the overriding conclusion is that the hazards associated with the use of LH_2 can be less than those with Jet A. For example, in an otherwise survivable crash in which equal energy quantities of Jet A and hydrogen fuel are burned, the hydrogen fire would result in significantly less damage to the surroundings, hence the passengers, because of its relatively rapid burning rate and its extremely low emissivity (radiant heat transfer).

3.2.3 Effect of Larger Payloads

The effect of larger payload requirements on LH_2 aircraft design and operational characteristics was investigated by establishing designs to carry 600 and 800 passengers over the specified ranges at Mach 0.85 cruise speed. All aircraft were designed to the same guidelines used throughout the study for the 400 passenger vehicles.

The same general arrangement of aircraft was retained in that passengers are carried in a double-deck arrangement with fuel tanks both forward and aft. In order to enlarge the passenger compartment to carry the required complement, yet not exceed a realistic fuselage length, the fuselage diameter as well as its length was increased. Thus, these larger aircraft retained about the same fuselage fineness ratio as the 400 passenger design and permitted appropriate rotation angles.

Trends of some of the significant parameters which are functions of aircraft size are plotted in Figures 9 and 10 for the 5560 km range and the 10,190 km range aircraft, respectively. Aircraft gross weight, block fuel fraction, production price, and direct operating cost are all plotted to show their variation with passenger capacity ranging from 400 to 800. The increasing flight efficiency of larger aircraft is apparent in the decrease of the percentage of block fuel consumed, and also in the lower direct operating cost as aircraft size increases.

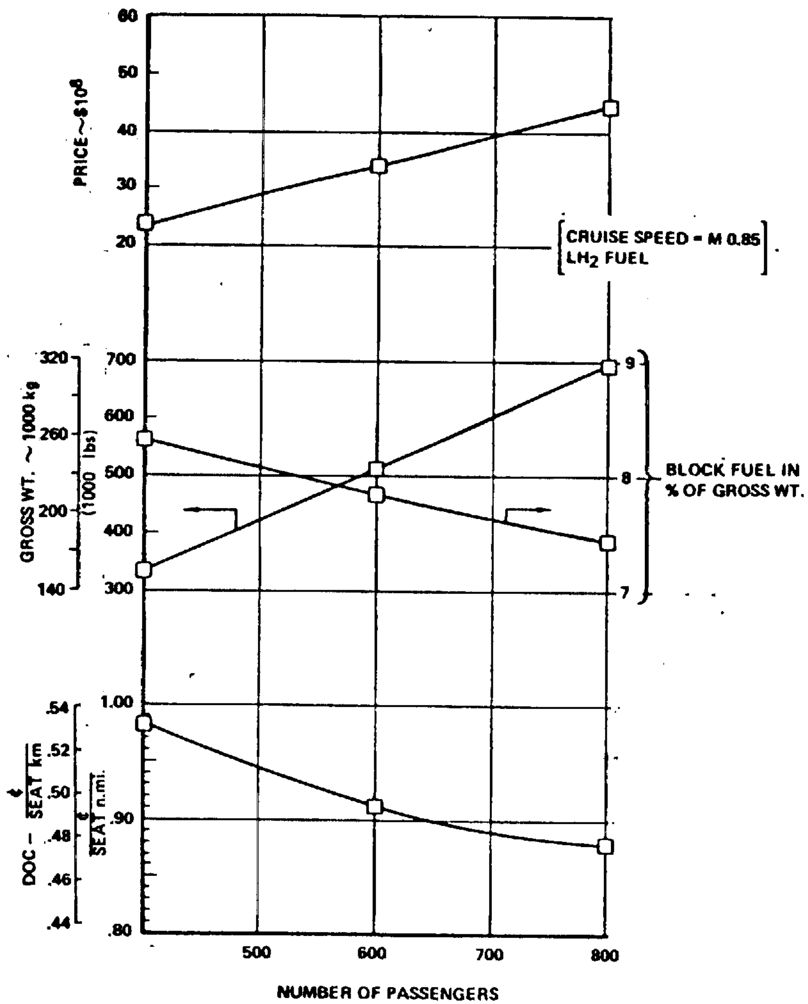


Figure 9. Effect of Larger Payloads on Passenger Aircraft Characteristics (5560 km (3000 nmi))

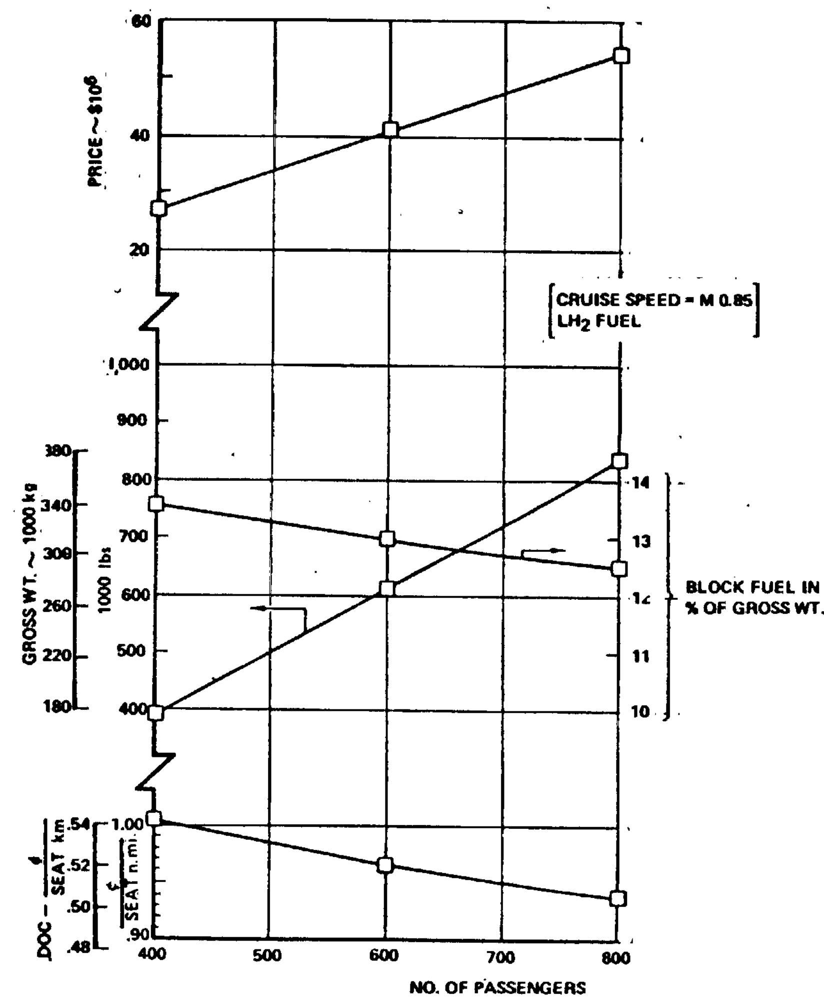


Figure 10. Effect of Larger Payloads on Passenger Aircraft Characteristics (10,190 km (5500 nmi))

3.3 CARGO AIRCRAFT

For convenience, cargo aircraft designed to carry a 56,700 kg (125,000 lb) load a distance of 5560 km (3000 nmi) are called "small." Aircraft designed for the 113,400 kg (250,000 lb), 10,190 km (5500 nmi) range mission are called "large."

3.3.1 Configuration Concepts

Schematic representations of the configuration concepts considered for the cargo aircraft are shown in Figure 11. The hydrogen tanks are shown crosshatched. Analysis of these designs showed that the swing tail concept has the lowest gross weight to perform a given mission and provides acceptable operational characteristics. Although the gross weights of the center and pod tank concepts are less than the gross weight of the nose loader concept, the former have poor cargo compartment design characteristics and low hydrogen tank efficiency, i.e., high surface-to-volume ratio, respectively. The wing tank and tip tank designs have inferior flight performance characteristics due to their low lift/drag ratio. Accordingly, the swing tail and nose-loader concepts were selected for more detailed study and evaluation.

Cargo carried by the subject aircraft was assumed to be packed in containers 2.59 m (8.5 ft) wide by 2.9 m (9.5 ft) high, and of lengths from 3.05 m (10 ft) to

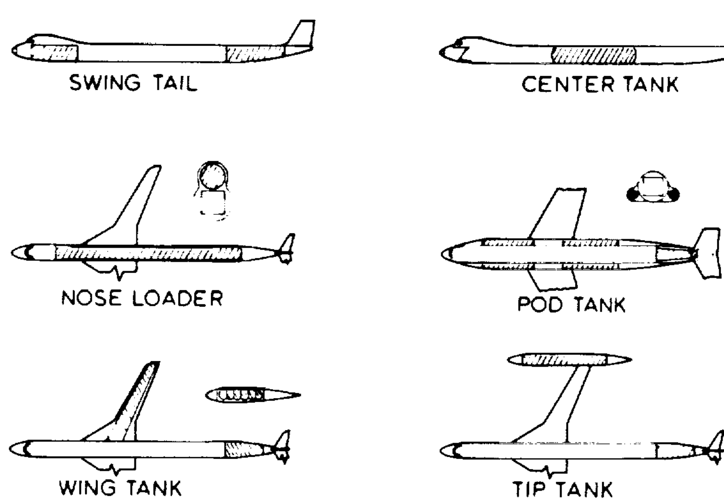


Figure 11. Candidate Cargo Aircraft Configuration Concepts

12.2 m (40 ft). All study aircraft were configured to carry these containers in a double-row arrangement. For the "small" aircraft, the double-row cargo compartment is 22.6 m (74 ft) long and capable of containing one 3.05 m, one 6.1 m, and one 12.2 m container in each row. For the "large" aircraft, the cargo hold is 43.9 m (144 ft) long and will contain three 12.2 m long containers and one 6.1 m, in each row.

3.3.2 Analysis of LH_2 Aircraft Designs

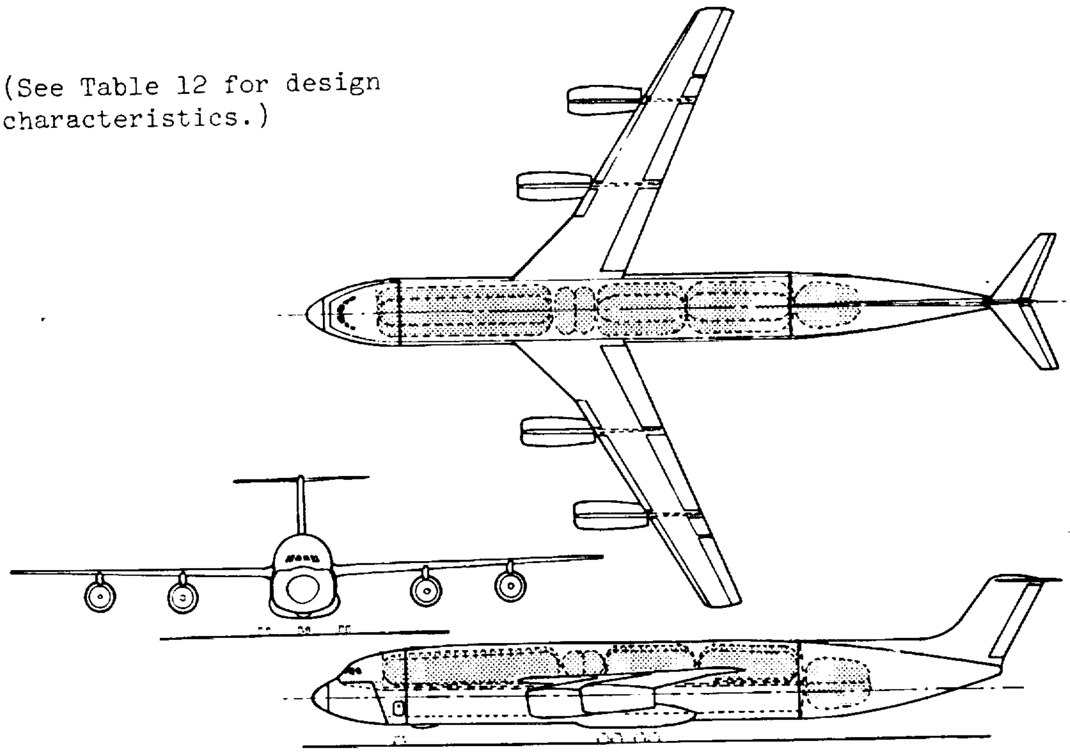
Nose Loader Aircraft

The configurations of the nose loader aircraft are illustrated in Figure 12. The large aircraft has the wing mounted in the mid-wing position to obtain proper nacelle ground clearance and to maintain a cargo floor height above ground level no greater than 4.72 m (15.5 ft). In contrast, the aircraft designed for the short range, small payload mission has a low-wing which enables it to be used more conveniently for landing gear attachment. The engines are small enough that sufficient nacelle ground clearance can be provided. Except for this difference in wing position, the aircraft designed for the large and the small missions are identical in concept.

The flight station is arranged to accommodate a crew of three including a flight engineer. In-flight access from the flight station to the cargo compartment is provided. Cargo is loaded through a full compartment cross section nose visor door. Air conditioning and pressurization systems are provided for the flight station, cargo compartment, and the upper fuselage lobe liquid hydrogen tank compartment. The tank compartment is pressurized by engine bleed air cooled to approximately the ambient stagnation temperature by a ram-air heat exchanger. The pressurized air enters the forward end of the tank compartment and exits at the aft end to provide airflow for continuous purging. The tank compartment is separated from the cargo compartment by a horizontal bulkhead and is maintained at a pressure approximately 10.3 kPa (1.5 psi) below that of the cargo compartment such that any leakage is always from the cargo compartment to the tank compartment. Blowout panels are provided in the separation bulkhead to prevent structural damage should decompression occur in either compartment.

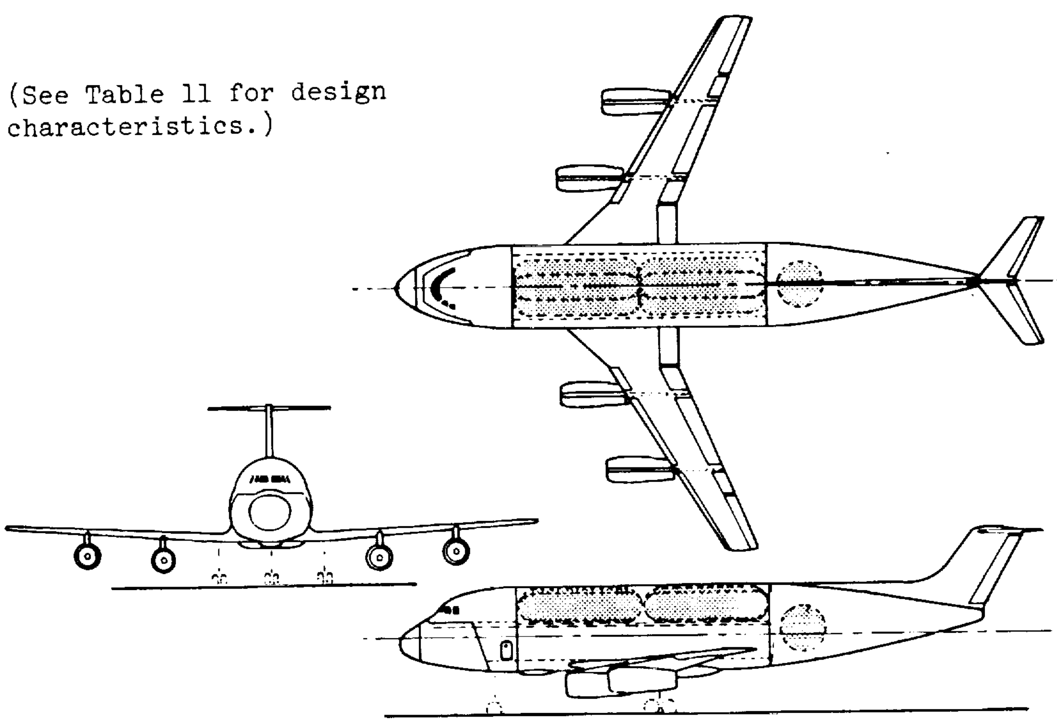
A supplemental tank is located in the unpressurized aft fuselage section. Aircraft balance consideration prevents the maximum utilization of the volume

(See Table 12 for design characteristics.)



LARGE

(See Table 11 for design characteristics.)



SMALL

Figure 12. General Arrangement - Nose Loader Cargo Aircraft

available in the aft fuselage. To maintain acceptable c.g. travel fuel from this supplemental tank is used first during a flight.

A three-lobe cross-section tank design was selected over other candidate shapes for the main tanks of the subject aircraft on the basis of overall vehicle performance advantages. It should be noted that this selected tank design, in contrast to that previously discussed for the passenger aircraft, uses the non-integral structural concept. In the nose loader cargo aircraft the integral design did not lend itself to full advantage because of the irregular shape of the volume along the spine of the aircraft above the cargo compartment. This difference between tank design concepts selected for the passenger and the cargo aircraft involved in this study illustrates that no one concept will necessarily be best for all applications. There are a large number of tank design and insulation concepts which should be investigated and evaluated before final choices are made for development of hardware for any particular application. In the subject study the effort was limited to simply selecting good representative tank designs to permit focusing on the broader objective of evaluation of the potential of LH_2 as a fuel for transport aircraft.

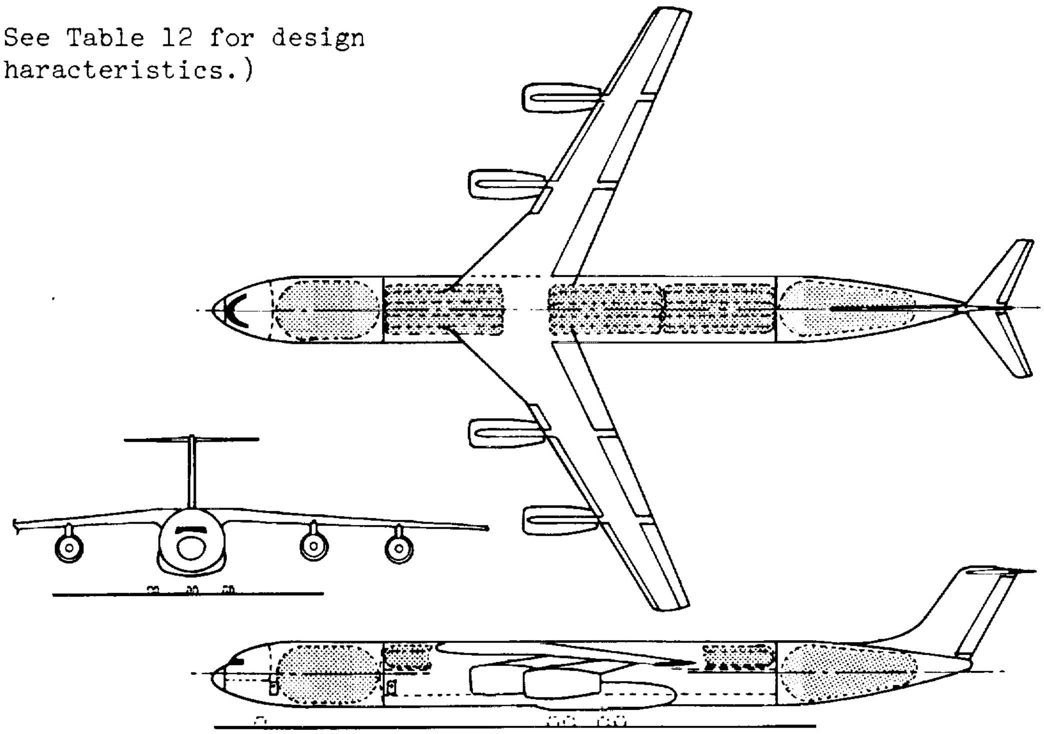
Swing Tail Aircraft

The swing tail aircraft are illustrated in Figure 13. Again the wing position for the large aircraft was dictated by the requirement for proper nacelle ground clearance while not exceeding the 4.72 m (15.5 ft) maximum cargo floor height above the ground. The small aircraft has the wing in the low position, again to provide efficient structural attachment of the landing gear.

The aircraft designed for the small payload, short range mission has two equal-volume tanks located in unpressurized areas immediately forward and aft of the cargo compartment. The forward tank is spherical in shape while the aft tank conforms closely to the aft fuselage taper and consists of spherical end domes of slightly different diameters connected by a tapering section.

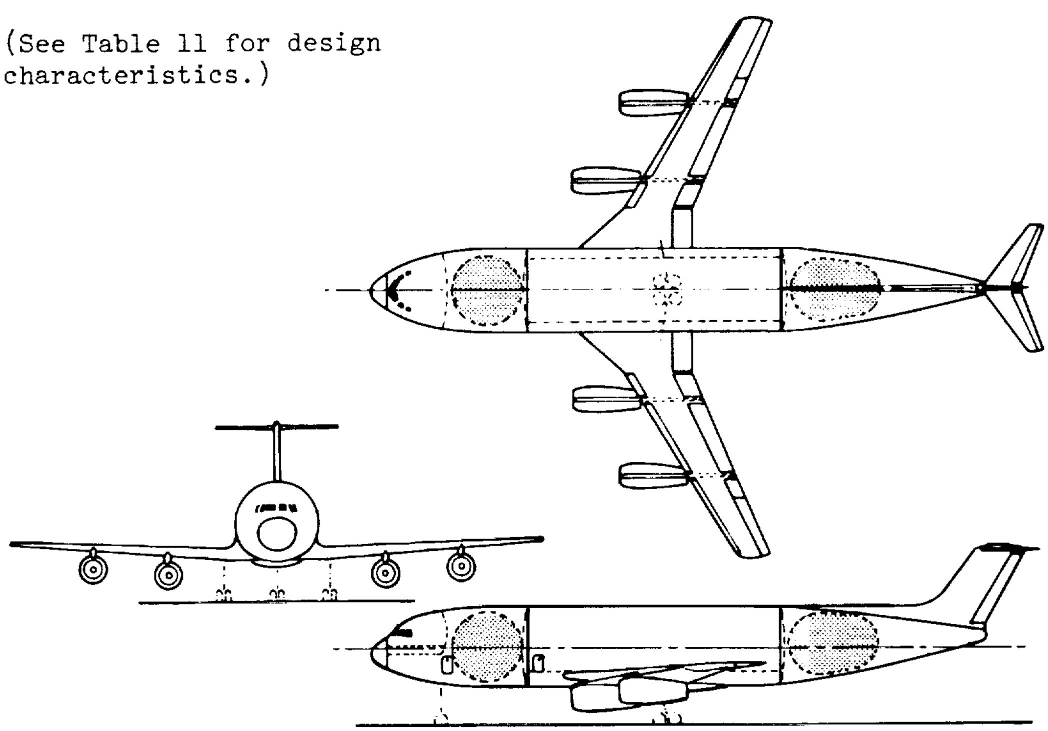
The large aircraft also carries most of the fuel in tanks located in unpressurized areas fore and aft of the cargo compartment; however, it also has three multi-lobe tanks located above the cargo compartment. The fuel is essentially balanced around the center of gravity of the aircraft for both cargo transport versions.

(See Table 12 for design characteristics.)



LARGE

(See Table 11 for design characteristics.)



SMALL

Figure 13. General Arrangement - Swing Tail Cargo Aircraft

In the swing tail airplane design, access to the cargo compartment is provided by swinging the tail horizontally around a vertical hinge line. The entire empennage and aft fuel tank is included in the structure which must be moved to provide for loading of the cargo through the aft end of the airplane. The center fuselage, which contains the cargo compartment, is pressurized and has a dome on either end. The flight station is also pressurized but it is separated from the cargo compartment by an unpressurized area containing the forward LH_2 tank. The design does not provide for in-flight access to the cargo compartment.

The two configurations of liquid hydrogen fueled cargo aircraft were compared on the basis of terminal operational environment compatibility, maintenance, safety, and performance.

The cargo terminal operational environment envisioned for 1990 - 1995 is one of maximum automation. Aircraft will be positioned at gate areas adjacent to fixed base cargo terminals. The nose loader configuration is judged to be more compatible with this concept of cargo terminal than is the swing tail. With the nose visor door open, that aircraft can be taxied directly into position to mate with the conveyor system of the cargo terminal. However, because the swing tail aircraft must be loaded from the aft end, ground equipment would be required to move that airplane into proper position for automatic loading after the empennage section has been rotated to provide access to the cargo compartment. This would require both extra ground-based equipment and additional time.

Analysis of aircraft maintenance operations also indicates a preference for the nose loader configuration. Removal of the forward hydrogen tank of the swing tail aircraft for inspection and/or maintenance requires that a break-joint be provided in the fuselage structure. Separation of the fuselage sections at this joint then would permit the tank to be removed. This separation of the fuselage, and subsequent remating on completion of tank maintenance, would require complex ground support equipment. The requirement for control and fuel feed lines to span the hinge joint of the aft fuselage on the swing tail aircraft also adds to the routine maintenance tasks of that configuration. In the case of the nose loader design, access to the fuselage upper lobe tanks would be provided by removable structural panels. These panels would be located along the crown of the upper lobe. After removal of the panels the tanks could be hoisted vertically for removal. The aft fuselage tank could be removed through fuselage lower surface doors.

In the area of safety, the nose loader is again the preferred design. The major portion of the hydrogen fuel is contained in tanks above the cargo compartment which offers some degree of protection to the tanks should the aircraft be involved in an accident during takoff or landing. The hinge joint of the swing tail aircraft is a potential source of hydrogen gas leaks and therefore a source of potential safety hazard. As noted above, hydrogen fuel lines must span this joint and are subject to abuse each time the aft fuselage is rotated.

Comparisons of performance and design characteristics of the nose loader and swing tail hydrogen-fueled aircraft are given in Tables 11 and 12 for the small and large missions, respectively. The column labeled "factor" in both of these tables gives a direct comparison of each parameter listed using the nose loader as the base. Inspection of these data shows the nose loader configuration to be preferred in nearly all instances.

In summary, the nose loader configuration of LH_2 cargo aircraft was found to offer advantages in all areas of comparison; terminal operational environment, maintenance, safety, and performance. Accordingly, it was selected as the LH_2 configuration to be compared to the hydrocarbon fueled (Jet A) reference cargo aircraft.

3.3.3 Reference (Jet A) Cargo Aircraft

The general arrangements of the Jet A-fueled cargo aircraft are illustrated in Figure 14. The configurations are essentially the same as that previously described for the hydrogen-fueled nose loader design with the following general exceptions:

- Fuel storage is relocated from fuselage tanks to wing tanks, thus providing structural load relief for the wing.
- The upper fuselage hydrogen tank storage lobe is removed, although the basic fuselage diameter is the same.
- The large aircraft uses a high-wing position rather than the mid-wing position on the large hydrogen aircraft.

This latter change stems from a basic structural difference between the aircraft designed for the two fuels for the large mission. The double lobe type fuselage shape of the hydrogen aircraft with its structural tie at the intersection

TABLE 11. DESIGN COMPARISON: NOSE LOADER VS SWING TAIL LH_2 SMALL CARGO AIRCRAFT

[56,700 kg (125,000 lb); 5560 km (3000 nmi); M = 0.85]

	SI	CUSTOMARY	SWING TAIL		NOSE LOADER		FACTOR (ST/NL)
			SI	CUSTOMARY	SI	CUSTOMARY	
Gross Wt.	kg	lb	137,441	303,000	135,763	299,300	1.012
Fuel Wt.	kg	lb	14,742	32,500	14,470	31,900	1.090
Operating Empty Wt.	kg	lb	65,999	145,500	64,638	142,500	1.021
Wing Area	m^2	ft^2	242.9	2615	240.1	2584	1.012
Span	m	ft	46.76	153.4	46.48	152.5	1.006
Fuselage Length	m	ft	54.77	179.7	52.03	170.7	1.053
FAR T.O. Field Length	m	ft	1758.7	5770	1767.8	5800	0.950
FAR Landing Field Length	m	ft	2231.1	7320	2231.1	7320	1.00
L/D (Cruise)			16.2	16.2	16.3	16.3	0.940
SFC (Cruise)	$\frac{kg}{hr}/daN$	$\frac{lb}{hr}/lb$	0.22	0.216	0.219	0.215	1.00
Thrust per Engine	N	lb	108,086	24,300	106,307	23,900	1.017
Energy Utilization	$\frac{kJ}{Mg\ km}$	$\frac{Btu}{ton\ nmi}$	4606	7346	4502	7181	1.023
Price	$\$10^6$	$\$10^6$	19.6	19.6	19.2	19.2	1.020
DOC*	$\frac{¢}{Mg\ km}$	$\frac{¢}{ton\ nmi}$	3.42	5.75	3.36	5.65	1.018

*LH_2 Fuel Cost = \$3/1.054 GJ = \$3/10^6 Btu = 15.48¢/lb

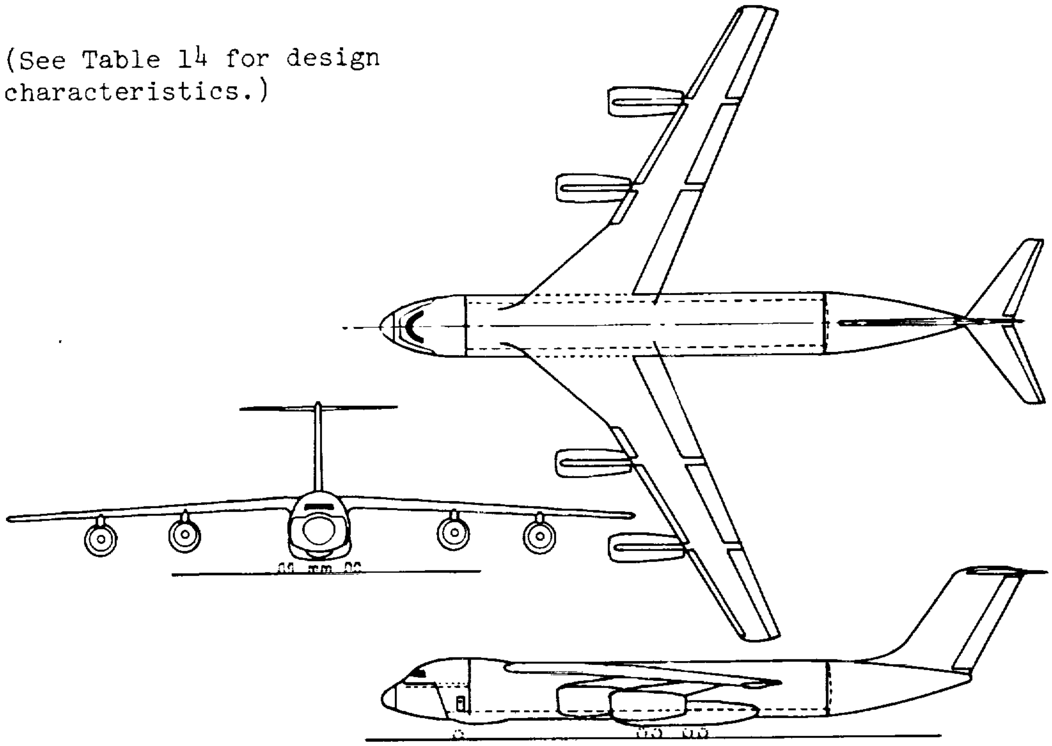
TABLE 12. DESIGN COMPARISON: NOSE LOADER VS SWING TAIL LH_2 LARGE CARGO AIRCRAFT

[113,400 kg (250,000 lb); 10,190 km (5500 nmi); M = 0.85]

	SI	CUSTOMARY	SWING TAIL		NOSE LOADER		FACTOR (ST/NL)
			SI	CUSTOMARY	SI	CUSTOMARY	
Gross Wt.	kg	lb	308,627	682,600	300,056	661,500	1.032
Fuel Wt.	kg	lb	49,442	109,000	47,991	105,800	1.030
Operating Empty Wt.	kg	lb	146,785	323,600	138,666	305,700	1.059
Wing Area	m^2	ft^2	498.6	5,367	483.3	5,203	1.032
Span	m	ft	66.9	219.8	65.9	216.4	1.016
Fuselage Length	m	ft	85.0	279.0	77.0	252.7	1.104
FAR T.O. Field Length	m	ft	2188	7,180	2185	7,170	1.00
FAR Landing Field Length	m	ft	2304	7,560	2304	7,560	1.00
L/D (Cruise)			18.07	18.07	18.03	18.03	1.00
SFC (Cruise)	$\frac{kg}{hr}/daN$	$\frac{lb}{hr}/lb$	0.223	0.219	0.223	0.219	1.00
Thrust per Engine	N	lb	218,396	49,100	212,170	47,700	1.029
Energy Utilization	$\frac{kJ}{Mg\ km}$	$\frac{Btu}{ton\ nmi}$	4413	7,039	4286	6,835	1.030
Price	$\$10^6$	$\$10^6$	41.441	44.441	39,121	39,121	1.059
DOC*	$\frac{¢}{Mg\ km}$	$\frac{¢}{ton\ nmi}$	3.01	5.06	2.89	4.86	1.041

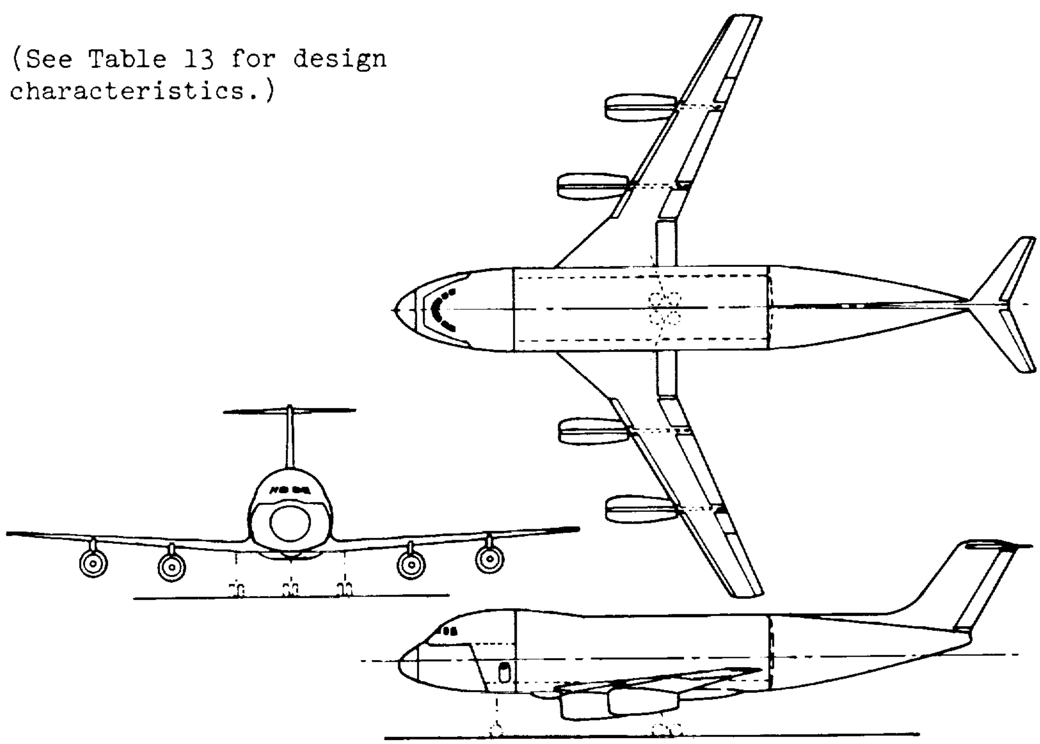
*LH_2 Fuel Cost = \$3/1.054 GJ = \$3/10^6 Btu = 15.48¢/lb

(See Table 14 for design characteristics.)



LARGE

(See Table 13 for design characteristics.)



SMALL

Figure 14. General Arrangement - Jet A Fueled Cargo Transport Aircraft

of the two lobes is compatible with the mid-wing position. However, the fuselage shape of the Jet A aircraft with its unbroken upper fuselage structural rings is not readily adaptable to the mid-wing position and must therefore use the high-wing position. Both the LH_2 and the Jet A-fueled aircraft designed for the small mission use the low wing position for ease of landing gear attachment.

3.3.4 Benefits Evaluation

The potential benefits to be realized from using liquid hydrogen as the fuel for cargo aircraft for the subject missions were explored by comparing the selected hydrogen fueled nose loader aircraft with the reference Jet A fueled aircraft. Basically the same advantages were found for hydrogen in cargo aircraft as were previously discussed for passenger aircraft. The type of payload carried had little effect on the benefits found for using LH_2.

A summary of performance and design characteristics data is given in Tables 13 and 14 for the hydrogen nose loader and the reference Jet A fueled aircraft designed to perform the small and large cargo missions, respectively. In both tables the data are compared by the "factor," which presents the ratio of Jet A-to-LH_2 values for each parameter. Analysis of these data shows a preference in almost all cases for the hydrogen fueled aircraft. For example, gross weights of the small and large Jet A-fueled aircraft are seen to be larger by 19 and 34 percent, compared to their respective LH_2 fueled counterpart aircraft. Block fuel weights of the hydrocarbon fueled aircraft are higher by factors of 2.86 and 3.13. Characteristics which minimize the spacing and area required at the cargo terminal gate, i.e., wing span and wing area, both favor the hydrogen fueled design. Fuselage length is not a particularly significant parameter relative to either cargo loading or aircraft refueling operation. It is, of course, significant when considering hanger and storage requirements. The Jet A-fueled aircraft are characteristically shorter in length than their hydrogen fueled counterparts for the same reason related earlier for the passenger aircraft, viz., the necessity of carrying LH_2 fuel in the fuselage. Finally, comparing the energy used by the subject aircraft in flying their design missions, it is seen that the LH_2-fueled designs provide improvements of 2 and 12 percent, respectively.

Table 15 is a summary tabulation of development and production costs of the hydrogen and Jet A-fueled cargo aircraft. The hydrogen fueled aircraft are seen to be somewhat higher in production price than their Jet A fueled counterparts.

TABLE 13. COMPARISON: LH_2 VS JET A SMALL CARGO AIRCRAFT

[56,700 kg (125,000 lb); 5560 km (3000 nmi); M = 0.85]

	SI	CUSTOMARY	LH_2 SI	LH_2 CUSTOMARY	JET A SI	JET A CUSTOMARY	FACTOR (JET A/LH_2)
Takeoff Gross Weight	kg	lb	135,760	299,300	161,480	356,000	1.19
Operating Empty Weight	kg	lb	64,640	142,500	63,730	140,500	0.99
Block Fuel Weight	kg	lb	11,860	26,140	33,880	74,700	2.86
Total Fuel Weight	kg	lb	14,470	31,900	41,100	90,600	2.84
Wing Area	m^2	ft^2	240.1	2584	263.2	2833	1.10
Wing Loading, Takeoff	kg/m^2	lb/ft^2	565	115.8	613	125.6	1.08
Landing	kg/m^2	lb/ft^2	536	109.7	536	109.7	1.00
Span	m	ft	46.5	152.5	51.3	168.3	1.10
Fuselage Length	m	ft	52.0	170.7	50.8	166.5	0.97
Lift/Drag (Cruise)			16.3	16.3	17.9	17.9	1.10
Specific Fuel Consumption (Cruise)	$\frac{kg}{hr}/daN$	$\frac{lb}{hr}/lb$	0.213	0.209	0.619	0.608	2.91
Thrust per Engine (SLS)	N	lb	106,310	23,890	112,980	25,400	1.06
Thrust/Weight (SLS)	N/kg	-	0.32	0.32	0.29	0.29	0.91
FAR T.O. Distance	m	ft	1786	5800	2207	7240	1.25
FAR Landing Distance	m	ft	2231	7320	2216	7270	0.99
Approach Speed (EAS)	m/s	knots	69.5	135	69.5	135	1.00
Weight Fractions	percent	percent					
Fuel			11	11	26	26	2.36
Payload			42	42	35	35	0.83
Structure			29	29	25	25	0.86
Propulsion			10	10	7	7	0.7
Equipment and Operating Items			8	8	7	7	0.88
Energy Utilization	$\frac{kJ}{Mg\ km}$	$\frac{Btu}{ton\ n\ mi}$	4502	7181	4596	7330	1.02

TABLE 14. COMPARISON: LH_2 VS JET A LARGE CARGO AIRCRAFT

[113,400 kg (250,000 lb); 10,190 km (5500 nmi); M = 0.85

	SI	CUSTOMARY	LH_2 SI	LH_2 CUSTOMARY	JET A SI	JET A CUSTOMARY	FACTOR (JET A/LH_2)
Takeoff Gross Weight	kg	lb	300,060	661,500	400,890	883,800	1.34
Operating Empty Weight	kg	lb	138,670	305,700	138,850	306,100	1.00
Block Fuel Weight	kg	lb	41,300	91,100	129,200	285,000	3.13
Total Fuel Weight	kg	lb	47,990	105,800	148,650	327,700	3.10
Wing Area	m^2	ft^2	483.4	5203	658.1	7084	1.36
Wing Loading, Takeoff	kg/m^2	lb/ft^2	620.5	127.1	609.3	124.8	0.98
Landing	kg/m^2	lb/ft^2	535.6	109.7	412.5	84.5	0.77
Span	m	ft	66	216.4	77	252.5	1.17
Fuselage Length	m	ft	77.0	252.7	72.0	236.0	0.94
Lift/Drag (Cruise)			18.0	18.0	19.5	19.5	1.08
Specific Fuel Comsumption (Cruise)	$\frac{kg}{hr}/daN$	$\frac{lb}{hr}/lb$	0.213	0.209	0.619	0.608	2.91
Thrust per Engine (SLS)	N	lb	212,170	47,700	258,430	58,100	1.22
Thrust/Weight (SLS)	N/kg	-	0.29	0.29	0.26	0.26	0.90
FAR T.O. Distance	m	ft	2185	7170	2438	8000	1.12
FAR Landing Distance	m	ft	2304	7560	2143	7030	0.93
Approach Speed (EAS)	m/s	knots	69.5	135	61.2	119	0.88
Weight Fractions	percent	percent					
Fuel			16	16	37	37	2.31
Payload			38	38	28	28	0.74
Structure			31	31	23	23	0.74
Propulsion			10	10	7	7	0.70
Equipment and Operating Items			5	5	5	5	1.00
Energy Utilization	$\frac{kJ}{Mg\ km}$	$\frac{Btu}{ton\ n\ mi}$	4286	6835	4782	7627	1.12

TABLE 15. COST COMPARISON: LH_2 VS JET A CARGO AIRCRAFT

MISSION	SMALL		LARGE	
FUEL	LH_2	JET A	LH_2	JET A
COST ($ MILLION)				
Development				
Airframe	540.6	520.3	1033.7	1091.7
Engine	390.0	418.4	578.3	580.0
Total	930.6	938.7	1612.0	1671.7
Production				
Airframe	13.4	13.1	28.8	27.7
Engine	3.0	2.5	5.6	5.5
Avionics	0.5	0.5	0.5	0.5
R&D Amortization*	2.3	2.3	4.2	4.3
Total	19.2	18.4	39.1	38.0

*Based on 350 aircraft and 2000 engines

Since both gross weight and engine thrust are lower for the LH_2 designs, the increase in price is due entirely to the complexity factor arbitrarily assigned to account for anticipated difficulty in manufacturing hydrogen-related components. This results in the higher price per unit operating empty weight noted earlier in the case of the passenger aircraft. A realistic appraisal of the true cost of the hydrogen related items can be determined only after preferred design approaches for such items as tanks, insulation, and other fuel system components have been determined.

Figure 15 illustrates the effect of fuel price on direct operating cost for the aircraft designed for the long range, large payload mission. A horizontal line drawn from the $3 per 1.054 GJ base price for liquid hydrogen indicates that a differential of an additional 50 cents per 1.05 GJ (10^6 BTU) can be paid for liquid hydrogen, relative to Jet A fuel, and still realize equal direct operating costs. The equivalent price differential which may be paid to maintain the same DOC for the shorter range, smaller payload cargo mission is 20 cents per 1.054 GJ.

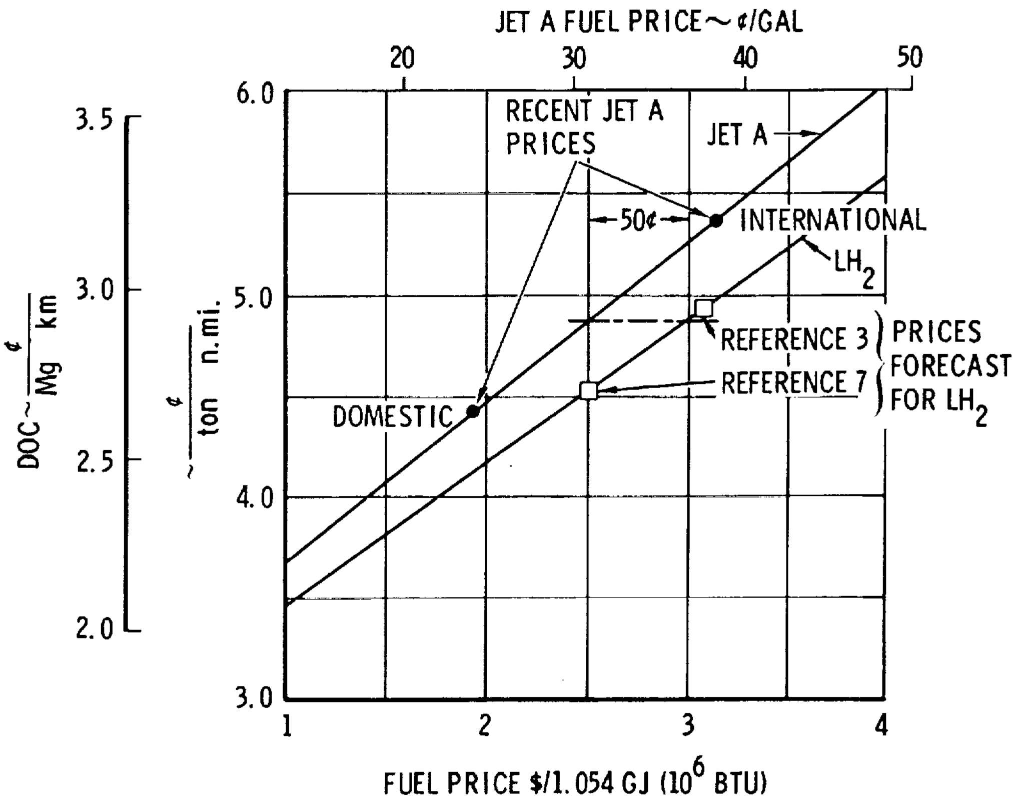


Figure 15. Direct Operating Cost vs Cost of Fuels (Large Cargo Aircraft)

A comparison of noise characteristics of the subject cargo aircraft is presented in Table 16. The flyover and sideline noise levels of the four aircraft are 13 to 20 EPNdB lower than the limit values defined by FAR Part 36. In every case save approach flyover, the LH_2-fueled aircraft are seen to be as quiet or quieter than their counterpart Jet A fueled aircraft. The explanation for LH_2-fueled aircraft being slightly noisier in approach is the same as previously explained for passenger aircraft. This characteristic is more pronounced in the case of the larger airplanes.

The noise footprint area defined by the 90 EPNdB contour is the sum of the approach plus takeoff conditions. The hydrogen fueled aircraft for both missions have significantly smaller footprint areas and would thus be considered better neighbors.

Considerations of emission characteristics and safety of LH_2 versus Jet A-fueled cargo aircraft are identical to those previously stated in Section 3.2.3 for passenger aircraft.

TABLE 16. NOISE COMPARISON: LH_2 VS JET A CARGO AIRCRAFT

AIRCRAFT	NOISE LEVELS (EPNdB)						AREA OF 90 EPNdB CONTOUR	
	FLYOVER		SIDELINE		APPROACH		km^2	Sq. Mi.
SMALL								
LH_2	88.7	(102.9)	86.8	(106.0)	94.5	(106.0)	4.439	1.714
JET A	90.7	(104.2)	86.8	(106.5)	94.5	(106.5)	5.063	1.955
LARGE								
LH_2	92.7	(108.0)	87.8	(108.0)	96.4	(108.0)	7.039	2.717
JET A	95.1	(108.0)	88.3	(108.0)	95.4	(108.0)	8.415	3.249

( ) = Far Part 36 Limits

4.0 RESEARCH AND TECHNOLOGY RECOMMENDATIONS

In view of the many attractive advantages which result from use of liquid hydrogen as fuel for long range subsonic transport aircraft, and because of the recognized problems of maintaining an adequate supply of petroleum-based conventional fuel throughout the world, it is recommended that development of appropriate technology be actively pursued. Figure 16, Technology Development Program, lists 17 items which constitute a recommended program for development of aircraft-related technology. A schedule and rough order-of-magnitude estimates of the cost of each item in the program are also shown in the figure.

Concurrently with this aircraft technology development program and starting at the conclusion of Item 7 in Figure 16 (indicated by the dashed portion of the bar), advanced econometric and operations analyses should be conducted to determine an economically feasible and viable plan for converting commercial transport aircraft to hydrogen. Along with that study would come a determination of preferred mission requirements for the initial design of LH_2 fueled transport aircraft.

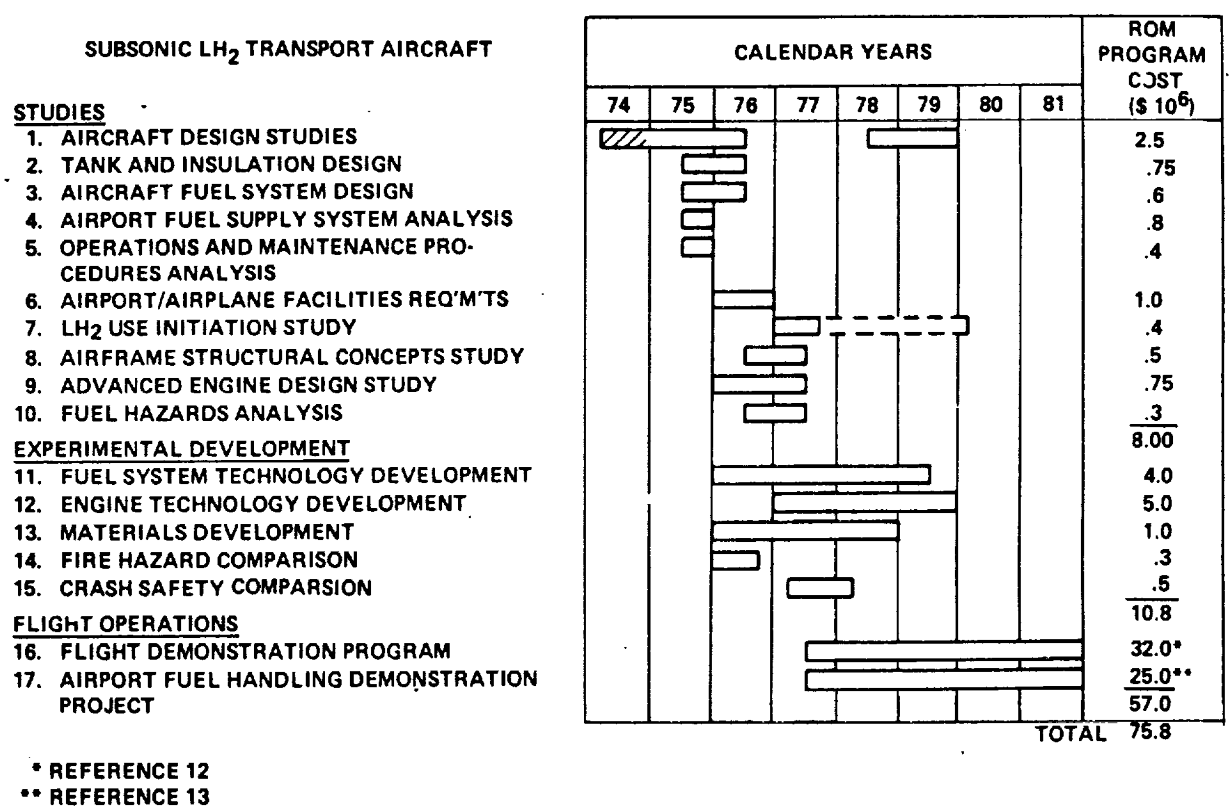


Figure 16. Technology Development Program

5.0 CONCLUSIONS

The use of liquid hydrogen as fuel in subsonic transport aircraft results in designs which are lighter, have smaller wings but larger fuselages, require smaller engines, can operate from shorter runways, minimize pollution of the atmosphere, and expend less energy in performing their missions than corresponding designs fueled with conventional hydrocarbon (Jet A). Depending on the payload-range design requirement, the cost of liquid hydrogen can be between 20¢ and 50¢ greater per 1.054GJ (10^6 Btu), relative to Jet A cost, and the LH_2-fueled aircraft can still provide equal or lower direct operating cost.

The preferred design concepts for hydrogen-fueled passenger and cargo transport aircraft evolved in this study have conventional appearance. Unusual configurations which were investigated to see if use of the new fuel would offer unique design possibilities proved to be flawed for the subject missions. Designs configured to provide specific advantages developed serious problems in other respects such that the net result was unsatisfactory.

The problems of designing and developing practical, realistic transport aircraft fueled with liquid hydrogen which can meet airline standards for maintenance, operations, and utilization in both passenger and cargo application, require technology development but are not dependent upon either a breakthrough in capability or invention of new products for success. Thus, it is considered technically feasible that hydrogen-fueled transport aircraft can be developed and ready to begin commercial operations by 1990. This allows 10 years for design and development of a production aircraft, assuming a one year overlap with the Technology Development Program of Section 4. However, the following significant conditions are recognized as mandatory and supplemental to the aircraft-related technology requirements in order to achieve this goal:

- A national (and international) commitment must be made to develop hydrogen for widespread use, and commercial transport aircraft must be mandated to use it.
- Hydrogen manufacture and distribution systems must be developed and implemented.
- Facilities must be provided at selected airports to liquify, store, and handle hydrogen.

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