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H_2-FUELED HIGH-BYPASS TURBOFAN

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INTRODUCTION

In 1976-77, the AiResearch Divisions of The Garrett Corporation,* under contract to the Lockheed-California Company, participated as team members in an effort to evaluate the potential of hydrogen fueled transport aircraft. The work was sponsored by the National Aeronautics and Space Administration, Langley Research Center, and is reported in full in the investigation final report, Brewer[1].

AiResearch developed design concepts and the preliminary design of a LH2 fueled turbofan engine and of the significant components of the engine fuel delivery and control system. The resulting data were used in the assessment of technical feasibility, size, weight, performance, and direct operating cost. Also, the development which would be required to bring this technology to a state of readiness for design application was defined.

The studies made extensive use of previous work by Lockheed, in which various configurations of LH_2 fueled transports were investigated, Brewer[2]. For the present study, the subject aircraft was a 400 passenger, Mach 0.85 transport, having a range of 5500 nautical miles. This particular aircraft is described in greater detail by Brewer[1].

ENGINE STUDIES

Engine studies were performed to establish a viable baseline concept for the turbofan engine for a LH_2 fueled transport and to assess technical feasibility and impact on aircraft direct operating cost. The investigation phases included:

- Feasibility investigation of various schemes to exploit the special properties of hydrogen, particularly the heat sink capacity.
- Parametric studies to select cycle variables and the engine configuration which minimized direct operating cost. The factors considered in evaluating direct operating cost were specific fuel consumption and engine weight.
- Detailed definition of the selected engine design; including determining engine performance throughout the flight envelope, weight and geometry, scaling laws, engine estimated cost, noise and emission levels, and operating limits and capabilities.
- Assessment of technology development required.

Hydrogen Exploitation

A study was made to determine how the unique properties of hydrogen could be exploited to provide engine performance and/or weight benefits. The concepts which were evaluated are shown schematically on the attached figure. The approach used

*Now divisions of the Allied-Signal Aerospace Company was to select a turbofan cycle compatible with the aircraft requirements and to investigate the effects of the selected concepts on this baseline. Previous Lockheed work, Brewer[2], resulted in the definition of a turbofan cycle for a liquid hydrogen-fueled transport, and this cycle was used as a baseline for the hydrogen exploitation feasibility studies.

A summary of the results of the hydrogen exploitation study is included in the attached table. The concepts which yield the largest reduction in DOC are fuel heating and the expander cycle. The fuel heating concept was selected as it is less complex and provides an equal DOC benefit. Hydrogen cooling of the turbine cooling air is also attractive and offers advantages if higher turbine inlet temperatures are selected.

Cycle Definition and Configuration Studies

The cycle definition and configuration studies were accomplished in three phases:

- A review of recent studies of advanced turbofan engines, references 3, 4, 5, to identify and confirm the state-of-the-art, and to establish the technology level expected to be available in the 1990-1995 time period.
- Selection of a preliminary cycle for the LH_2 fueled turbo fan engine, based upon the results of the first phase study, plus other inputs.
- Optimization of the preliminary cycle based upon trade-off studies, including special consideration of a high temperature, high pressure ratio cycle.

The final cycle selected as a result of the hydrogen exploitation studies and cycle selection investigations has the following significant features at the engine design point (maximum cruise power, 10 668 m (35 000 ft) M 0.85):

- Fan pressure ratio of 1.7:1 and a bypass ratio of 10:1
- A booster pressure ratio of 1.45:1
- A compressor pressure ratio of 16.5:1
- A rotor inlet temperature of 1379°C (2514°F) [1482°C (2700°F) maximum rotor inlet temperature]
- A cycle pressure ratio of 40:1

The selected engine is a twin spool, direct drive, separately exhausted turbofan. A single stage fan and two booster stages are driven by a multistage, uncooled, axial turbine. The gas generator consists of a 10-stage axial compressor, a through-flow circular combustor and a single-stage cooled axial turbine. The spool shafts are concentric and the low pressure spool shaft passes through the high pressure shaft.

Four heat exchangers are included as part of the engine to provide (a) hydrogen cooling of the turbine cooling air, (b) engine oil cooling, (c) hydrogen cooling of the aircraft environmental control system air and (d) fuel heating.

Basic cycle and performance data are listed in the attached table.

Technology Development Required

The technology postulated for the LH_2-fueled engine is representative of that which would be incorporated in an engine entering service in the 1990 time period. Much of the technology is not, however, unique to use of LH_2 fuel and will be developed in existing programs. Aerodynamics, materials, mechanical design and manufacturing processes, while advanced, are equally applicable to future kerosene-fueled advanced transport engines. However, technology development is recommended for two items pertinent to the LH_2 fueled engine:

- Combustor
- H_2 cooling of the turbine cooling air

Combustor—Technology development is required to take advantage of the properties of hydrogen and to execute a combustor design which is smaller, provides an improved pattern factor, and is low in oxides of nitrogen emissions.

The design of hydrogen combustion systems is particularly amenable to analysis relative to conventional kerosene combustion systems. The kinetic schemes and reaction rates are well established except for turbulent flow. Therefore, a technology program to develop a hydrogen combustion system would consist of analytical design augmented by an experimental program to establish the turbulent flow kinetics and to verify the analytical design.

H_2 cooling of turbine cooling air—There are two problems introduced when hydrogen cooling of turbine cooling air is incorporated in an engine. The first is a design problem. Normally turbine cooling air is routed internally through the engine from the compressor to the cooled turbine. The routing is different when the turbine cooling air is hydrogen cooled. Complex design problems would have to be addressed but the task could be best undertaken concurrently with engine design.

The second problem is caused by the lower temperature of the turbine cooling air. Thermal gradients in the blades would be more severe than presently experienced for a similar blade heat transfer system. These high thermal gradients can result in low cycle fatigue damage. In order to realize the advantages of H_2 cooling of the turbine cooling air, it is recommended that parallel technology programs be undertaken to

1. Develop heat transfer systems which produce more uniform temperatures
2. Extend development of single crystal turbine blades which have higher cyclic fatigue strength.

ENGINE FUEL DELIVERY AND CONTROL SYSTEM STUDIES:

Three main items were investigated:

- The engine high pressure fuel pump: including preliminary definition of design requirements; identification and tradeoff study of candidate pump and drive systems; special consideration of the pump bearing problem; and selection of a final candidate, followed by further detailed definition.
- The engine fuel control system: including preliminary definition of requirements; identification of candidate systems, followed by a final selection; and preliminary consideration of engine starting and operating procedures.
- The development which would be required to bring this technology to a state of readiness for design application.

These items are illustrated in the attached figures.

Technology Development Required

The study of the engine fuel supply system identified and brought into focus various areas of risk in the technology where advances in the state of the art are either necessary or highly desirable to facilitate the timely and economic development of a flight system. The more significant of these items are:

Engine fuel pump—The engine high-pressure pump bearing system is a major technical risk item requiring advanced development. The current state of the art in advanced high pressure LH_2 pumps has evolved mainly from the development work which has been done on rocket engine turbopumps. As a result of this work, the problems of designing for pump performance (head, flow range, and suction performance), and also the problems of mechanical design and materials selection for cryogenic service, have been adequately resolved and may be considered state of the art.

However, all rocket engine components inherently have a very short mission duty cycle, while air transport equipment has a typical overhaul period of 5000 hours and service life of 40,000 hours. The most critical problem in the development of a high-pressure LH_2 pump suitable for airline service is the pump bearing system, and it is recommended that the approaches described in this report be investigated.

It should be noted that these comments apply only to the bearings of the high-pressure LH_2 pump, which are relatively highly loaded and which operate at high rotational speed. The very lightly loaded bearings of a LH_2 fuel boost pump, which run at lower rotational speed, can probably be developed adequately for airline service as a further evolution of the existing design approach, using rolling element bearings and separators having a dry lubricant capability.

Engine fuel control system—Operation of the cryogenic hydrogen fuel control system presents several new problems such as starting with the supply line full of vapor, the necessity for extremely rapid chill down of the engine high pressure pump, the probable necessity to control the flow of fuel in both the vapor and liquid states, and the presence of significant volume capacitance in the fuel system combined with the use of the relatively compressible H_2 fuel. These problems make desirable analysis and computer simulation of the selected engine fuel delivery and control system, followed by fabrication and test of a breadboard system.

Overall system—It is desirable to make a preliminary investigation of systems interactions involved in utilizing H_2 as a heat sink for cabin air conditioning, engine oil cooling, engine stator vane and rotor blade cooling, in combination with the engine exhaust fuel heating concept. This may be done initially by computer simulation, and particular attention should be paid to identifying critical off-design conditions.

CONCLUDING REMARKS

The study developed preliminary design concepts for the exploitation of the properties of LH_2 in a turbofan engine intended for air transport use, and showed the benefits which accrue in reduction of aircraft direct operating cost. Design concepts for the engine fuel delivery and control system, including the engine high pressure fuel pump, were developed and general concept feasibility was shown. For both the engine and the fuel delivery and control system, recommendations were made for the advanced development which is necessary to bring the technology to a state of readiness for design application. The study was of necessity abbreviated in nature: more intensive study of both the engine and fuel delivery and control system is recommended.

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LH_2 FUEL SYSTEM STUDY FOR SUBSONIC TRANSPORT

- PROGRAM OBJECTIVE
  - EVALUATE POTENTIAL OF HYDROGEN FUELED TRANSPORT AIRCRAFT
  - SELECTION CRITERIA AIRCRAFT D.O.C., AND ENGINE SYSTEM WEIGHT
- PARTICIPANTS
  - SPONSOR: NASA LANGLEY RESEARCH CENTER
  - AIRCRAFT STUDIES: LOCKHEED CALIFORNIA COMPANY
  - ENGINE AND FUEL SYSTEM STUDIES: GARRETT - AIRESEARCH
- TIME OF STUDY: 1976 - 1977

STUDY APPROACH

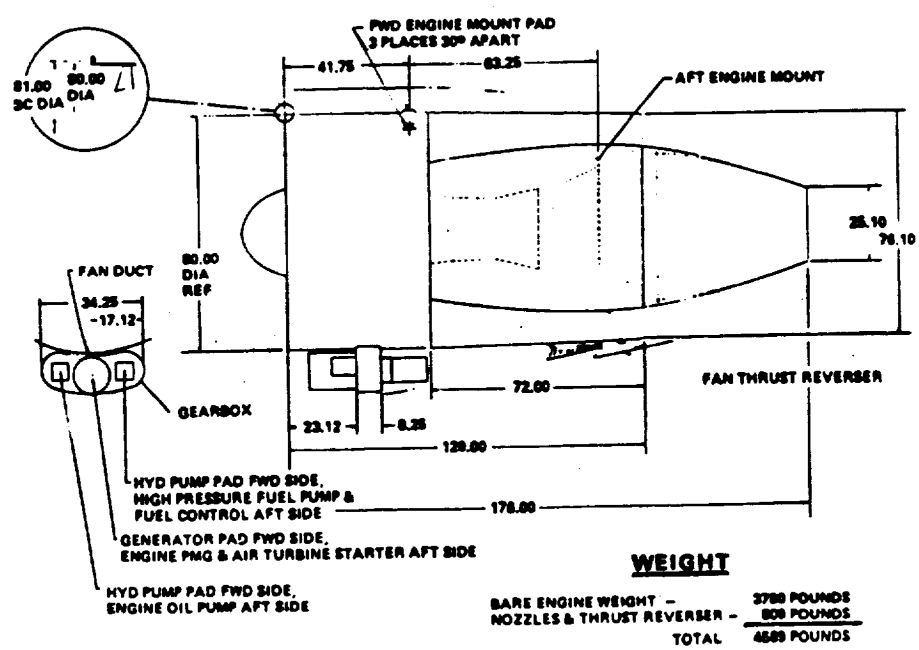
- ASSUME BASELINE AIRCRAFT: 400 PASSENGER, MACH 0.85, 5500 NM RANGE
- PERFORM PARAMETRIC STUDIES OF ENGINE CYCLE VARIABLES AND CONFIGURATION TO MINIMIZE AIRCRAFT D.O.C.
- IDENTIFY SCHEMES TO EXPLOIT LH_2 PROPERTIES. INVESTIGATE FEASIBILITY AND EFFECT ON AIRCRAFT D.O.C.
- ESTABLISH DETAILED DEFINITION OF SELECTED ENGINE DESIGN AND PERFORMANCE
- ASSESS TECHNOLOGY DEVELOPMENT REQUIRED

CYCLE AND INSTALLED PERFORMANCE CHARACTERISTICS - SELECTED LH_2 FUELED BASELINE ENGINE

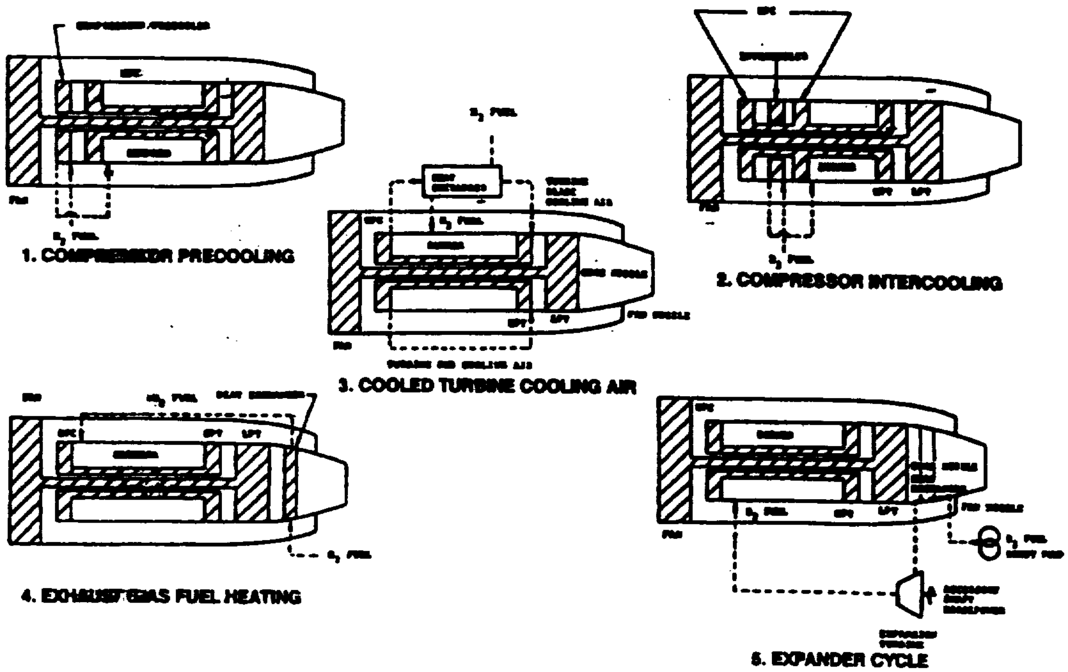
	SLS, STANDARD DAY	M 0.85 10,668 M (35,000 FT)
POWER SETTING	TAKEOFF	MAX. CRUISE
NET THRUST N, (LB)	136,587 (30,706)	29,100 (6542)
SFC, (kg/hr)/daN ((lb/hr)/lb)	0.1045 (0.1025)	0.2064 (0.2014)
BYPASS RATIO	10.25	10.0
FAN AIRFLOW, kg/sec (lb/sec)	483.7 (1066.4)	217.2 (478.8)
FAN PRESSURE RATIO (TIP)	1.594	1.7
FAN PRESSURE RATIO (HUB)*	2.26	2.466
COMPRESSOR PRESSURE RATIO	15.5	16.5
ROTOR INLET TEMPERATURE, °C, (°F)	1482°C (2700)	1379°C (2514)

*HUB PRESSURE RATIO INCLUDES BOOSTER STAGES

INSTALLATION DRAWING – SELECTED ENGINE



HYDROGEN EXPLOITATION CONCEPTS



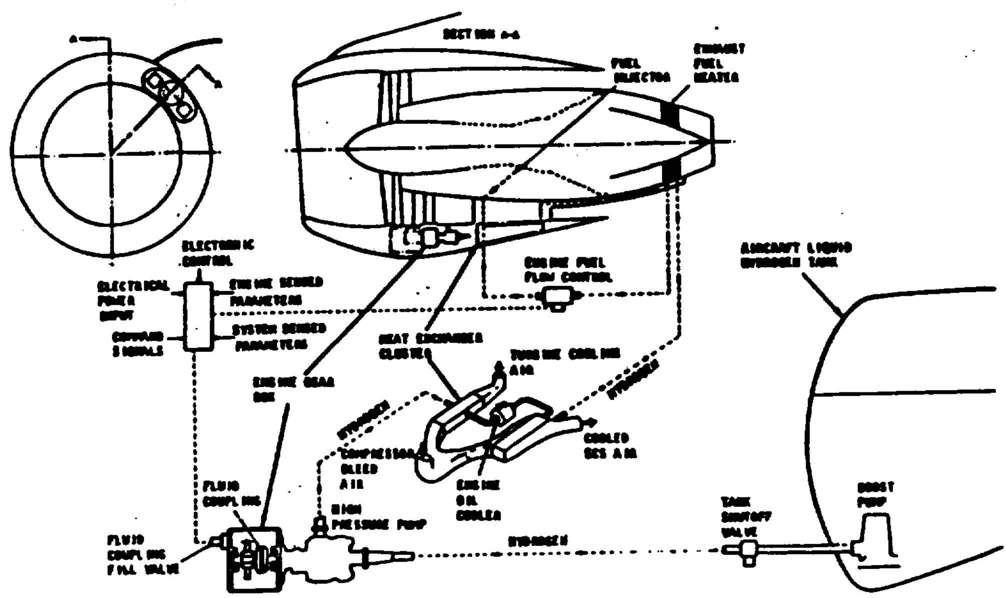
HYDROGEN EXPLOITATION SUMMARY

	ϵ_{H2}	$\frac{\Delta P}{P_{AIR}}$	ΔSFC** %	ENGINE ΔWT,KG	HX ΔWT,KG	ΔDOC* %
PRECOOLING	0.8	0.06	−1.86	−63	+75	−1.33
INTER COOLING	0.8	0.04	−0.93	−40	+100	−0.57
COOLED TURBINE COOLING AIR	0.8	N/A	−0.63	−27	+10	−0.41
FUEL HEATING	0.8	0.04	−4.31	+27	+112	−2.90
H_2 EXPANDER CYCLE	0.8	0.04	−4.31	+27	+112	−2.90

**RELATIVE TO THE BASELINE SFC = 0.2042 $\left(\frac{LB}{HR}\right)$/LB

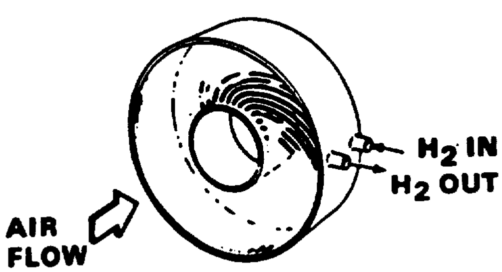
$$*DOC\ (\%) = \frac{\frac{7.75}{10^6}\ (\Delta WT) + 1.332\ \frac{SFC}{SFC_{BL}} - 1}{DOC_{BASE}} \times 100$$

LH_2 ENGINE FUEL DELIVERY AND CONTROL SYSTEM



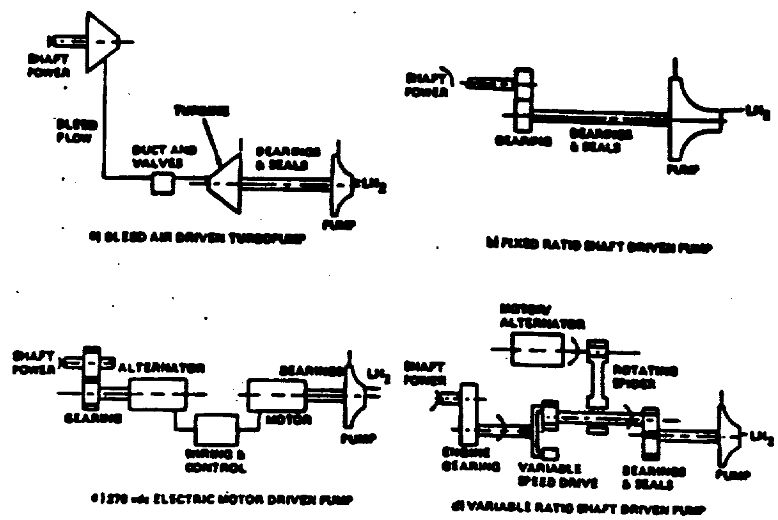
ENGINE STUDIES

ENGINE EXHAUST GAS FUEL HEATER

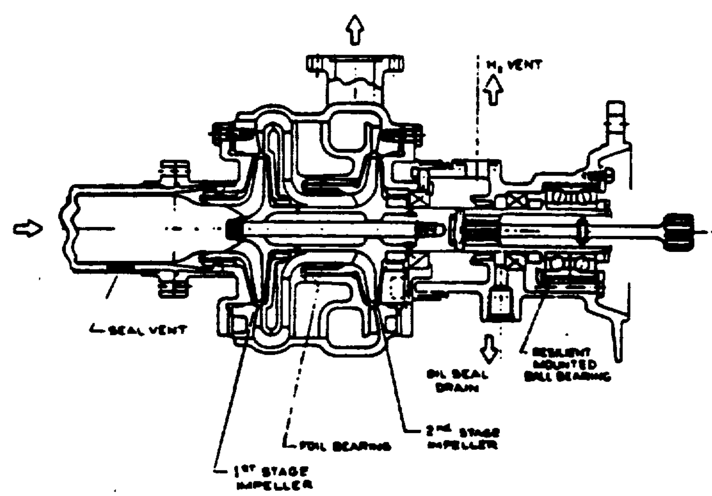


NO. H_2 PASSES	8
OUTSIDE DIA.	49.8 IN.
INSIDE DIA.	22.2 IN.
LENGTH	7.5 IN
TOTAL WEIGHT	170 LB
MATERIAL	304 CRES
TUBE O.D.	0.188 IN
TUBE WALL	0.012 IN.

ALTERNATIVE ENGINE PUMP DRIVE CONCEPTS



LAYOUT OF ENGINE HIGH PRESSURE LH_2 PUMP



REQUIRED UNIQUE TECHNOLOGY DEVELOPMENT

- COMBUSTOR DEVELOPMENT TO TAKE ADVANTAGE OF H_2 PROPERTIES
  - SMALLER COMBUSTOR
  - IMPROVED PATTERN FACTOR
  - LOW NO_X EMISSIONS
- H_2 COOLING OF THE TURBINE COOLING AIR
  - ROUTING OF H_2 THRU THE ENGINE TO COOL THE TURBINE
  - ADDRESS THE HIGHER THERMAL GRADIENTS PROBLEM
- ENGINE HIGH PRESSURE FUEL PUMP
  - BEARING SYSTEM
- FUEL CONTROL SYSTEM
  - POTENTIAL FOR 2 PHASE FLOW
  - SYSTEM VOLUME AND COMPRESSIBLE H_2

CONCLUSIONS

- EXPLOITATION OF H2 PROPERTIES PROVIDES SIGNIFICANT IMPROVEMENT IN AIRCRAFT D.O.C. AND WEIGHT
- GENERAL FEASIBILITY OF THE DESIGN CONCEPTS WAS SHOWN
- REQUIRED UNIQUE TECHNOLOGY DEVELOPMENT WAS IDENTIFIED