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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

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INTRODUCTION

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 LH_2 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 LH_2 (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 LH_2 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 LH_2 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. LH_2 and LCH_4 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; LH_2 subsonic and supersonic transport design possibilities, the fuel system and ground side problems associated with LH_2 distribution, then a comparison of LCH_4 with LH_2, the design possibilities for LCH_4 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.

LH_2 fuel systems studies to date have covered cryogenic insulation (Bell and A. D. Little); the effects of LH_2 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 LH_2 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 LH_2 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. <u>radius</u> and

400 passengers. Characteristics are shown for LH_2 designs and Jet A designs. All LH_2 designs carry the LH_2 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 LH_2 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 (LH_2/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 4×10^5 but below this point liquid hydrogen fueled aircraft are apparently less efficient than Jet A types. On the price side, all LH_2 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 LH_2 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 LH_2 aircraft becomes financially more attractive than a Jet A aircraft, yet 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 LH_2 have produced less efficient vehicle designs. One other point which is obvious is that while the energy ratio shows apparent gains for large LH_2 aircraft, this is only the on-board energy; the total energy used from production through conversion for LH_2 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 an.. 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 LH_2 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 LH_2 aircraft is the cryogenic insulation system for LH_2 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 LH_2 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 LH_2 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 LH_2 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 years. 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 LH_2, oxygen and nitrogen can liquify on tank walls whereas with LCH_4 only the carbon monoxide and water vapor in the surrounding atmosphere will liquify. A potential for gaseous insulation exists with CH_4 because of the lower conductivity (.18 of H_2).

An interesting comparison of the cost and efficiency of producing Syn Jet A, LH_2 and LCH_4 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 LCH_4 can be produced more efficiently and at lower cost. Also included in the table are the efficiency ratio and cost for producing LH_2 from water using electrical energy; it appears to be the least desirable approach by far.

The well-known physical characteristics of Jet A, LCH_4 and LH_2 are listed in Table IX for reference purposes.

Design Trends

Only very cursory looks have been taken at the possible application of LCH_4 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 LCH_4 was 1996 BTU/passenger N.mi. in comparison to 2020 for Jet A and 1724 for LH_2. 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 LH_2, 3830 BTU for Syn Jet A, and 3190 for LCH_4. From this standpoint, methane looks particularly attractive.

A somewhat more in-depth look at the application of LCH_4 to supersonic transports is the study by Lewis (reference 8) in which comparisons were made with Jet A and LH_2 designs. Some of the results of the study are listed in Table X. In essence, the LCH_4 design is quite similar in size and noise characteristics to their Jet A design with an energy utilization almost as low as the LH_2 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 LH_2 to transport aircraft are shown on Figure 12. Essentially the same list would be compiled for LCH_4 applications although, because of the higher cryogenic temperature of LCH_4, the problems tend to be less severe.

NASA's plans for the near term are to conduct a more in-depth LCH_4 subsonic aircraft study; to continue testing various insulation concepts, to begin LH_2 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 LCH_4 for supersonic transports.

SUMMARY

Some general observations may be made on the basis of studies conducted to date with regard to LH_2 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 10^6 BTU still keeps LH_2 in a competitive range with Jet A fueled aircraft;

c) LH_2 aircraft are quieter;

d) LH_2 aircraft are cleaner;

e) production and distribution problems are significant.

With regard to LCH_4, 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 LH_2 or LCH_4 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.

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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

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PROPERTIES
LH_2 AND JET A

FUEL	HEAT OF COMBUSTION BTU/LB.	HEAT OF COMBUSTION BTU/GAL.	BOILING POINT °F
JET A	18,600	121,000	210
LH_2	51,600	30,400	-423

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Table I

CHARACTERISTICS OF
LH_2 AND JET A SUBSONIC TRANSPORT AIRCRAFT

RANGE, n. mi.	1,500		3,000		3,000		5,500		5,000 RADIUS	
PAYLOAD, passengers	130		200		400		400		400	
	LH_2	JET A	LH_2	JET A	LH_2	JET A	LH_2	JET A	LH_2	JET A
GROSS WEIGHT, lbs.	98,300	108,700	179,500	216,900	335,200	404,300	391,700	523,200	587,400	992,500
NO. ENGINES	2	2	4	4	4	4	4	4	4	4
THRUST/ENGINE, lbs.	17,000	18,900	15,000	15,300	24,720	25,770	28,700	32,700	39,400	49,600
SPAN, ft.	96	101	123	127	165.6	170.6	174	194.1	224	280
FUSELAGE L[illegible]GTH, ft.	140	113	173	145	210	197	219	197	254	225
FAR T.O. DIS[illegible], ft.	7,890	7,970	5,380	7,980	5,860	7,980	6,240	7,990	6,910	11,970

Table II

ECONOMIC AND ENVIRONMENTAL CHARACTERISTICS LH_2 AND JET A SUBSONIC TRANSPORT AIRCRAFT

RANGE, n. mi.	1,500		3,000		3,000		5,500		5,000 RADIUS	
PAYLOAD, passengers	130		200		400		400		400	
	LH_2	JET A	LH_2	JET A	LH_2	JET A	LH_2	JET A	LH_2	JET A
PRICE, PER AIRCRAFT, $\$10^6$	7.85	7.51	13.95	13.33	23.41	22.62	26.92	26.46	38.90	40.00
SIDELINE NOISE, EPNdB	86	86	86	86	106	107	107	108	94	93
FLYOVER NOISE, EPNdB	79	79	82	86	104	105	105	107	93	100
ENERGY UTILIZATION, BTU/seat n. mi.	1,340	1,290	1,460	1,540	1,200	1,260	1,240	1,380	1,700	2,120

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Table III

PARAMETRIC VARIATIONS - SUBSONIC TRANSPORTS

RATIO - LH_2 TO JET A AIRCRAFT

RANGE X PAYLOAD (n. mi. x passengers)	GROSS WEIGHT RATIO	SIDELINE NOISE RATIO	FLYOVER NOISE RATIO	ENERGY RATIO	PRICE RATIO
1.95×10^5	.905	1.00	1.00	1.040	1.042
6.0×10^5	.825	1.00	.95	.950	1.046
12.0×10^5	.832	.99	.99	.955	1.037
22.0×10^5	.750	.99	.98	.895	1.016
40.0×10^5	.592	1.01	.93	.788	.974

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Table IV

LH_2 SST CONCEPTS

CRUISE M= 2.7

	LOCKHEED		LANGLEY		LEWIS	
RANGE, n. mi.	4200		4138		4000	
PAYLOAD, Passengers	234		292		250	
	JET A	LH_2	JET A	LH_2	JET A	LH_2
GROSS WEIGHT, lb.	762,000	395,000	762,000	588,500	842,000	504,000
ENERGY UTILIZATION, BTU/Pass. n. mi.	6189	4483	4340	4234	6120	5260
			RATIO LH_2/JET A			
GROSS WEIGHT RATIO	.518		.770		.597	
ENERGY UTILIZATION RATIO	.725		.975		.859	

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Table V

LH_2 SST CONCEPTS (CONTINUED)

CRUISE M=2.7

	LOCKHEED		LANGLEY	
	JET A	LH_2	JET A	LH_2
GROSS WEIGHT, lbs.	762,000	395,000	762,000	588,500
BLOCK FUEL, lbs.	330,600	85,400	290,500	101,100
ENGINE	DHTF	DHTF	TURBOJET	TURBOJET
THRUST/ENGINE, lbs.	86,900	52,800	77,600	74,600
SIDELINE NOISE, EPNdB	108.0	104.0	113.1	109.3
FLYOVER NOISE, EPNdB	108.0	102.2	106.9	91.4
L/D CRUISE	8.65	7.42	8.57	8.03
SONIC BOOM CRUISE, lbs/ft^2	1.6	1.2	2.4	1.8

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Table VI

IMPACTS ON AIRCRAFT DESIGN

	JET A	LCH_4	LH_2
ENERGY PER UNIT WEIGHT	1	1.16	2.77
FUEL TANK RELATIVE VOLUME	1	1.62	3.96
EXHAUST PRODUCTS	$NO_x + CO + CO_2 + H_2O + C_xH_y$	SAME AS JET A, DIFFERENT HYDRO-CARBONS	H_2O, SOME NO_x
TEMPERATURE EFFECTS ON LIQUEFACTION		CO AND WATER VAPOR CAN LIQUIFY ON TANK WALLS	O_2 AND N_2 CAN ALSO LIQUIFY
CONDUCTIVITY EFFECTS		LOW CONDUCTIVITY (.18 OF H_2) POTENTIAL FOR GASEOUS INSULATION	

Table VII

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SOME AVIATION ENERGY ALTERNATIVES

	$\frac{E_{IN}}{E_{OUT}}$	$\frac{\$^*}{10^6\ BTU}$
COAL + WATER ⟶ SYNTHETIC JP	1.6-1.9	5.50
COAL + WATER ⟶ LH_2	2.1	6.80
WATER + ELECTRICITY ⟶ LH_2	4.3	16.00
COAL + WATER ⟶ LCH_4	1.6	4.20

* $20/TON COAL

Table VIII

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SYNTHETIC AVIATION FUELS PROPERTIES

FUEL	HEAT OF COMBUSTION BTU/LB	HEAT OF COMBUSTION BTU/GAL	BOILING POINT °F
JET-A	18,600	121,000	210
LCH_4	21,500	74,500	-259
LH_2	51,600	30,400	-423

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4-19-77

Table IX

LEWIS SUPERSONIC AIRCRAFT STUDY

	JET A	LH_2	LCH_4
RANGE, n. mi.	4000	4000	4000
PAYLOAD, passengers	250	250	250
GROSS WEIGHT, lbs.	842000	504000	765000
BLOCK FUEL, lbs.	331000	100000	252000
ENGINE	DBTF	DBTF	DBTF
SPAN, ft.	156	120	148
FUSELAGE LENGTH, ft.	322	358	319
SIDELINE NOISE, EPNdB (NO SUPPRESSORS)	110.0	108.4	109.7
ENERGY UTILIZATION, BTU/passenger n. mi.	6120	5260	5450
L/D CRUISE	9.9	7.5	9.3

Table X

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4-7-77

EARLY LH_2 AIRCRAFT CONCEPTS
(CIRCA 1955)

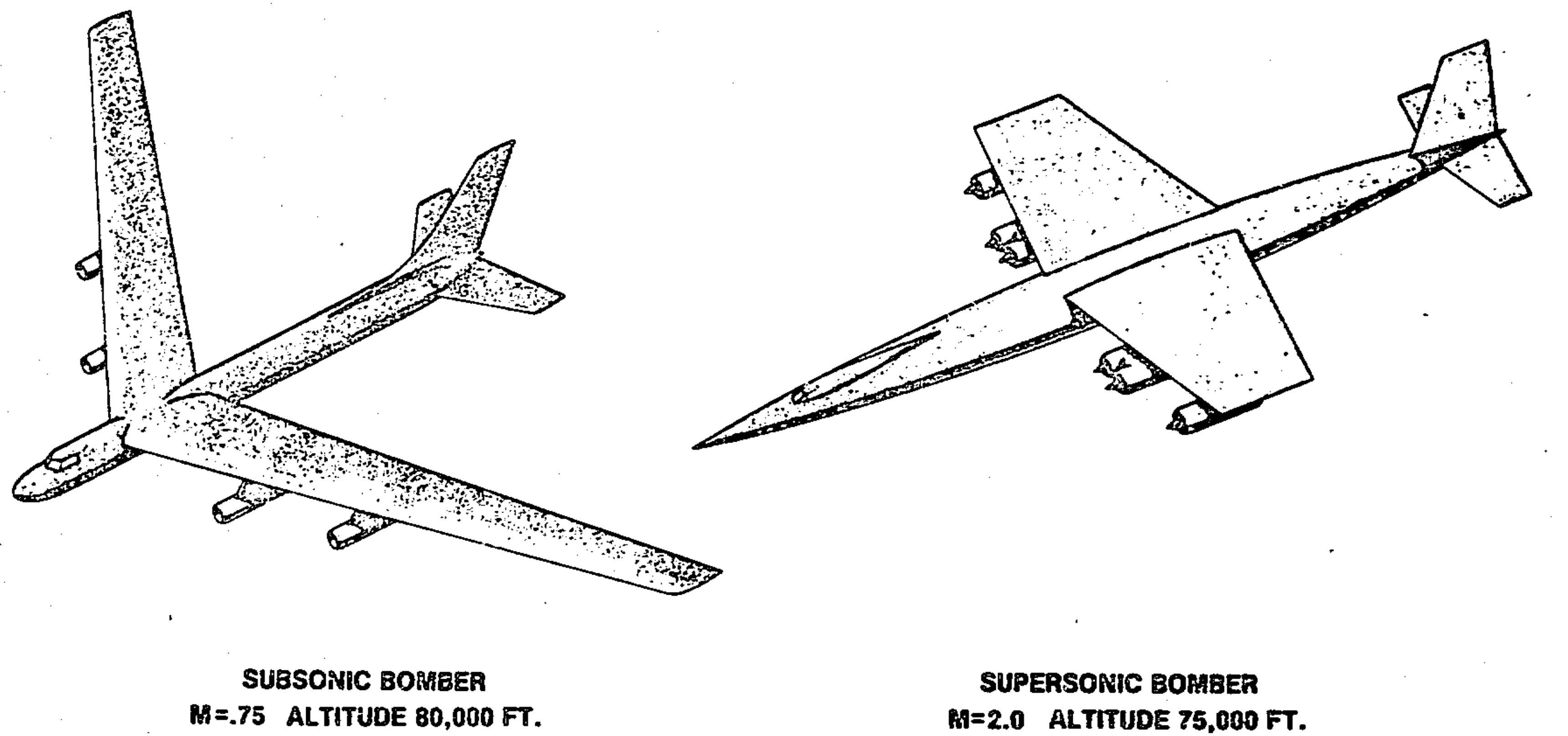

Figure 1

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

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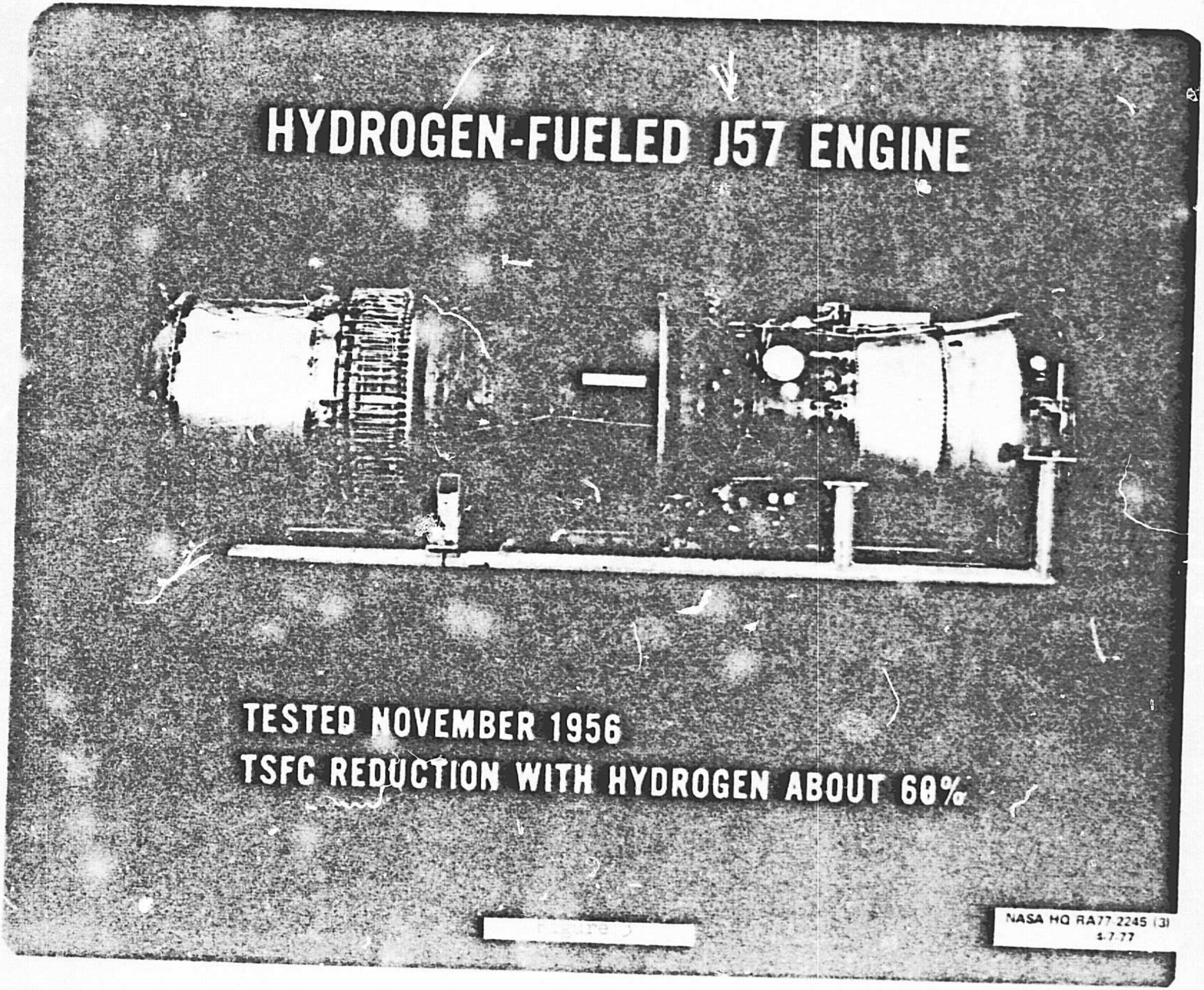
4-7-77

Figure 2


HYDROGEN-FUELED J57 ENGINE
TESTED NOVEMBER 1956
TSFC REDUCTION WITH HYDROGEN ABOUT 60%
NASA HQ RA77-2245 (3)

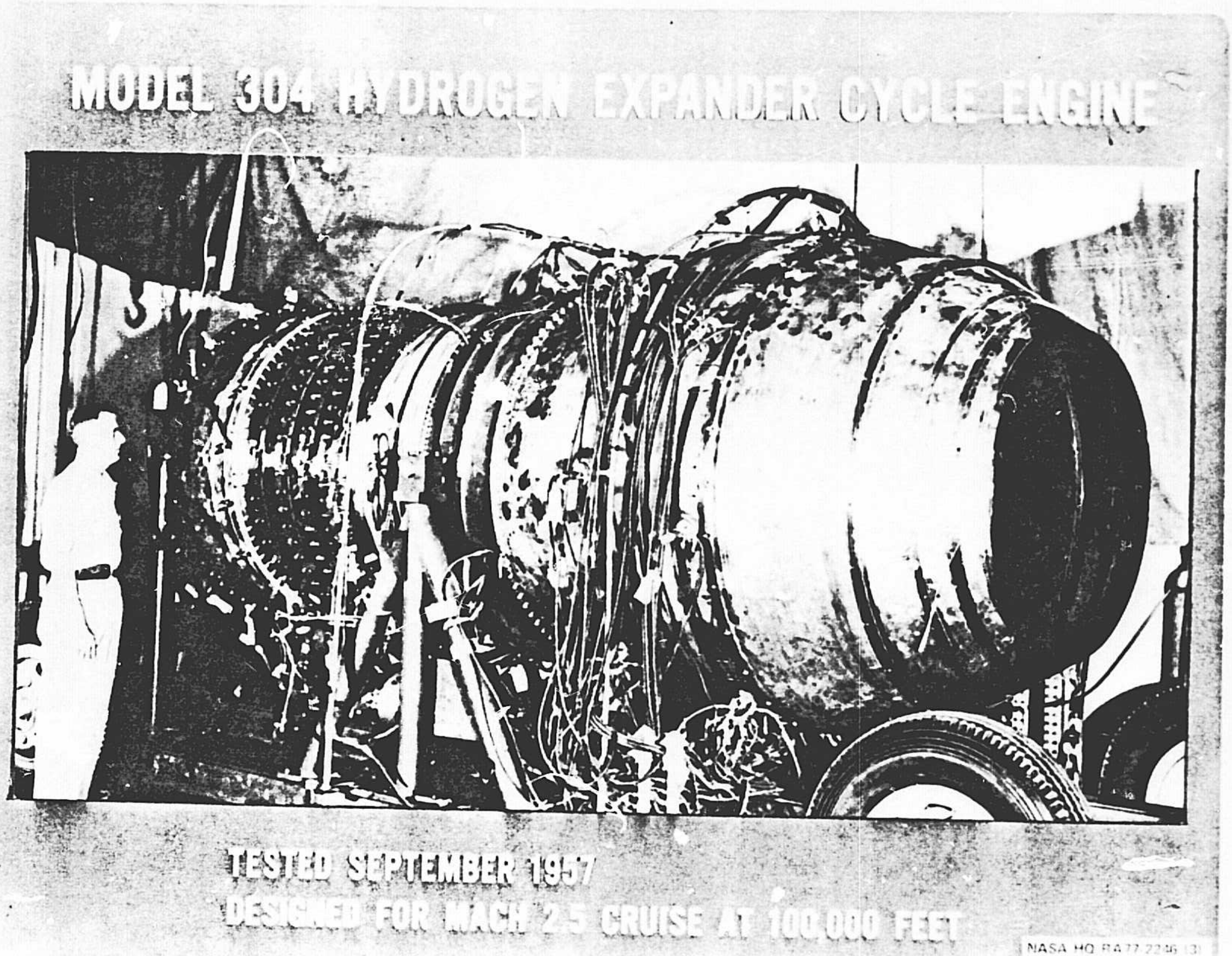
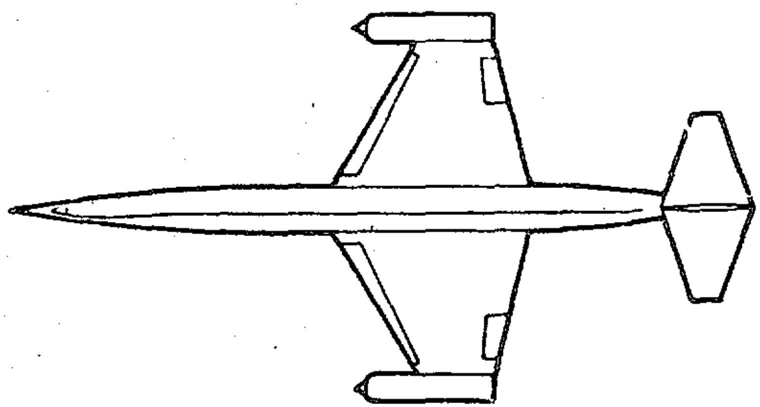

MODEL 304 HYDROGEN EXPANDER CYCLE ENGINE
TESTED SEPTEMBER 1957
DESIGNED FOR MACH 2.5 CRUISE AT 100,000 FEET
NASA HQ RA77-2246 (3)
4-7-77

Figure 4

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

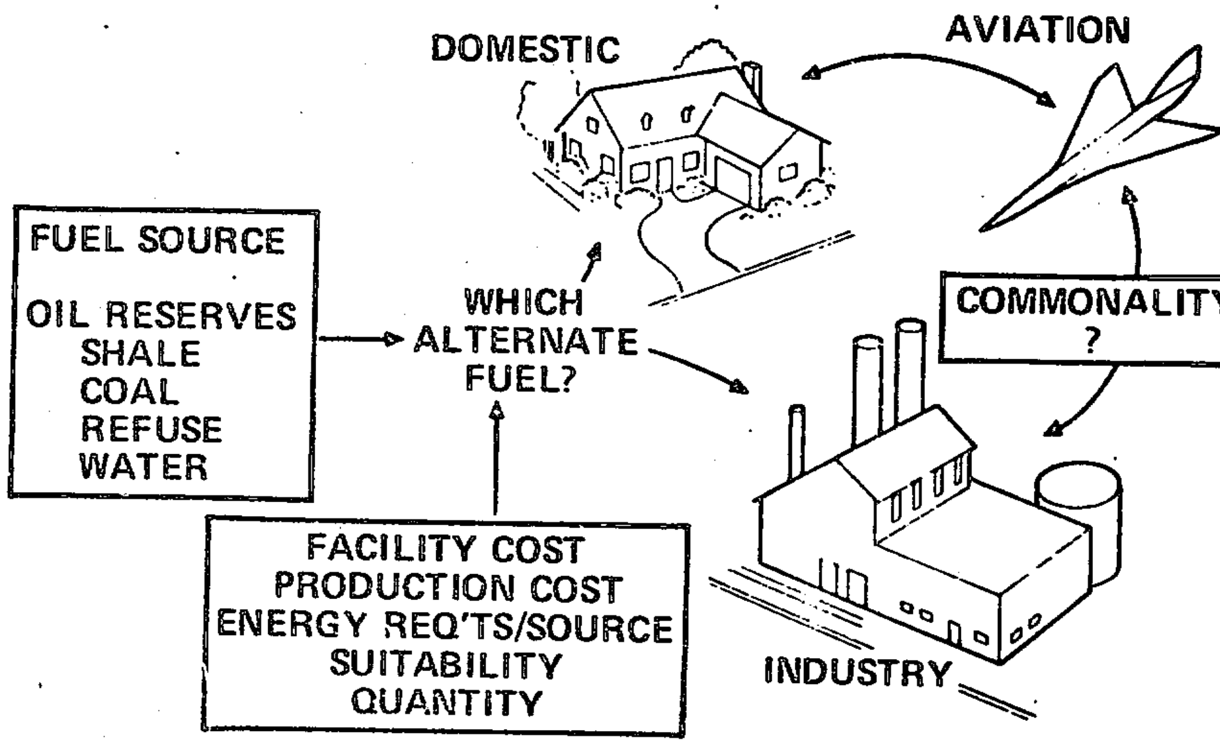
REASONS FOR TERMINATION

- OPERATIONAL REQUIREMENTS UNATTAINABLE
- INADEQUATE LH_2 LOGISTICS FACILITIES

NASA HQ RA77-2242 (1)
4-7-77

Figure 5

ALTERNATE FUEL CONSIDERATIONS



NASA HQ RA77-2241 (1)
4-7-77

Figure 6

CRYOGENICALLY FUELED AIRCRAFT TECHNOLOGY PROGRAM

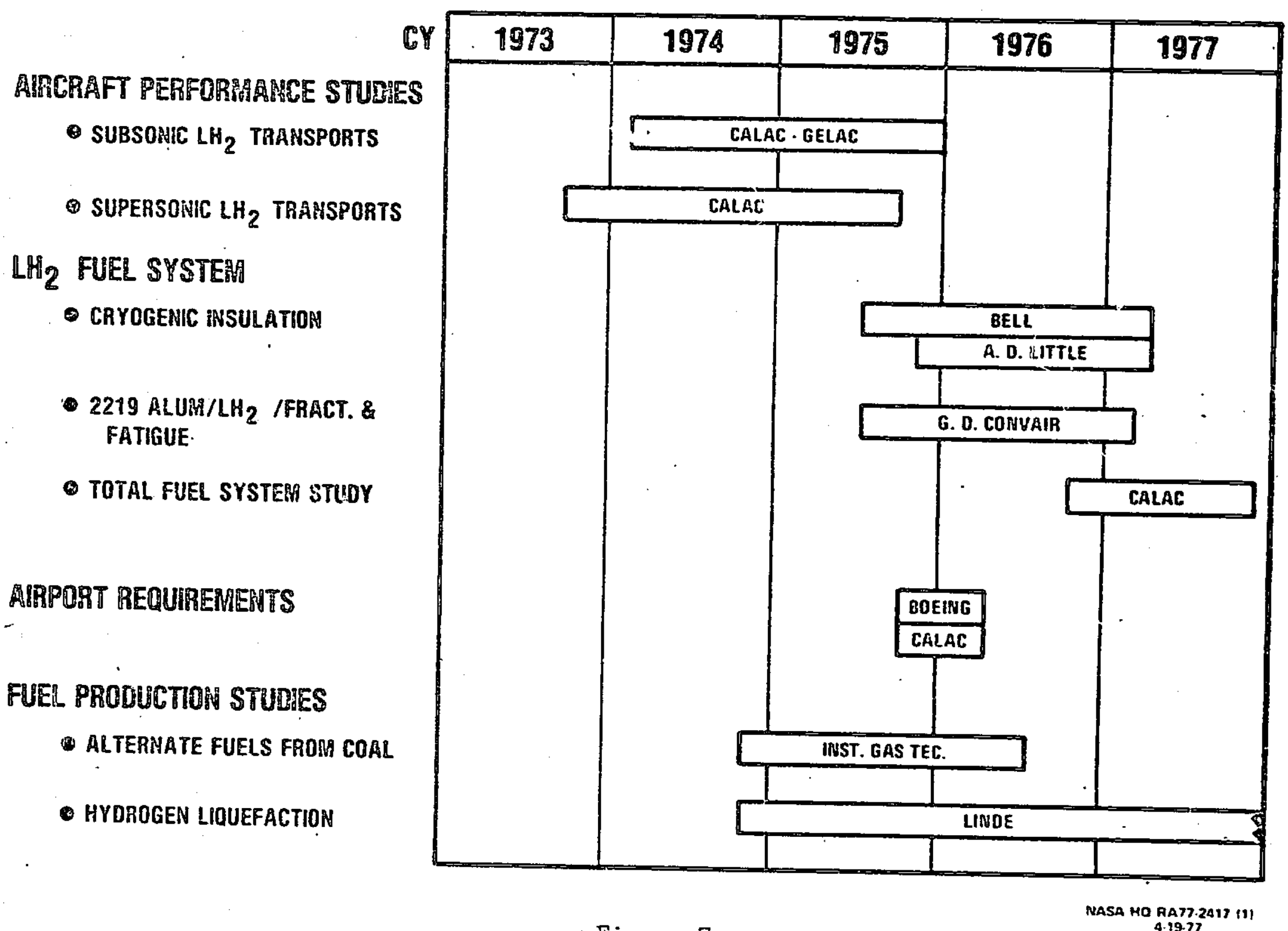
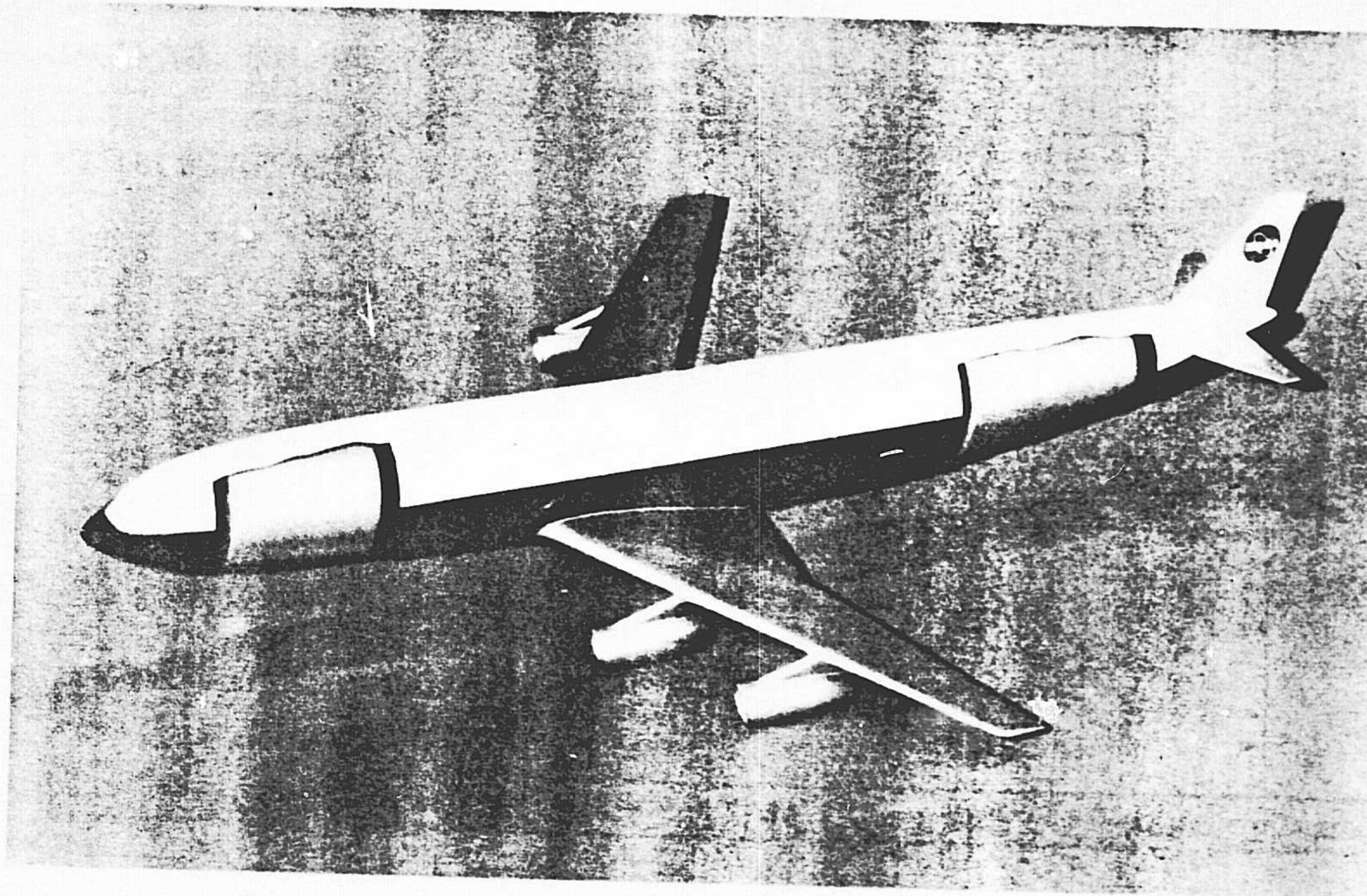


Figure 7

INTERNAL TANK SUBSONIC TRANSPORT MODEL



NASA HQ RA77-2243 (3)
4-7-77

Figure 6

EXTERNAL TANK SUBSONIC TRANSPORT MODEL

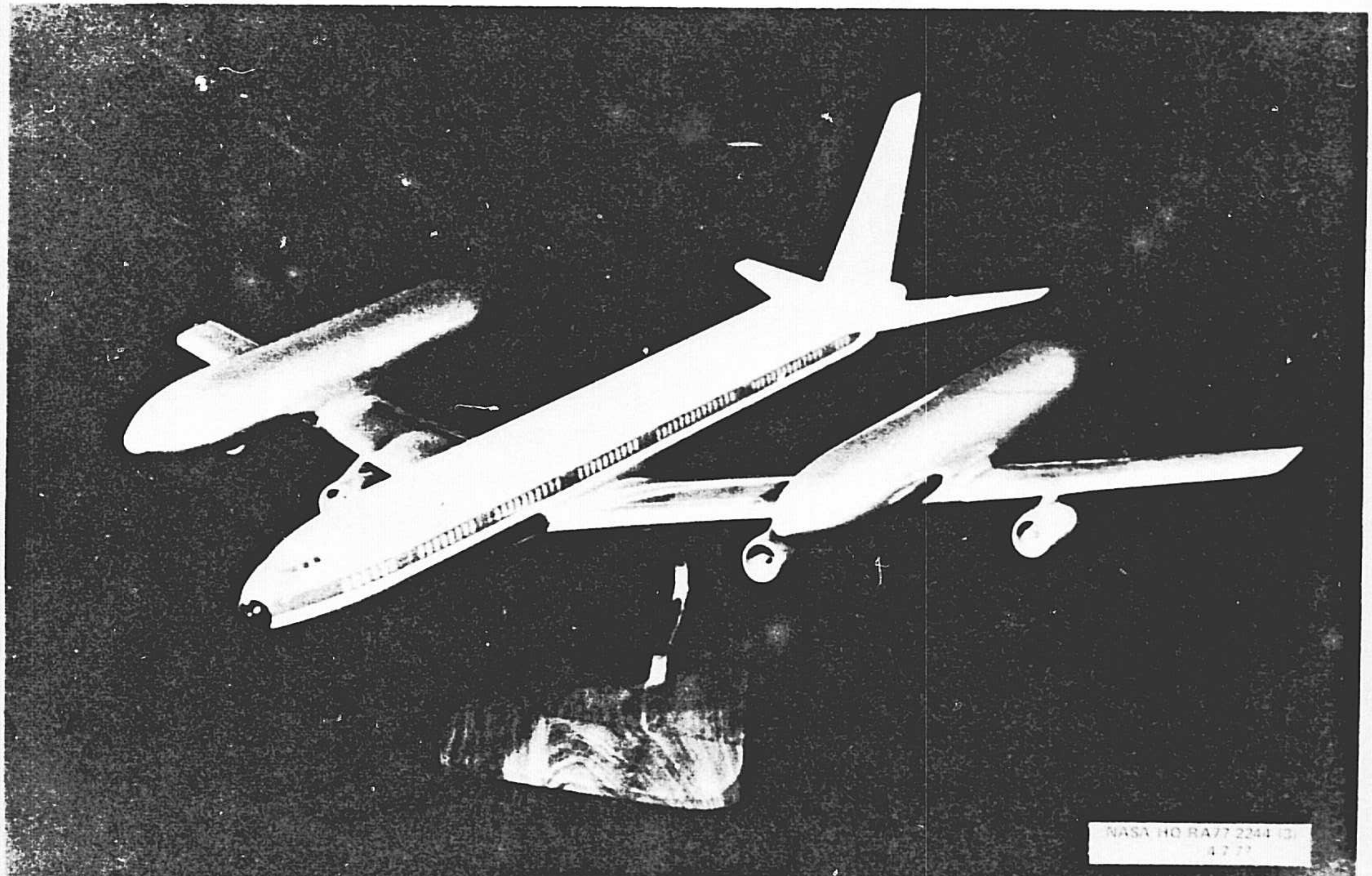
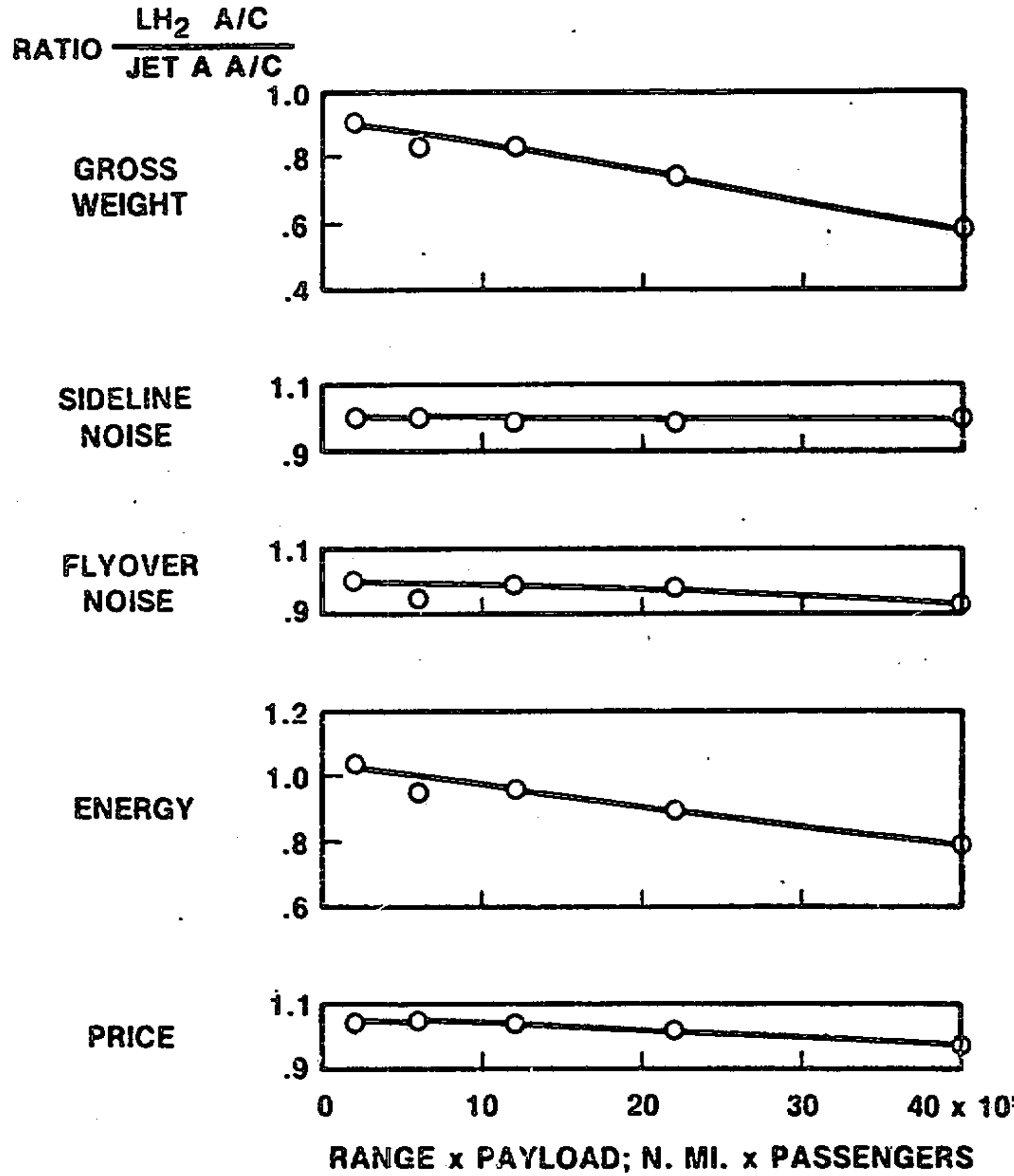


Figure 9

PARAMETRIC VARIATIONS - LH_2 AND JET A SUBSONIC TRANSPORTS



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4-19-77

Figure 10

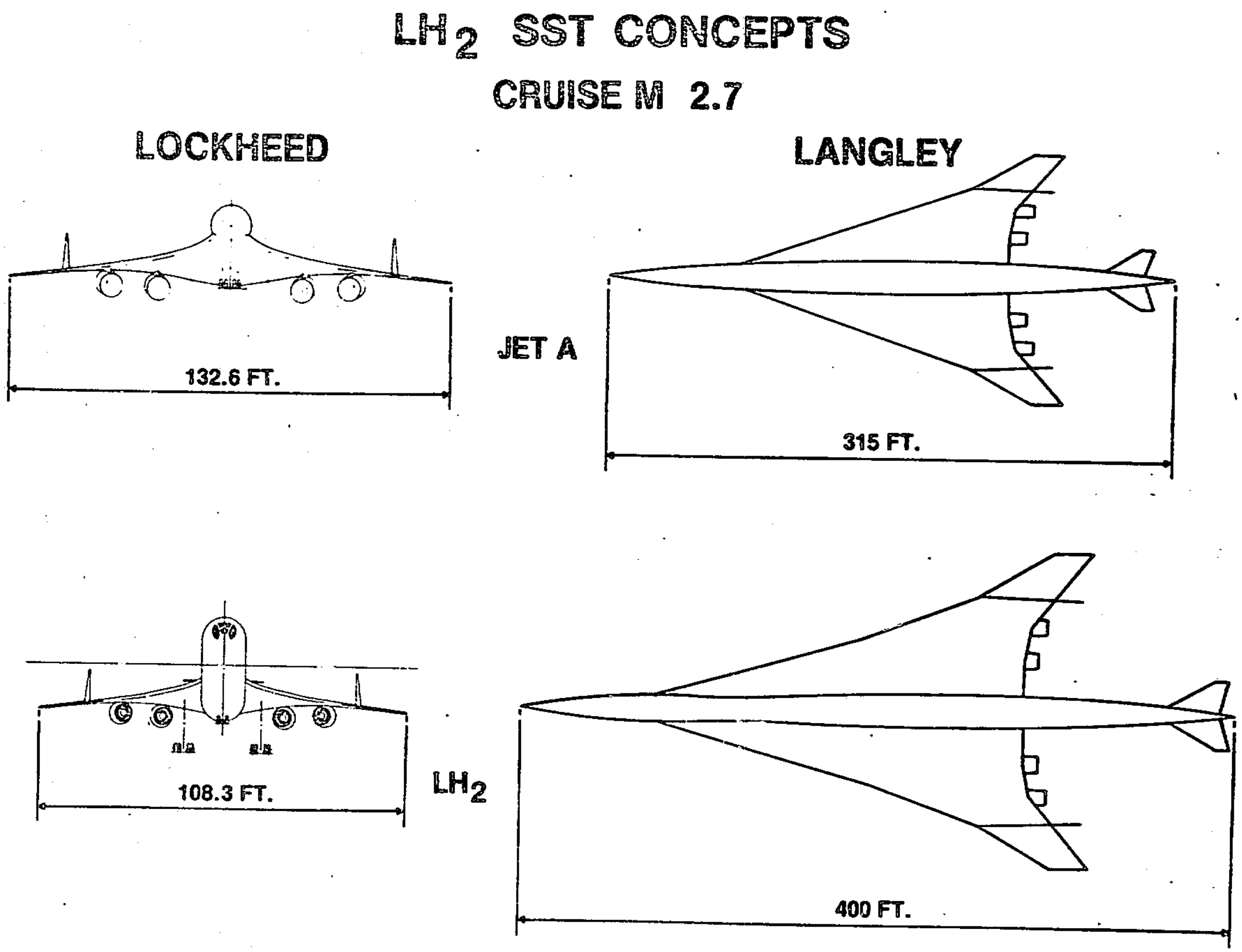

Figure 11

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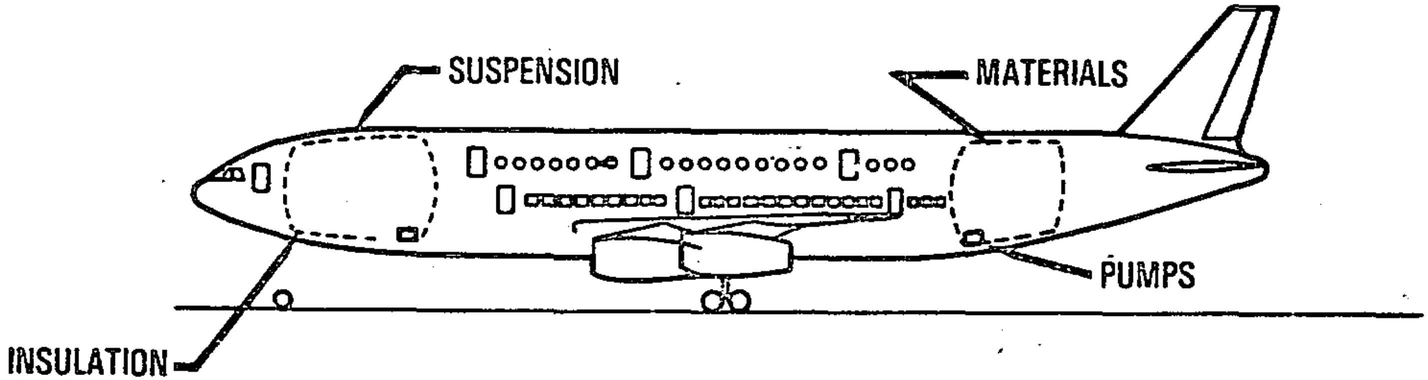
4-19-77

LIQUID HYDROGEN FUELED TRANSPORT AIRCRAFT TECHNOLOGY



- FUEL SYSTEM
  - LONG-LIFE INSULATION
  - THERMAL FRACTURE CONTROL
  - LIGHTWEIGHT PURGE SYSTEM
  - LOW THERMAL-CONDUCTIVITY TANK SUSPENSION
  - LONG-LIFE PUMPS, VALVES, CONTROLS, ETC.
- SAFETY—GROUND, FLIGHT, CRASH ENVIRONMENTS
  - LEAKS
  - SPILLS
  - FIRES

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1-21-76

Figure 12

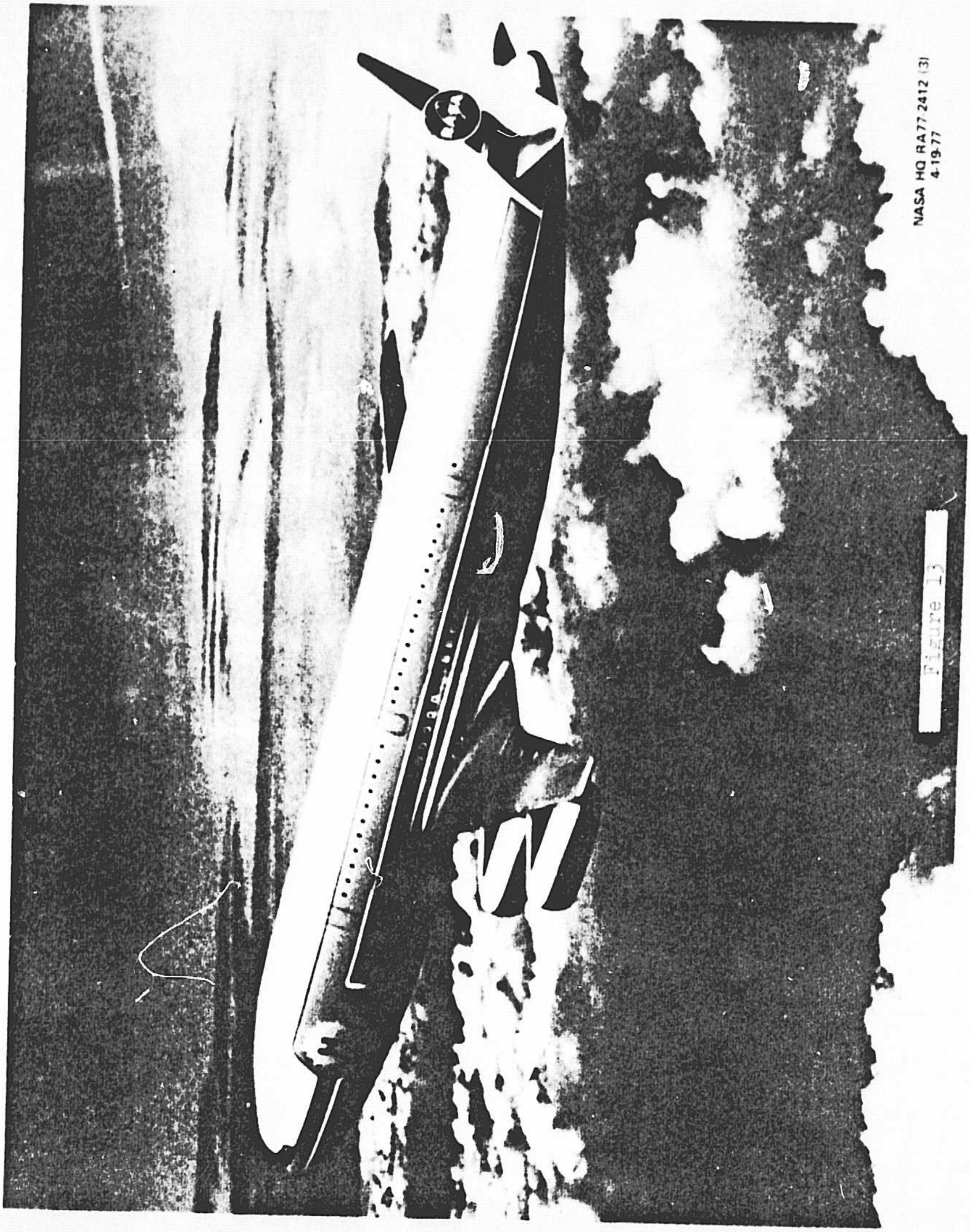

Figure 13

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