General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)
ALTERNATE-FUELED TRANSPORT
AIRCRAFT POSSIBILITIES

by

W.S. AIKEN
ALTERNATE-FUELED TRANSPORT
AIRCRAFT POSSIBILITIES

William S. Aiken, Jr.
Director, Aerodynamics and Vehicle Systems
Office of Aeronautics and Space Technology
National Aeronautics and Space Administration
Washington, D. C. USA

Presented at the
13ème CONGRES INTERNATIONAL AERONAUTIQUE
June 2-3, 1977
Paris, France
The earliest relatively serious interest in liquid hydrogen as an energy source for aircraft was in the 1950's. The National Advisory Committee for Aeronautics (NACA), the predecessor of NASA, conducted studies of the application of liquid hydrogen as a jet fuel for high-altitude high-speed aircraft. The results of this work, some of which were reported by Silverstein and Hall in reference 1, were interesting in that 6,000 to 7,000 N.mi. radius subsonic bomber and reconnaissance aircraft and 1500 N.mi. radius M=2.0 bombers seemed feasible at that time providing substantial research and development activities were undertaken. Sketches of these early concepts are shown in Figure 1.

In this same time period, some actual hardware was tested and a serious attempt was made to design a high speed interceptor. These activities are outlined on Figure 2. The NACA Lewis Research Center conducted flight tests of a J-65 engine fueled by LH2 on a B-57A aircraft. The tests were successful in that no problems were encountered in engine operation. In November 1956 Pratt and Whitney conducted extensive ground tests of a J-57 engine fueled by LH2 (Figure 3) and about a year later had developed and tested their Model 304-Hydrogen Expander Engine (Figure 4) which took advantage of the lower pressure required for combustion of hydrogen resulting in lower engine pressure ratios. Lockheed applied the Model 304 engine in the design of a high-altitude fighter (Figure 5) in 1957. While the aircraft was never built, the fuel tanks were designed and fabricated and ground simulation environmental tests of the fuel system were carried out. The project was terminated because operational requirements were unattainable and the LH2 logistics problems were considered insurmountable.

With the termination of these programs, there has been little serious U. S. activity on alternate energy sources for aircraft for almost 20 years. It is not an interest in high altitude aircraft which has revived NASA's interest in LH2 but the availability of domestic crude oil and in the long run a concern over the depletion of world-wide oil reserves. I believe it is unrealistic to suppose that alternate fuel sources will be developed for domestic, industrial and ground transportation use and the world's petroleum reserves will be set aside for air transportation.
Some aspects of alternate fuel considerations are noted in Figure 6. Various energy sources must be weighed in terms of availability, facility cost, production cost, etc., as they may be applied to domestic and industrial uses and aviation must eventually use fuels derived from these alternative energy sources. The commonality eventually must include distribution systems as well as source. Alternate fuels applicable to aircraft include synthetic Jet A, liquid hydrogen and liquid methane. Synthetic Jet A will have the characteristics of present aircraft fuels and poses no major problems to aircraft design. LH₂ and LCH₄ have major impacts on design and it is the purpose of this paper to explore some of these impacts as apparent from the studies conducted to date.

The paper is organized to describe NASA's cryogenically fueled aircraft program; LH₂ subsonic and supersonic transport design possibilities, the fuel system and ground side problems associated with LH₂ distribution, then a comparison of LCH₄ with LH₂, the design possibilities for LCH₄ fueled aircraft, and finally a summary of where NASA's cryogenically fueled programs are headed.

THE NASA PROGRAM

The NASA cryogenically fueled aircraft technology program is illustrated in its major elements in Figure 7. Beginning in 1973, studies of the application of liquid hydrogen to supersonic transport designs were initiated by Ames with the Lockheed-California Company; these studies, reported in reference 2, provided some background for the joint study by the Lockheed-California and Georgia Companies on subsonic transport designs for Langley. The subsonic study results are reported in references 3 and 4.

LH₂ fuel systems studies to date have covered cryogenic insulation (Bell and A. D. Little); the effects of LH₂ on the fracture and fatigue properties of 2219 aluminum and a total fuel system study recently initiated with Lockheed-California. Final reports of these studies have not yet been published.

In the airport requirements area Boeing and Lockheed-California conducted studies for Langley and the results are given in references 5 and 6.

Fuel production studies covering alternate fuels from coal by the Institute of Gas Technology and hydrogen liquefaction studies by Linde have also been supported by NASA-Langley.
NASA's plans for future studies will be covered later in the paper. All in all NASA has invested about $2,000,000 beginning in 1973 on various aspects of hydrogen fuel and LH₂ aircraft design studies.

LIQUID HYDROGEN

NASA's reasons for renewed interest in liquid hydrogen have been that it is

(a) an apparent alternate energy source

(b) there is the potential for the alleviation of some pollution problems, and

(c) experience in production, transportation and handling has been very successful in the space program.

The familiar characteristics (heat of combustion and boiling point) listed in Table 1 in comparison to Jet A fuel are, of course, key to the impacts which LH₂ will have on aircraft design. One immediately suspects that the high heating value per pound for liquid hydrogen in comparison to Jet A should provide the possibility for lower gross weight aircraft but this is immediately tempered somewhat by the poor volumetric efficiency comparison. The problems to be created by the necessity of maintaining hydrogen at cryogenic temperatures are also recognized to have a profound impact on design.

Subsonic Design Trends

The studies conducted by Lockheed for NASA-Langley covered passenger and cargo type aircraft with external and internal tank arrangements for various ranges and payloads. In all cases reference aircraft were also designed for Jet A fuel use as a basis of comparison. Typical internal and external fuel passenger configurations are illustrated in Figures 8 and 9. The results of the studies are reported in detail in references 3 and 4.

For brevity, some of the data for passenger type aircraft has been extracted from these studies and displayed in Tables II and III. Tables II and III list the aircraft characteristics and economic and environmental characteristics for 5 different missions ranging from a 1500 N.mi. 130 passenger vehicle to one with 5000 N.mi. radius and
400 passengers. Characteristics are shown for LH₂ designs and Jet A designs. All LH₂ designs carry the LH₂ in internal tanks since these have been determined to be the most efficient. The 5000 N.mi. radius aircraft is interesting in that it is designed for a nonrefueling mission. Comparisons of estimated aircraft price, noise and on-board energy utilization carry no surprises although one might have expected LH₂ aircraft to be higher priced and with much lower noise and energy utilization.

There are some general trends which may be estimated and this has been done by attempting to show the trends of some selected parameters. The product of range and payload was chosen as a variable in an attempt to represent productivity (since all aircraft were designed to fly at about the same speed). This product, and gross weight, noise, energy utilization and price ratios (LH₂/ Jet A) were calculated for the five aircraft sets of Tables II and III. The results are tabulated in Table IV and plotted in Figure 10. It is immediately evident that as the range and/or payload of this class of aircraft increases, the gross weight ratio decreases markedly; sideline noise is relatively unaffected and flyover noise decreases. Energy utilization decreases for aircraft with range x payload greater than about 4x10⁵ but below this point liquid hydrogen fueled aircraft are apparently less efficient than Jet A types. On the price side, all LH₂ fueled aircraft are more expensive than Jet A ones except for the 5000 N.mi. radius type which has a built-in penalty to start with, having to haul over half the fuel without using any of it on the outbound leg.

These data, in my view, are not anything to get very excited about. If anything, about all they really prove is that it appears to be possible to design competitive LH₂ transports if the cost of energy is not a primary consideration. There is a lot of fancy arithmetic that one could do to establish at which point an LH₂ aircraft becomes financially more attractive than a Jet A aircraft, but this will ultimately depend upon the relative price in the future of the two energy sources we are considering. It is important to observe that no unusual configuration arrangements have to be developed; in fact, all attempts to improve on basic subsonic designs to accommodate LH₂ have produced less efficient vehicle designs. One other point which is obvious is that while the energy ratio shows apparent gains for large LH₂ aircraft, this is only the on-board energy; the total energy used from production through conversion for LH₂ aircraft is from 2 to 4 times higher depending on the production process.
Supersonic Design Trends

The subsonic studies just described were done in considerably more depth than the SST design studies to be referred to next. Lockheed studied a $M = 2.7$ SST LH$_2$ aircraft under contract to NASA-Ames, the results being reported in references 2 and 7. In 1973, the NASA-Lewis Research Center conducted an in-house study which covered hydrogen and methane, reference 8. The NASA-Langley Research Center also conducted a study with the support of LTV Aerospace Corporation on a $M = 2.7$ LH$_2$ concept; however, the report is not available for distribution. These three studies were done on an independent basis and in varying depths and do not provide much common ground for comparison.

Front views of the Lockheed $M = 2.7$ Jet A and LH$_2$ concepts are illustrated to the left in Figure 11. The impact of the volume required for hydrogen tankage is immediately apparent. The Langley LH$_2$ concept is shown in planform to the right in Figure 11 in comparison with their Jet A version. In this approach it was necessary to greatly increase the fuselage length and diameter to carry the hydrogen. In both the Lockheed and Langley approaches, the wing had to be resized for the most efficient overall configuration.

The range, payload, gross weight and energy utilization characteristics for the Lockheed and Langley Jet A and LH$_2$ designs are listed in Table V as well as similar characteristics for the Lewis designs of reference 8. The ranges chosen vary slightly and the payloads are different. There appear to have been major differences in the assumptions used for aerodynamic, propulsion and structural parameters as evidenced by the wide variation in gross weight and energy utilization ratios listed at the bottom of the table. The Lockheed design is the most optimistic in terms of these ratios while the Langley design is the most pessimistic. The energy utilization ratio for the Langley design is so high that one would be tempted to discard LH$_2$ concepts completely if this were the only data available. The answer may lie in the higher propulsive efficiency used for the Langley design computations.

Additional information on the Lockheed and Langley designs is given in Table VI. Sideline noise and flyover noise are seen to be reduced significantly for both LH$_2$ designs. The Lockheed L/D for cruise is significantly lower for the LH$_2$ airplane whereas Langley's resized LH$_2$ airplane
maintains the L/D level of the Jet A version. The significant differences between Lockheed and Langley sonic boom cruise overpressures are not readily explainable since both Jet A aircraft have the same weight and L/D.

As in the case of subsonic designs, it is my own view that LH₂ fueled SST's do not seem to provide any real breakthrough possibility although there does seem to be a greater payoff from a noise relief standpoint than for the subsonics. This is not to say that the technology should not be further developed, but the pace should be such to assure that a careful look has been taken at other alternate fuel possibilities.

Fuel Systems

At the present time, the most critical technology element associated with either subsonic or supersonic LH₂ aircraft is the cryogenic insulation system for LH₂ storage aboard the aircraft. While successful applications have been made in space programs, the useful life may not be sufficient for aircraft use. It almost goes without saying that the insulation system must be very light, economically practical and safe. The results of studies by Bell and A. D. Little which cover cryogenic insulation concepts will be available later this year. These efforts have involved the testing of available foam insulations and the formulation of additional materials.

The engineering analysis of the characteristics of the total fuel system for LH₂ aircraft being conducted by Lockheed will include consideration of all components of the aircraft fuel system from the fuel tank to the combustion chamber of the engine. The results from this study will also be available by the end of this year.

Other major aspects of fuel system problems are in the ground side or airport requirements. References 5 and 6 report the results of studies by Boeing and Lockheed to determine the total ground systems requirements for the provision of LH₂ for civil transports. San Francisco International Airport was selected as the subject for the Lockheed study and Chicago-O'Hare International Airport for the Boeing study. In both cases it was found to be technically feasible and that LH₂ could be delivered to aircraft competitive with Jet A fuel costs if these are in the range of .72 to 1.50 $/gal. or 19 to 40¢/liter.
The timing for the possible use of LH$_2$ for the first city pair operation would require a high priority commitment in 1980 to reach operational status in the mid 1990's. Development of coal production capacity in order to meet the requirements for manufacturing gaseous hydrogen beyond present plans would be required in the United States. While all potential technical problems lend themselves to straightforward engineering solutions, additional technology must be developed in the following areas:

1. Ground to aircraft, fuel and vent connections
2. Liquefaction cycle efficiency and control
3. Vacuum-jacketed line-failure sensing systems
4. Ground supply pumps
5. Means of recovery of gaseous H$_2$

Obviously the above list is not complete and more detailed systems and hazards studies are required to determine technical and economic characteristics that would affect decisions regarding the adoption of LH$_2$ on a system wide basis.

LIQUID METHANE

The first question is, of course, why consider methane as a fuel for aircraft and the most obvious answer is that it can be made from coal with relative ease and there are estimates that there is a recoverable coal supply sufficient for 500 yrs. It appears to be cheaper to produce LCH$_4$ from coal than to produce either Syn Jet A or LH$_2$ and the thermal efficiency of production is higher. In addition, gas pipelines to almost all airports are in existence today so that distribution is not really a problem.

Some of the factors which impact aircraft design are listed in Table VII in a comparison of LCH$_4$ with Jet A and LH$_2$. While LCH$_4$ does not have the high energy content per unit weight of LH$_2$, it is 16% higher than Jet A and the volumetric penalty is not as great as LH$_2$. LCH$_4$ exhaust products are similar to Jet A's although the hydrocarbons are different; LH$_2$ exhaust, of course, contains no hydrocarbons. Two other characteristics which should not be overlooked are the effects of temperature and conductivity. With the very low temperatures associated
with LH₂, oxygen and nitrogen can liquify on tank walls whereas with LCH₄ only the carbon monoxide and water vapor in the surrounding atmosphere will liquify. A potential for gaseous insulation exists with CH₄ because of the lower conductivity (0.18 of H₂).

An interesting comparison of the cost and efficiency of producing Syn Jet A, LH₂ and LCH₄ is shown in Table VIII. If it is assumed that coal will be used in the future to produce all of these products, it is immediately obvious that LCH₄ can be produced more efficiently and at lower cost. Also included in the table are the efficiency ratio and cost for producing LH₂ from water using electrical energy; it appears to be the least desirable approach by far.

The well-known physical characteristics of Jet A, LCH₄ and LH₂ are listed in Table IX for reference purposes.

Design Trends

Only very cursory looks have been taken at the possible application of LCH₄ to either subsonic or supersonic transport designs by NASA. An unpublished in-house quick look of several years ago for a 5500 N.mi. range, 400 passenger subsonic design indicated that the on-board energy utilization for LCH₄ was 1996 BTU/passenger N.mi. in comparison to 2020 for Jet A and 1724 for LH₂. If it is assumed that all of these fuels were derived from coal and water and the energy in/energy out ratios of Table VIII were applied, the energy use per passenger nautical mile would then be 3620 BTU for LH₂, 3830 BTU for Syn Jet A, and 3190 for LCH₄. From this standpoint, methane looks particularly attractive.

A somewhat more in-depth look at the application of LCH₄ to supersonic transports is the study by Lewis (reference 8) in which comparisons were made with Jet A and LH₂ designs. Some of the results of the study are listed in Table X. In essence, the LCH₄ design is quite similar in size and noise characteristics to their Jet A design with an energy utilization almost as low as the LH₂ design. Results such as these are encouraging enough to cause us to consider taking a harder look at methane possibilities in the future.
FUTURE PROGRAMS

The technology requirements for the application of LH₂ to transport aircraft are shown on Figure 12. Essentially the same list would be compiled for LCH₄ applications although, because of the higher cryogenic temperature of LCH₄, the problems tend to be less severe.

NASA's plans for the near term are to conduct a more in-depth LCH₄ subsonic aircraft study; to continue testing various insulation concepts, to begin LH₂ pump development and to conduct an analysis of the capture and reliquefaction of hydrogen boiloff during aircraft fueling. It is also possible that we may begin to take a harder look at LCH₄ for supersonic transports.

SUMMARY

Some general observations may be made on the basis of studies conducted to date with regard to LH₂ fueled aircraft, as:

a) from an airframe standpoint, the costs appear competitive;

b) from an operating cost standpoint, a differential of about $1.05 per 10⁶ BTU still keeps LH₂ in a competitive range with Jet A fueled aircraft;

c) LH₂ aircraft are quieter;

d) LH₂ aircraft are cleaner;

e) production and distribution problems are significant.

With regard to LCH₄, it appears to be very competitive but the studies to date have not been in sufficient depth for really valid comparisons. The aircraft systems and production and distribution problems are certainly less difficult than for liquid hydrogen. Liquid methane also appears to provide the greatest overall efficiency from production through use in the aircraft if future aviation fuels are to be derived from coal and water.
It should be noted that all of the technologies being developed for more fuel efficient conventional subsonic transports will be directly applicable to either LH₂ or LCH₄ aircraft. So perhaps in the early 1990's an active control, all-composite cryogenic transport similar to that shown in Figure 13 may be a reality.
REFERENCES


5. Preliminary Design Department, the Boeing Commercial Airplane Company: "An Exploratory Study to Determine the Integrated Technological Air Transportation System Ground Requirements of Liquid-Hydrogen-Fueled Subsonic, Long-Haul Civil Air Transports" NASA CR-2699, September 1976


# Properties

## LH₂ and Jet A

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet A</td>
<td>18,600</td>
<td>121,000</td>
<td>210</td>
</tr>
<tr>
<td>LH₂</td>
<td>51,600</td>
<td>30,400</td>
<td>-423</td>
</tr>
</tbody>
</table>

RASA HQ RA77-2235 (1)  
4-7-77

Table I
<table>
<thead>
<tr>
<th></th>
<th>LH2</th>
<th>JET A</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANGE, n. mi.</td>
<td>1,500</td>
<td>3,000</td>
</tr>
<tr>
<td>PAYLOAD, passengers</td>
<td>130</td>
<td>200</td>
</tr>
<tr>
<td>GROSS WEIGHT, lbs.</td>
<td>98,300</td>
<td>108,700</td>
</tr>
<tr>
<td>NO. ENGINES</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>THRUST/ENGINE, lbs.</td>
<td>17,000</td>
<td>18,800</td>
</tr>
<tr>
<td>SPAN, ft.</td>
<td>96</td>
<td>101</td>
</tr>
<tr>
<td>FUSELAGE L.'TH, ft.</td>
<td>140</td>
<td>113</td>
</tr>
<tr>
<td>FAR T.O. DIS., ft.</td>
<td>7,800</td>
<td>7,970</td>
</tr>
</tbody>
</table>

Table II
ECONOMIC AND ENVIRONMENTAL CHARACTERISTICS
LH₂ AND JET A SUBSONIC TRANSPORT AIRCRAFT

<table>
<thead>
<tr>
<th>RANGE, n. mi.</th>
<th>PAYLOAD, passengers</th>
<th>LH₂</th>
<th>JET A</th>
<th>LH₂</th>
<th>JET A</th>
<th>LH₂</th>
<th>JET A</th>
<th>LH₂</th>
<th>JET A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,500</td>
<td>130</td>
<td>7.85</td>
<td>7.51</td>
<td>13.95</td>
<td>13.33</td>
<td>23.41</td>
<td>22.62</td>
<td>26.92</td>
<td>26.46</td>
</tr>
<tr>
<td>3,000</td>
<td>200</td>
<td>7.85</td>
<td>7.51</td>
<td>13.95</td>
<td>13.33</td>
<td>23.41</td>
<td>22.62</td>
<td>26.92</td>
<td>26.46</td>
</tr>
<tr>
<td>3,000</td>
<td>400</td>
<td>7.85</td>
<td>7.51</td>
<td>13.95</td>
<td>13.33</td>
<td>23.41</td>
<td>22.62</td>
<td>26.92</td>
<td>26.46</td>
</tr>
<tr>
<td>5,500</td>
<td>400</td>
<td>7.85</td>
<td>7.51</td>
<td>13.95</td>
<td>13.33</td>
<td>23.41</td>
<td>22.62</td>
<td>26.92</td>
<td>26.46</td>
</tr>
<tr>
<td>5,000 RADIUS</td>
<td>400</td>
<td>7.85</td>
<td>7.51</td>
<td>13.95</td>
<td>13.33</td>
<td>23.41</td>
<td>22.62</td>
<td>26.92</td>
<td>26.46</td>
</tr>
</tbody>
</table>

PRICE, PER AIRCRAFT, $10⁶
- SIDELINE NOISE, EPNdB
- FLYOVER NOISE, EPNdB
- ENERGY UTILIZATION, BTU/seat n. mi.

Table III
# Parametric Variations - Subsonic Transports

## Ratio - LH₂ to Jet A Aircraft

<table>
<thead>
<tr>
<th>Range x Payload (n. mi. x passengers)</th>
<th>Gross Weight Ratio</th>
<th>Sideline Noise Ratio</th>
<th>Flyover Noise Ratio</th>
<th>Energy Ratio</th>
<th>Price Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.95 x 10⁵</td>
<td>.905</td>
<td>1.00</td>
<td>1.00</td>
<td>1.040</td>
<td>1.042</td>
</tr>
<tr>
<td>6.0 x 10⁵</td>
<td>.825</td>
<td>1.00</td>
<td>.95</td>
<td>.950</td>
<td>1.046</td>
</tr>
<tr>
<td>12.0 x 10⁵</td>
<td>.832</td>
<td>.99</td>
<td>.99</td>
<td>.955</td>
<td>1.037</td>
</tr>
<tr>
<td>22.0 x 10⁵</td>
<td>.750</td>
<td>.99</td>
<td>.98</td>
<td>.695</td>
<td>1.016</td>
</tr>
<tr>
<td>40.0 x 10⁵</td>
<td>.592</td>
<td>1.01</td>
<td>.93</td>
<td>.788</td>
<td>.974</td>
</tr>
</tbody>
</table>

Table IV
# LH$_2$ SST Concepts

**Cruise $M=2.7$**

<table>
<thead>
<tr>
<th></th>
<th>Lockheed</th>
<th>Langley</th>
<th>Lewis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range, n. mi.</strong></td>
<td>4200</td>
<td>4138</td>
<td>4000</td>
</tr>
<tr>
<td><strong>Payload, Passengers</strong></td>
<td>234</td>
<td>292</td>
<td>250</td>
</tr>
<tr>
<td><strong>Gross Weight, lb.</strong></td>
<td>JET A 762,000</td>
<td>LH$_2$ 395,000</td>
<td>JET A 762,000</td>
</tr>
<tr>
<td><strong>Energy Utilization, BTU/Pass. n. mi.</strong></td>
<td>6189</td>
<td>4483</td>
<td>4340</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Ratio LH$_2$/JET A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gross Weight Ratio</strong></td>
<td>.518</td>
</tr>
<tr>
<td><strong>Energy Utilization Ratio</strong></td>
<td>.725</td>
</tr>
</tbody>
</table>

*Table V*
**LH₂ SST CONCEPTS (CONTINUED)**

**CRUISE M=2.7**

<table>
<thead>
<tr>
<th></th>
<th>LOCKHEED</th>
<th></th>
<th>LANGLEY</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JET A</td>
<td>LH₂</td>
<td>JET A</td>
<td>LH₂</td>
</tr>
<tr>
<td>GROSS WEIGHT, lbs.</td>
<td>762,000</td>
<td>395,000</td>
<td>762,000</td>
<td>588,500</td>
</tr>
<tr>
<td>BLOCK FUEL, lbs.</td>
<td>330,600</td>
<td>85,400</td>
<td>290,500</td>
<td>101,100</td>
</tr>
<tr>
<td>ENGINE</td>
<td>DHTF</td>
<td>DHTF</td>
<td>TURBOJET</td>
<td>TURBOJET</td>
</tr>
<tr>
<td>THRUST/ENGINE, lbs.</td>
<td>86,900</td>
<td>52,800</td>
<td>77,600</td>
<td>74,600</td>
</tr>
<tr>
<td>SIDELINE NOISE, EPNdB</td>
<td>108.0</td>
<td>104.0</td>
<td>113.1</td>
<td>109.3</td>
</tr>
<tr>
<td>FLYOVER NOISE, EPNdB</td>
<td>108.0</td>
<td>102.2</td>
<td>106.9</td>
<td>91.4</td>
</tr>
<tr>
<td>L/D CRUISE</td>
<td>8.65</td>
<td>7.42</td>
<td>8.57</td>
<td>8.03</td>
</tr>
<tr>
<td>SONIC BOOM CRUISE, lbs/ft²</td>
<td>1.6</td>
<td>1.2</td>
<td>2.4</td>
<td>1.8</td>
</tr>
</tbody>
</table>

*NASA HQ RA77-26028 (1) 4-20-77*

Table VI
# IMPACTS ON AIRCRAFT DESIGN

<table>
<thead>
<tr>
<th></th>
<th>JET A</th>
<th>LCH₄</th>
<th>LH₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per unit weight</td>
<td>1</td>
<td>1.16</td>
<td>2.77</td>
</tr>
<tr>
<td>Fuel tank relative volume</td>
<td>1</td>
<td>1.62</td>
<td>3.96</td>
</tr>
<tr>
<td>Exhaust products</td>
<td>NOₓ + CO + CO₂ + H₂O + CₓHᵧ</td>
<td>SAME AS JET A, DIFFERENT HYDROCARBONS</td>
<td>H₂O, SOME NOₓ</td>
</tr>
<tr>
<td>Temperature effects on liquefaction</td>
<td>CO AND WATER VAPOR CAN LIQUEFY ON TANK WALLS</td>
<td>C₂ AND N₂ CAN ALSO LIQUEFY</td>
<td></td>
</tr>
<tr>
<td>Conductivity effects</td>
<td>LOW CONDUCTIVITY (.18 OF H₂)</td>
<td>POTENTIAL FOR GASEOUS INSULATION</td>
<td></td>
</tr>
</tbody>
</table>

Table VII
## SOME AVIATION ENERGY ALTERNATIVES

<table>
<thead>
<tr>
<th>Process</th>
<th>$\frac{E_{IN}}{E_{OUT}}$</th>
<th>$\frac{$}{10^6 \text{ BTU}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>COAL + WATER $\rightarrow$ SYNTHETIC JP</td>
<td>1.6-1.9</td>
<td>5.50</td>
</tr>
<tr>
<td>COAL + WATER $\rightarrow$ LH$_2$</td>
<td>2.1</td>
<td>6.80</td>
</tr>
<tr>
<td>WATER + ELECTRICITY $\rightarrow$ LH$_2$</td>
<td>4.3</td>
<td>16.00</td>
</tr>
<tr>
<td>COAL + WATER $\rightarrow$ LCH$_4$</td>
<td>1.6</td>
<td>4.20</td>
</tr>
</tbody>
</table>

* $\$20/TON COAL

Table VIII
<table>
<thead>
<tr>
<th>FUEL</th>
<th>HEAT OF COMBUSTION BTU/LB</th>
<th>BTU/GAL</th>
<th>BOILING POINT °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>JET-A</td>
<td>18,600</td>
<td>74,500</td>
<td>-259</td>
</tr>
<tr>
<td>LCH₄</td>
<td>21,500</td>
<td>51,600</td>
<td>-423</td>
</tr>
<tr>
<td>LH₂</td>
<td>30,400</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table IX
## LEWIS SUPERSONIC AIRCRAFT STUDY

<table>
<thead>
<tr>
<th></th>
<th>JET A</th>
<th>LH₂</th>
<th>LCH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANGE, n. mi.</td>
<td>4000</td>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td>PAYLOAD, passengers</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>GROSS WEIGHT, lbs.</td>
<td>842000</td>
<td>504000</td>
<td>765000</td>
</tr>
<tr>
<td>BLOCK FUEL, lbs.</td>
<td>331000</td>
<td>100000</td>
<td>252000</td>
</tr>
<tr>
<td>ENGINE</td>
<td>DBTF</td>
<td>DBTF</td>
<td>DBTF</td>
</tr>
<tr>
<td>SPAN, ft.</td>
<td>156</td>
<td>120</td>
<td>148</td>
</tr>
<tr>
<td>FUSELAGE LENGTH, ft.</td>
<td>322</td>
<td>358</td>
<td>319</td>
</tr>
<tr>
<td>SIDELINE NOISE, EPNdB (NO SUPPRESSORS)</td>
<td>110.0</td>
<td>108.4</td>
<td>109.7</td>
</tr>
<tr>
<td>ENERGY UTILIZATION, BTU/passenger n. mi.</td>
<td>6120</td>
<td>5260</td>
<td>5450</td>
</tr>
<tr>
<td>L/D CRUISE</td>
<td>9.9</td>
<td>7.5</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Table X

NASA HQ RA77-2233 (1) 4-7-77
EARLY LH₂ AIRCRAFT CONCEPTS
(CIRCA 1955)

SUBSONIC BOMBER
M=0.75 ALTITUDE 80,000 FT.

SUPersonic BOMBER
M=2.0 ALTITUDE 75,000 FT.

Figure 1
LH$_2$ AIRCRAFT AND ENGINE EXPERIENCE

- NACA FLIGHT TESTS - 1954/55
  - B-57A
  - J-65/LH$_2$
- PRATT & WHITNEY GROUND TESTS - NOV. 1956
  - J-57/LH$_2$
- PRATT & WHITNEY GROUND TESTS - SEPT. 1957
  - MODEL 304 - HYDROGEN EXPANDER ENGINE
- LOCKHEED CL-400 AIRCRAFT DESIGN - c. 1957
  - 2 MODEL 304 ENGINES

Figure 2
HYDROGEN-FUELED J57 ENGINE

TESTED NOVEMBER 1956

TSFC REDUCTION WITH HYDROGEN ABOUT 68%
CL-400 PROJECT

CONFIGURATION

PROGRESS REALIZED

• ENGINE DESIGNED, BUILT AND TESTED
• FUEL TANK DESIGNED AND FABRICATED
• GROUND SIMULATION OF REAL-ENVIRONMENT FUEL SYSTEM DEVELOPED AND OPERATED

REASONS FOR TERMINATION

• OPERATIONAL REQUIREMENTS UNATTAINABLE
• INADEQUATE LH2 LOGISTICS FACILITIES

Figure 5
ALTERNATE FUEL CONSIDERATIONS

DOMESTIC

AVIATION

FUEL SOURCE

OIL RESERVES
SHALE
COAL
REFUSE
WATER

WHICH
ALTERNATE
FUEL?

COMMONALITY

? 

INDUSTRY

FACILITY COST
PRODUCTION COST
ENERGY REQ'TS/SOURCE
SUITABILITY
QUANTITY

Figure 6
CRYOGENICALLY FUELED AIRCRAFT TECHNOLOGY PROGRAM

AIRCRAFT PERFORMANCE STUDIES
- SUBSONIC LH₂ TRANSPORTS
- SUPersonic LH₂ TRANSPORTS

LH₂ FUEL SYSTEM
- CRYOGENIC INSULATION
- 2219 ALUM/LH₂ /FRACt. & FATIGUE
- TOTAL FUEL SYSTEM STUDY

AIRPORT REQUIREMENTS

FUEL PRODUCTION STUDIES
- ALTERNATE FUELS FROM COAL
- HYDROGEN LIQUEFACTION

Figure 7
INTERNAL TANK SUBSONIC TRANSPORT MODEL
REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

EXTERNAL TANK SUBSONIC TRANSPORT MODEL
PARAMETRIC VARIATIONS - LH₂ AND JET A SUBSONIC TRANSPORTS

RATIO \frac{LH₂ A/C}{JET A A/C}

- GROSS WEIGHT
- SIDELINE NOISE
- FLYOVER NOISE
- ENERGY
- PRICE

RANGE x PAYLOAD; N. MI. x PASSENGERS

Figure 10
LH$_2$ SST CONCEPTS
CRUISE M 2.7

LOCKHEED

LANGLEY

132.6 FT.  315 FT.

108.3 FT.  400 FT.

Figure 11
Ce document peut être obtenu :
- sur place,
  à la Régie de Documentation Technique, 2, Avenue de la Porte d'Issy - 75015 PARIS
- ou par correspondance adressée,
  à la Section des Diffusions du CEDOCAR, 26, Boulevard Victor - 75996 PARIS
  ARMÉES aux conditions suivantes :
    - pour la France et le Marché Commun : 25 F
    - pour l'Etranger : 29 F
  paiement d'avance, par virement au C.C.P. 90 80 55 PARIS, ou par chèque bancaire
  payable à PARIS

Dépôt légal 3ème trimestre 1977 - n° 11909

ISBN 2-7170-0455-6