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A FUEL CONSERVATION STUDY FOR TRANSPORT AIRCRAFT UTILIZING ADVANCED TECHNOLOGY AND HYDROGEN FUEL

by the

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FOREWORD

The work described herein was conducted by the Hampton Technical Center of LTV Aerospace Corporation, under NASA Project Manager, Mr. W. J. Alford, Jr., and Technical Coordinator, Mr. J. D. Pride, Jr., Advanced Transport Technology Office, NASA Langley Research Center. The report was prepared by W. Berry, R. Calleson, J. Espil, C. Quartero, and E. Swanson under the direction of R. R. Lynch, the Hampton Technical Center Advanced Aircraft Technology Manager.

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SUMMARY

The increasing concern regarding the projected depletion of our fossil fuel supply has prompted requests for investigating major uses and methods of conservation. One of the major uses selected for investigation was commercial aviation, which is predicted to double in operation over the next decade.

This study was directed towards present and future, conventional and advanced technology aircraft. Four categories of aircraft were selected for investigation, 1) conventional, medium range, low take-off gross weight, 2) conventional, long range, high take-off gross weight, 3) large take-off gross weight aircraft that might find future applications using both conventional and advanced technology, and 4) advanced technology aircraft of the future powered with liquid hydrogen fuel.

Baseline parameters were established for existing transcontinental range low take-off weight commercial aircraft. These aircraft were then modified to incorporate advanced transport technologies: supercritical wing, composite materials, and active control systems. This reduced the structural weight of the candidate aircraft, subsequently reducing the wing area, aircraft size and power requirements. The result was an eight percent lower fuel requirement.

A similar analysis was made on a conventional, higher take-off gross weight, long range aircraft (Boeing 747), utilizing advanced technology. This resulted in a 22 percent reduction in fuel requirement when compared to the same payload/range mission.

Studies were then directed toward the gross weight category of aircraft anticipated for the next generation of transports. Based on the rationale that historically aircraft double in payload approximately every decade, a 1.5 million pound take-off gross weight aircraft was selected as representative. This aircraft was synthesized using conventional fuels for both current and advanced technology construction. The evaluation showed a significant weight reduction for utilizing advanced technology concepts with a resultant 25 percent fuel savings.

The final iteration investigated the use of hydrogen fuel to power an advanced technology aircraft. The same payload/range mission as the 1.5 million pound conventional construction, JP-4 fueled, aircraft was used for comparison purposes. The comparison showed that an advanced technology, liquid hydrogen powered aircraft was capable of performing the same payload/range mission, but weighing approximately 50 percent less than the current technology aircraft using JP-4 fuel. The advanced technologies reduced the liquid hydrogen fuel consumption by 18 percent. In addition, as a result of the burning efficiency of liquid hydrogen, coupled with resizing of the advanced technology aircraft to utilize the benefits of

reduction in fuel requirements, the liquid hydrogen fueled aircraft (see Table I, - 6 A/C) can perform the mission of its current technology fossil fueled counterpart (Table I, - 4 A/C) at a net fuel weight reduction, relative to JP-4 fuel, of 82 percent.

Incorporating advanced technologies into conventionally designed aircraft indicates there would be a significant reduction in fuel requirements for the same mission. The use of hydrogen fuel shows marked promise as a replacement for fossil fuel for future transports.

INTRODUCTION

There is increasing concern about the depletion of the nation's fossil fuel supply. This study assesses the use of advanced aeronautical technologies as a means of more efficiently using fossil fuels to power transport aircraft and the use of hydrogen fuel as an alternate source of power for large transport aircraft.

Recognizing the importance of conserving the nation's earth resources, and the part that the long-range airplane plays in world commerce, NASA is studying the application of advanced technologies to future long-range aircraft to assure that designs will be fully responsive to national needs. This Advanced Transport Technology Program consists of a broad evaluation of the benefits of technology advances in aerodynamics, propulsion, structures, controls and avionics. This report describes an integrated advanced transport technology Liquid Hydrogen fueled aircraft study to support national needs, performed under the direction of the Advanced Transport Technology Office, Langley Research Center.

Commercial aviation, like automotive transportation, is a major user of fossil fuels. A 747 size aircraft carries more than 50,000 gallons of fuel. It uses about 30,000 pounds or 5000 gallons of fuel per hour. At a cruise speed of 500 miles per hour, this is using approximately 100 gallons of fuel per minute, or enough fuel to run a loaded passenger car half way across the country. This is an area where small increments of fuel economy will conserve large quantities of fuel.

The purpose of this report is to determine the potential fossil and/or hydrogen fuel savings attainable through the incorporation of advanced technologies. The advanced technologies such as supercritical wing, active control systems, and composite materials, currently being investigated for future commercial transports, will allow aircraft to fly farther, faster and quieter than their present day counterparts without increases in fuel consumption. These technologies, when incorporated into current generation aircraft, have promise for significant reductions in fuel consumption, holding the other variables constant.

SYMBOLS

ATT	Advanced Transport Technology
c	Specific Fuel Consumption
D	Drag
JP-4	Jet Engine Fossil Fuel
L	Lift
LH_2	Liquid Hydrogen
R	Range
SFC	Specific Fuel Consumption
TOGW	Take-off Gross Weight
V	Velocity
w_o	Initial Weight
w_1	Final Weight

ANALYSIS

GENERAL CONSIDERATIONS

In order to select the size aircraft to be investigated, it was necessary to establish certain baseline parameters that would be held constant. For purposes of this study, the constants were mission, payload and range. To provide a meaningful comparison, two payload/range category aircraft were considered for selection. The payload/ranges considered were 1) low TOGW, medium range, and 2) long range high TOGW.

Aircraft Sizing

A series of parametric weight evaluations were conducted in order to properly size and select an airplane capable of performing a given mission with a fixed payload and range. This entailed investigating aircraft of various design gross weights. For each design gross weight, there is a corresponding amount of fuel available (fuel fraction). At one end of the spectrum, the aircraft are incapable of performing the mission because they are too small to carry an adequate fuel supply. At the other end of the spectrum, the aircraft are too large, contain more fuel than necessary, and, therefore, are inefficient. However, within the matrix there exist aircraft of the proper size; i.e., the design gross weight is sufficient to contain the desired payload, the airframe capable of supporting and flying at that gross weight, and an adequate amount of fuel to meet the range requirements. This is the optimally sized aircraft for a given mission, the gross weight, the operating weight, and the fuel quantity are all matched.

The optimized aircraft was selected by Mission Analysis based on the Brequet Range Equation: $R = (L/D)(V/c)\log_{10} w_0/w_1$. The Brequet equation was used in that it is applicable to all sizes aircraft.

Fuel Comparison

The baseline aircraft selected for comparison purposes was the Boeing 727, 737 and the McDonnell-Douglas DC-9 for medium range, 3000 nautical miles, and the Boeing 747 for long range, 5000 nautical miles. The fuel consumption was based on the assumption that LH_2 provides 2 1/2 times as much energy per pound of fuel as conventional JP-4 fuel (Reference 1). An additional assumption was made that an LH_2 engine would operate at the same efficiency as a JP-4 fuel burning engine. For purposes of this study, the Pratt and Whitney JT9D-3A engine with a SFC of 0.721 pounds/hour/pound of thrust was selected as the JP-4 fueled engine. The mission/range selected was that of the 747 which was 5000 nautical miles with an approximate block to block time of 10 hours. A tank pressure requirement of 5 psi over all altitude ranges was provided by NASA to perform this study. After the parametric sizing, the mission fuel requirements of the selected aircraft were compared with those of the baseline airplane to determine the amount of fuel savings attained.

Advanced Technology Concepts

In the first part of the study, advanced technology concepts were incorporated into the current technology aircraft. The concepts included aerodynamic technology consisting of supercritical airfoil wing with active flight control system and the use of composite materials in lieu of aluminum for the aircraft structure. Incorporation of these features resulted in a reduction in aircraft weight.

Since the wing and power plant loadings were held constant, the lower gross weight allowed a reduction in the engine size, wing area, and tail areas resulting in a smaller aircraft. Incorporating advanced concepts and continued iteration resulted in a reduction in both size and operating weight of an advanced technology aircraft.

FUEL CONSERVATION

Conventional-Medium Range Aircraft

For the smaller, present day aircraft, including the 727-200, 737-100, and DC9-40, the introduction of advanced technologies was limited to the composite material supercritical wing with active control system. Due to the limited application of advanced technologies and shorter range requirements, the fuel savings, 8 to 9 percent, are less than for the larger long range aircraft.

Conventional-Long Range Aircraft

The 747 was selected as a current technology long range aircraft for comparison purpose. The 747 baseline aircraft was designated Dash one (-1) and the resized advanced technology 747 Dash two (-2) in the comparative summary Table I. Utilizing full application of advanced technologies resulted in a reduced size and operating weight of the advanced technology aircraft. This reduced size resulted in a 22.5 percent reduction in the fuel requirements for an advanced technology 747 aircraft over a conventional 747 for the same payload/range mission.

Larger-Fossil Fuel Aircraft

The historical growth trend for aircraft is to approximately double in gross weight every 10 to 11 years. Based on this trend, growth versions of the 747 with a 265,000 pound design payload were evaluated. For purposes of this study, it was considered as a pure cargo freighter with fore and aft cargo doors and two cargo floors. The Dash three and Dash four (-3, -4) models designate the aircraft selections for this part of the study. The -3 baseline is of conventional aluminum construction while the -4 is cycled with full application of the advanced technologies.

The result of this study established the baseline aircraft, -3, as a 1.5 million pound TOGW aircraft. This configuration has a wing area of

11,619.7 ft^2, wing span of 284.4 ft., with an overall length of 370.6 ft., and required 750,000 pounds of JP-4 fuel for the 5000 mile mission. The Dash three (-3) configuration is shown in Figure 1. The (-3) cycled with full application of advanced technologies using the same length (370.6 ft.) and payload (265,000 pounds) results in the Dash 4 aircraft with a TOGW of 1,130,000 pounds, a wing area of 8753.8 ft^2, wing span of 246.8 ft., and required 565,000 pounds of JP-4 fuel for the same 5000 mile mission; a fuel savings of 185,000 pounds or 24.6 percent

Liquid Hydrogen Fueled Aircraft

The fuel conservation study culminated with two hydrogen fueled aircraft designated Dash 5 and Dash 6. The -5 represents the conventional aluminum construction while the -6 is the cycled advanced technology airplane. These aircraft differ from the -3 and -4 configurations primarily in the fuselage size and the fuel system. Because of low volumetric efficiency, thickness of required insulating material and other thermal and safety consideration, all hydrogen fuel was carried within the confines of the fuselage. This resulted in a large volume requirement to accomodate the tank system. In addition, the loss of the wing bending relief benefits due to fuel weight causes an increase in wing structural weight. It also becomes necessary to treat the fuel as cargo or dead weight; therefore, increased weight allowances are necessary for the fuselage, wing, and landing gear. Structural allowances were provided for supporting and restraining the tank system under crash load conditions, as well as weight allocation for the complex tank, plumbing and insulation system.

A preliminary design was initiated for this configuration prior to the weight analysis. It was assumed that the LH_2 would be carried in separate insulated cylindrical tanks in the upper portion of the fuselage. A structural analysis of this concept is contained in the Appendix.

Based on an assumed fuel volume requirement of 50,000 cubic feet (220,000 pounds) and 300,000 pounds of cargo, a 375 foot overall length fuselage was required. This configuration was estimated to have a TOGW of 1,000,000 to 1,200,000 pounds.

Substituting the 265,000 pound payload used in the previous runs, the TOGW was reduced to 915,000 pounds, which reduced the wing area and wing span to 7088 square feet and 222.7 feet, respectively. This configuration, -5, required 157,000 pounds of LH_2 to meet the 5000 mile mission constraints and is shown in Figure 2.

When the advanced technologies were applied to the -5 configuration, the TOGW was lowered to 753,000 pounds, wing area to 5833.1 ft^2, wing span to 201.5 feet, while overall length of 375 feet, cargo weight of 265,000 pounds, and fuel weight of 157,000 pounds were retained as above.

Since the amount of LH_2 required was considerably less than estimated, an effort to shorten the overall length was initiated. It was determined that the fuel and payload volume requirements could be satisfied with a

325 foot long fuselage using several combinations of fuel and cargo containers, Figures 6, 7 and 8. A configuration with a typical fuselage arrangement is shown in Figure 5. The wing and tail geometrics are the same as the Dash 5 shown in Figure 2.

A preliminary configuration for 3000 nautical miles range airplane, arranged internally according to Figure 6, with a fuselage overall length of 325 feet, is shown in Figure 9. Ten LH_2 tanks with a diameter of 10 feet carries 66,000 pounds of fuel. Two rows of 8 ft. x 8 ft. cargo containers result in 281,600 pounds of cargo plus 100,000 pounds of bulk cargo. Another peliminary configuration was based on fuselage cross-section of Figure 7 using three rows of cargo containers. This configuration has an overall length of 367 feet and has a cargo capacity of 500,000 pounds, plus additional bulk cargo for the same range mission. The 144,000 pounds of LH_2 fuel will be stored in twenty-two 10 foot diameter tanks. Figure 10 depicts this configuration.

CONCLUSIONS

All study aircraft incorporating advanced technology indicate significant reductions in fuel requirements over the conventional baseline aircraft with either of the fuels investigated. The fuel savings derived from the application of advanced technologies to current commercial transports is sufficiently great (eight to nine percent) to merit serious consideration. Future aircraft with higher design gross weights, in the range of 1.5 million pounds, can benefit from even greater fuel savings of approximately 24.6 percent. However, the extremely low density of LH_2 fuel, 4.4 pounds per cubic feet, dictates carrying most of the fuel in the fuselage in the area that normally would be available cargo space for a conventional JP-4 fueled airplane. The result is that the flexibility of the LH_2 aircraft is compromised in that the benefit of off-loading fuel for cargo on varied range operations does not appear to be obtainable at this time and further study will be required. For example, the current B-747F which carries 130,000 pounds of cargo for approximately 5000 nautical miles, can carry 270,000 pounds of cargo for 3000 nautical miles.

The fuselage length to wing span ratio for the study aircraft reviewed is 1.3 compared to 1.15 for the B-747. Resizing and refinement of design should reduce this difference to same extent. For the LH_2 fueled aircraft, the fuselage to wing span ratio varies from 1.46 to 1.68. Because of fuselage fuel volume requirements for LH_2, this ratio cannot be reduced to a great degree without reducing the range. The impact of fuselage length to wing span ratio is not readily known, therefore, further study in this area would be required.

The aircraft inertia about all axes for these large aircraft are much higher than those of conventional aircraft. However, for this preliminary study the control requirements to meet standard maneuver rates and their effect on control surface sizes was based on current technology and assumed to be scaleable. Also, the aeroelastic interface between fuselage and wing/empennage is unknown for this size aircraft. More study is required in these areas.

Further detailed investigation into the venting and inerting requirements of LH_2 fuel as well as the insulating and structural mounting of the fuel tanks will be required.

Despite some apparent penalties, this preliminary LH_2 study clearly indicates that the hydrogen fueled aircraft can perform, at reduced size and gross weight, the same payload/range mission as conventionally fueled airplanes with a significantly lower fuel fraction. A comparative summary table for the selected aircraft in the study is presented in Table I. The General Dynamics ATT aircraft, Reference 2, are included for comparison purposes.

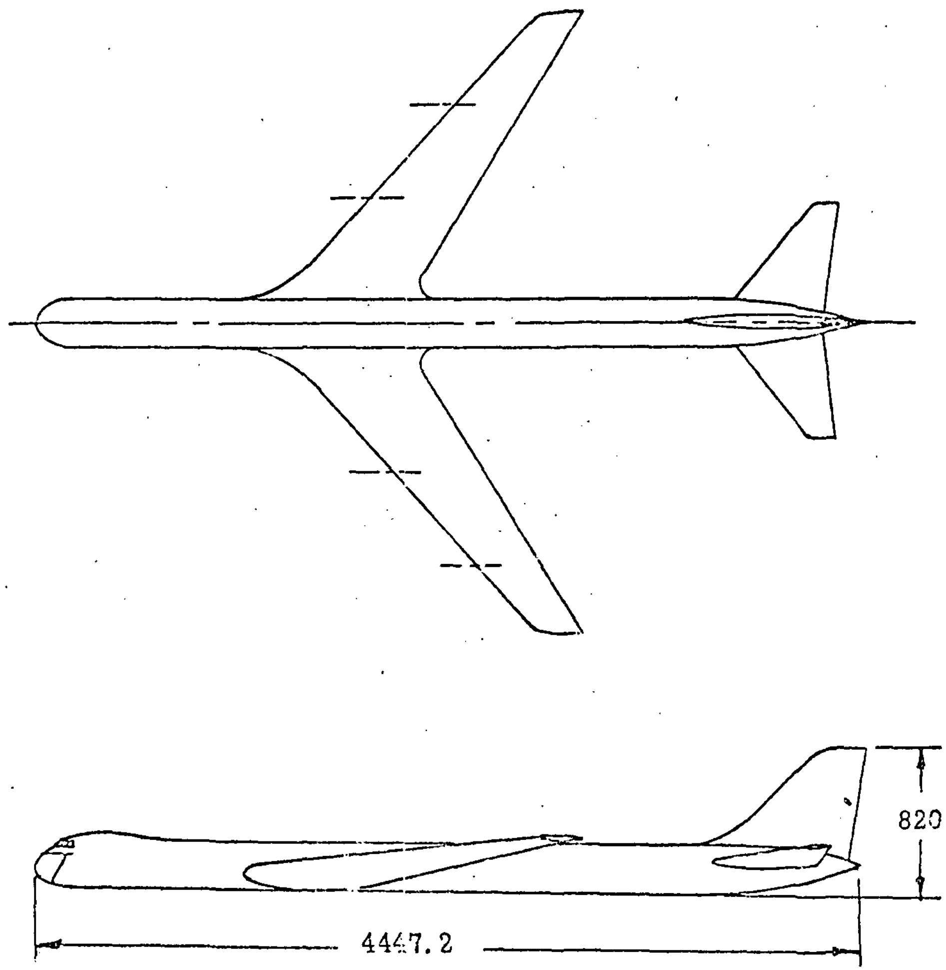
The full application of advanced technology yields greater fuel savings than just partial applications to the wing. However, the wing incorporating supercritical aerodynamics, composite materials, and active controls shows good potential for retrofit applications.

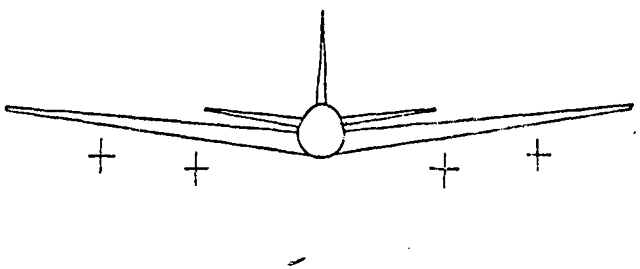
Hydrogen fueled aircraft have the distinct advantage of performing the same mission with lower gross weight and greatly reduced fuel weight consumption. Since hydrogen is not a fossil fuel, an operating fleet of hydrogen fueled aircraft would represent a tremendous conservation of fossil fuels. Additionally, the hydrogen combustion process would solve most of the emission problems inherent with fossil fuels.

The promise of the LH_2 aircraft is evident. However, further investigation is required in engine sizing, terminal compatibility, landing gear integration, LH_2 tankage and handling technology, and the aerodynamic and aeroelastic requirements for these aircraft to more accurately assess the total integrated system feasibility.

DASH 3 TOGW 1,500.000 lbs.

GEOMETRY	WING	HORIZ	VERT
AREA S FT^2	11619.7	3105.6	1753.5
SPAN b FT	284.4	106.0	46.8
ASPECT RATIO	6.96	3.62	1.25
TAPER RATIO	.322	.250	.340
SWEEP Λ DEG	37.5	37.5	45.0
ROOT CHORD IN	741.8	562.4	682.0
TIP CHORD IN	239.8	140.6	232.0
MAC $\bar{C}$ IN	528.3	389.7	489.0
ROOT T/C %	15.8	—	—
TIP T/C %	7.8	—	—
DIHEDRAL DEG	7.0	7.0	—



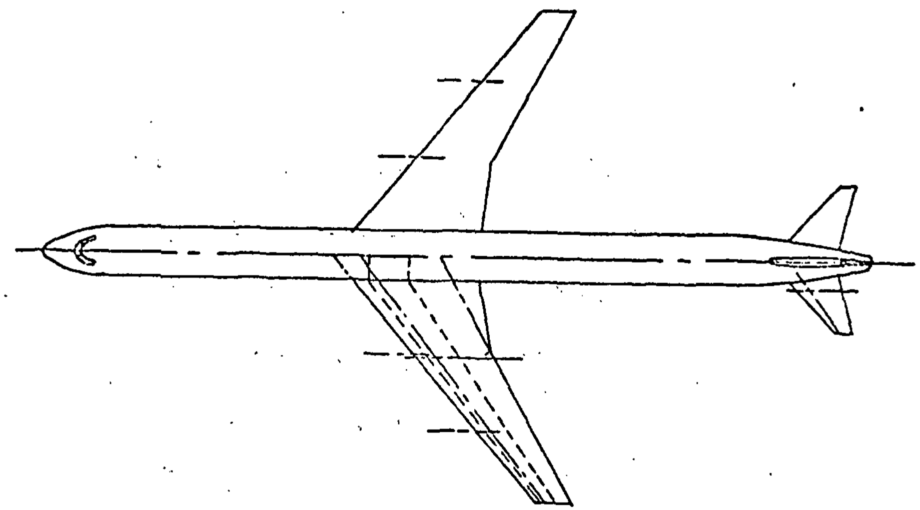


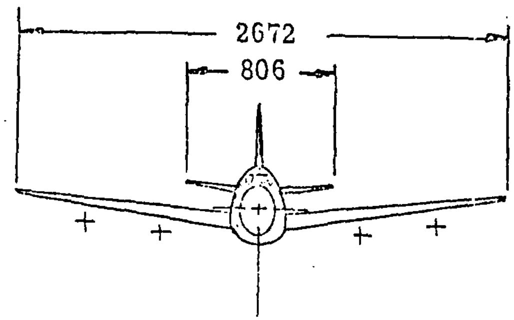
LARGE FOSSIL FUEL STUDY AIRCRAFT
CONVENTIONAL CONSTRUCTION

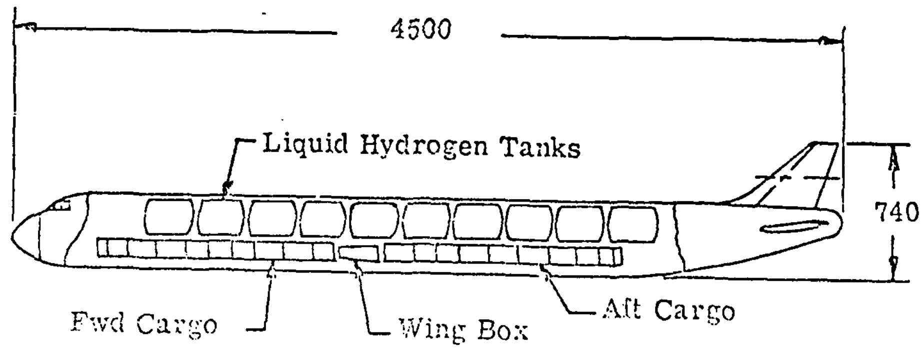
FIGURE 1

DASH 5 TOGW 915,000 lbs.

GEOMETRY	WING	HORIZ	VERT
AREA S FT^2	7088.0	1255.55	683.87
SPAN b FT	222.7	67.2	29.2
ASPECT RATIO	6.96	3.62	1.25
TAPER RATIO	.322	.250	.340
SWEEP ΛC/4 DEG	37.5	37.5	45.0
ROOT CHORD IN	578.0	359.0	420.0
TIP CHORD IN	185.0	90.0	143.0
MAC $\bar{C}$ IN	415.3	251.3	304.2
ROOT T/C %	15.8		
TIP T/C %	7.8		
DIHEDRAL DEG	7.0	7.0	







LIQUID HYDROGEN FUEL STUDY AIRCRAFT
CONVENTIONAL CONSTRUCTION

FIGURE 2

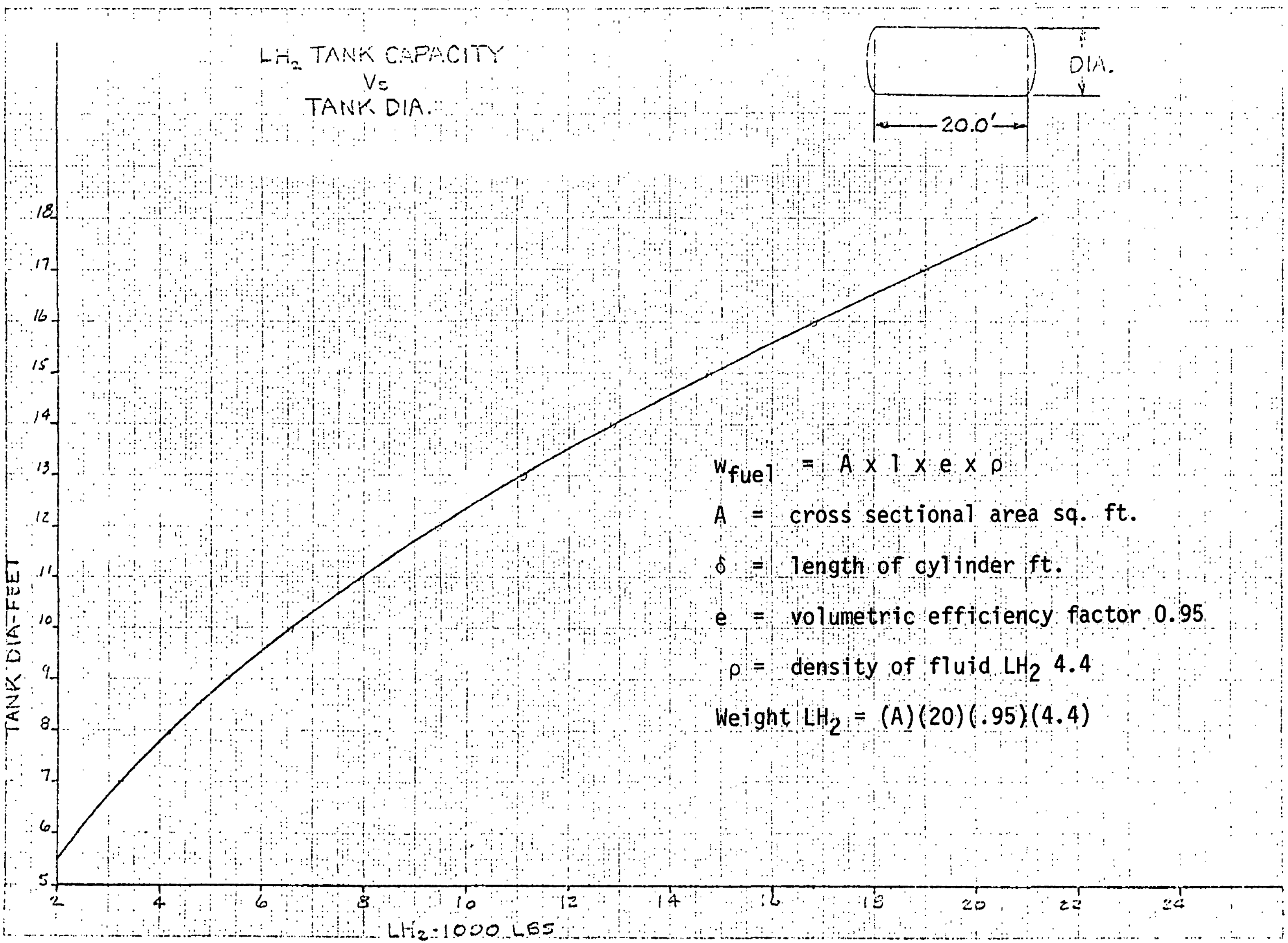

LH$_2$ TANK CAPACITY
Vs
TANK DIA.
DIA.
20.0′
W_{fuel} = A x l x e x ρ
A = cross sectional area sq. ft.
ℓ = length of cylinder ft.
e = volumetric efficiency factor 0.95
ρ = density of fluid LH$_2$ 4.4
Weight LH$_2$ = (A)(20)(.95)(4.4)
TANK DIA-FEET
LH$_2$-1000 LBS

FIGURE 3

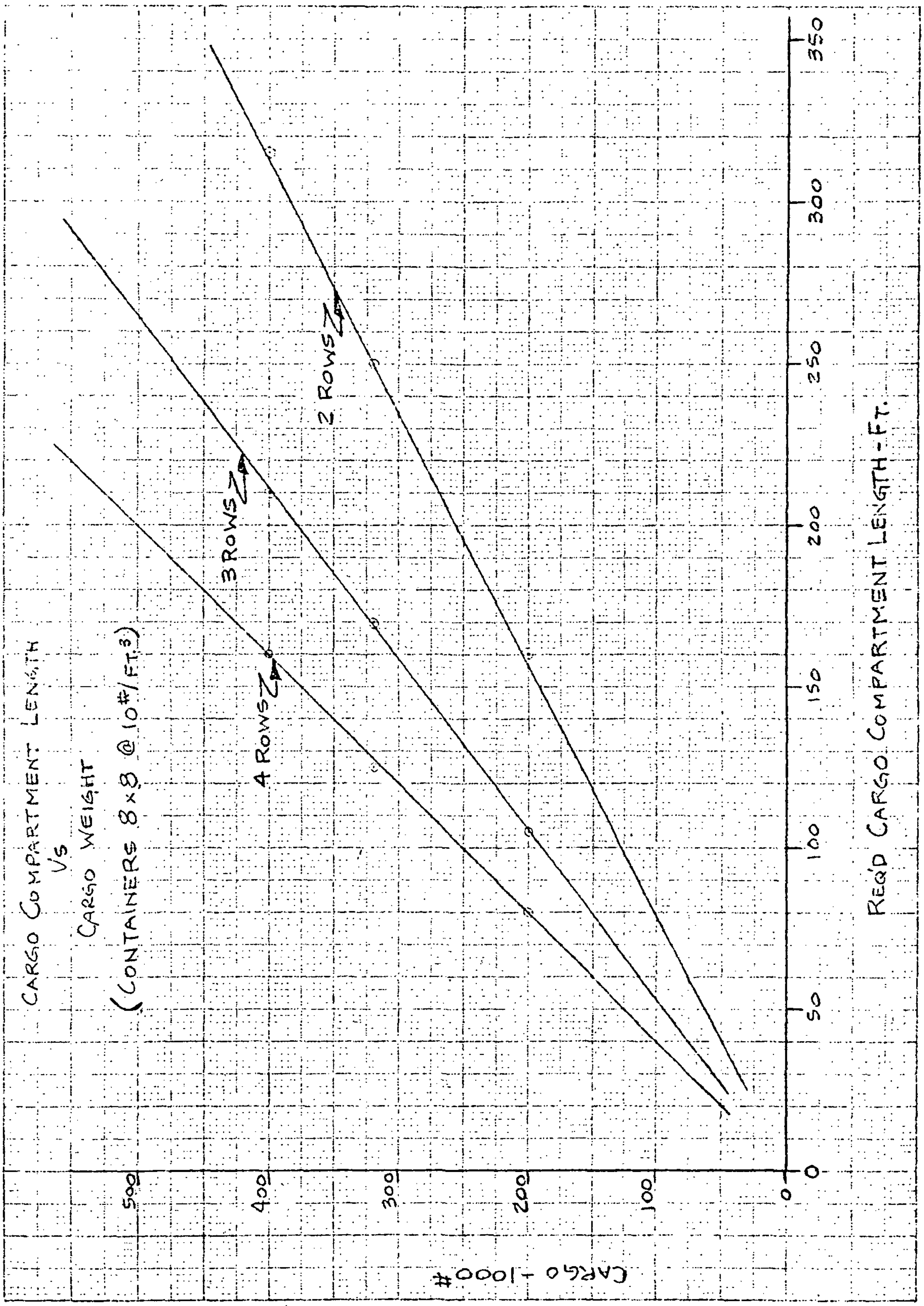
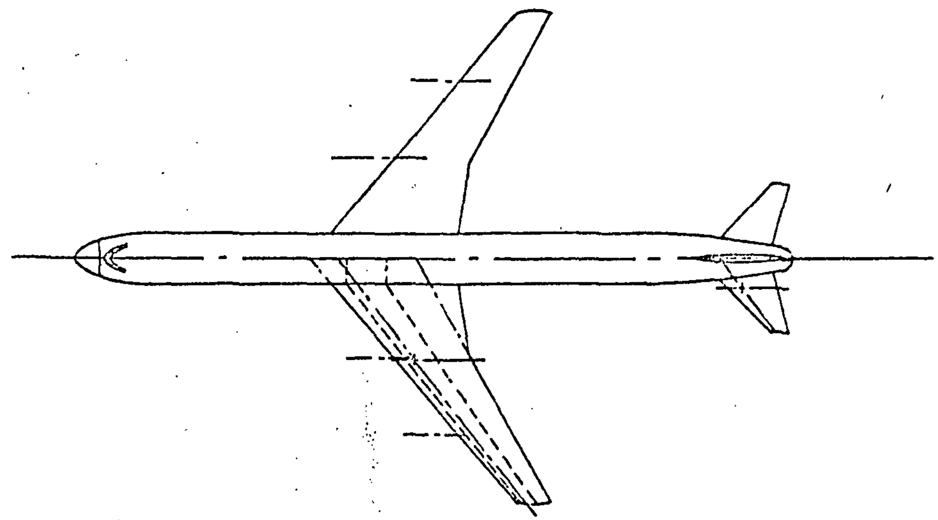
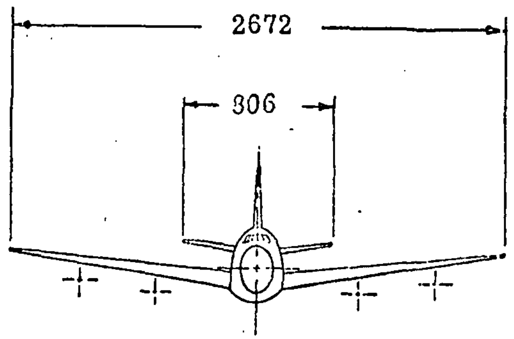

CARGO COMPARTMENT LENGTH
VS
CARGO WEIGHT
(CONTAINERS 8×8 @ 10#/FT.3)
4 ROWS
3 ROWS
2 ROWS
0
50
100
150
200
250
300
350
REQ'D CARGO COMPARTMENT LENGTH - FT.
0
100
200
300
400
500
CARGO - 1000#

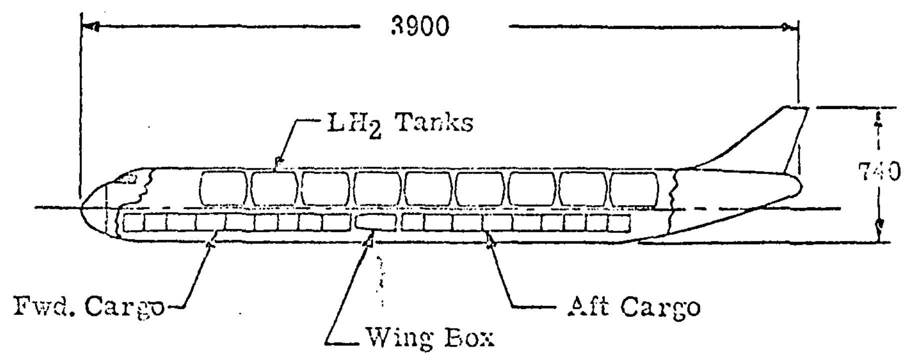
FIGURE 4

DASH 5 REDUCED FUSELAGE LENGTH

GEOMETRY	WING	HORIZ	VERT
AREA S FT^2	7083.0	1255.55	683.87
SPAN b FT	222.7	67.2	29.2
ASPECT RATIO	6.96	3.62	1.25
TAPER RATIO	.322	.250	.340
SWEEP ΛC/4 DEG	37.5	37.5	45.0
ROOT CHORD IN	578.0	359.0	420.0
TIP CHORD IN	185.0	90.0	143.0
MAC $\bar{C}$ IN	415.3	251.3	304.2
ROOT T/C %	15.8	—	—
TIP T/C %	7.8	—	
DIHEDRAL DEG	7.0	7.0	

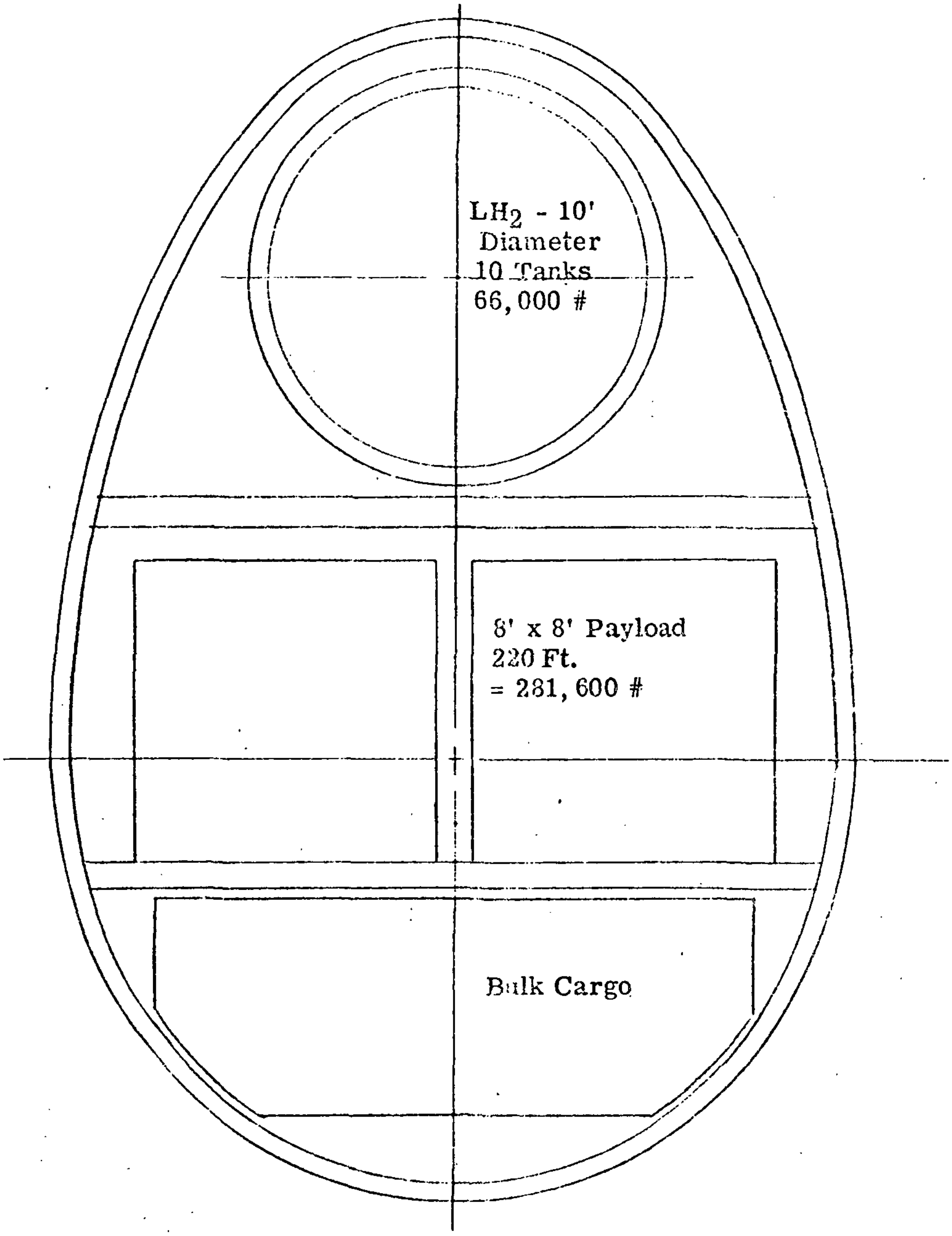






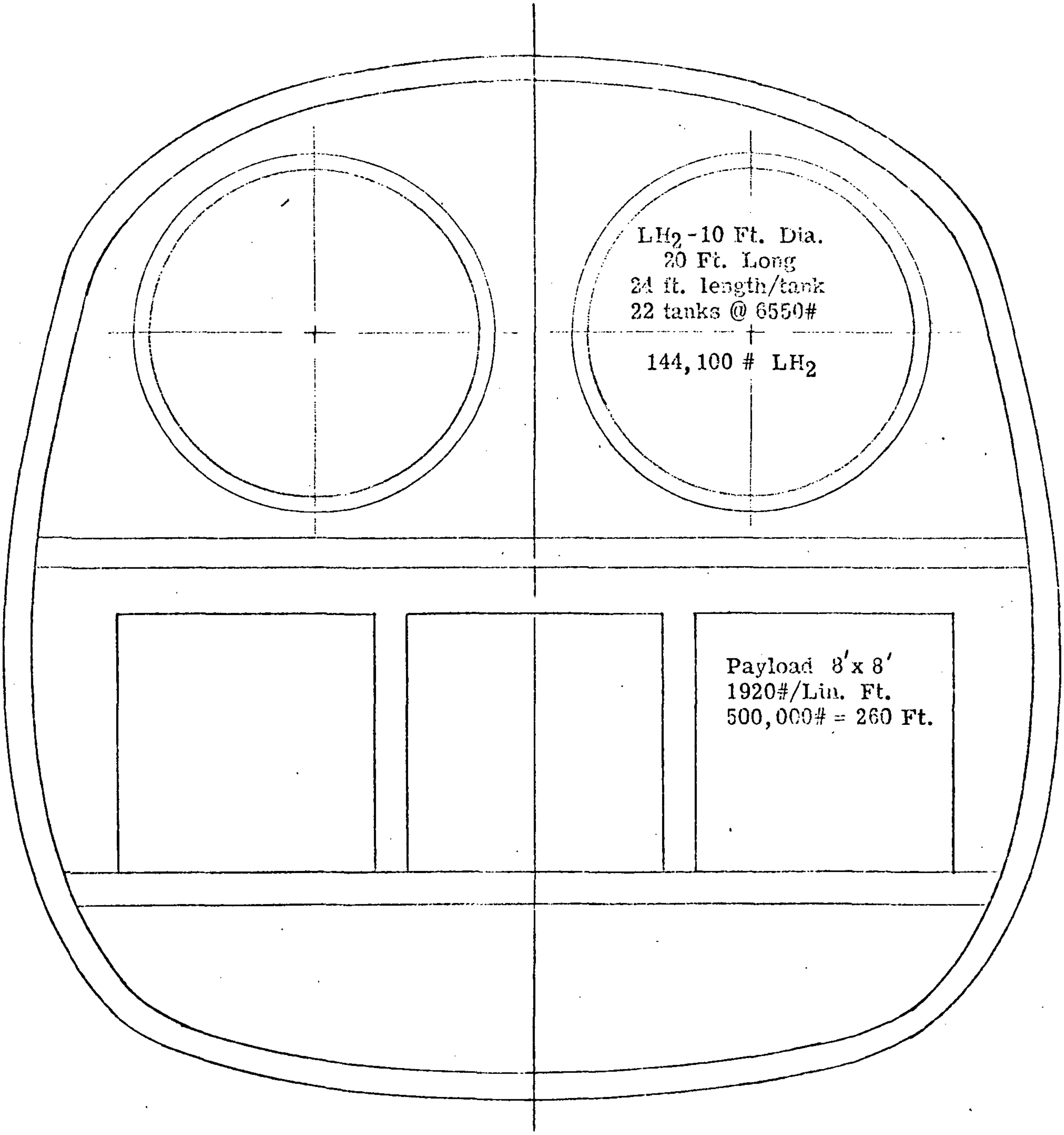
LIQUID HYDROGEN FUEL - ADVANCED TECHNOLOGY
STUDY AIRCRAFT

FIGURE 5



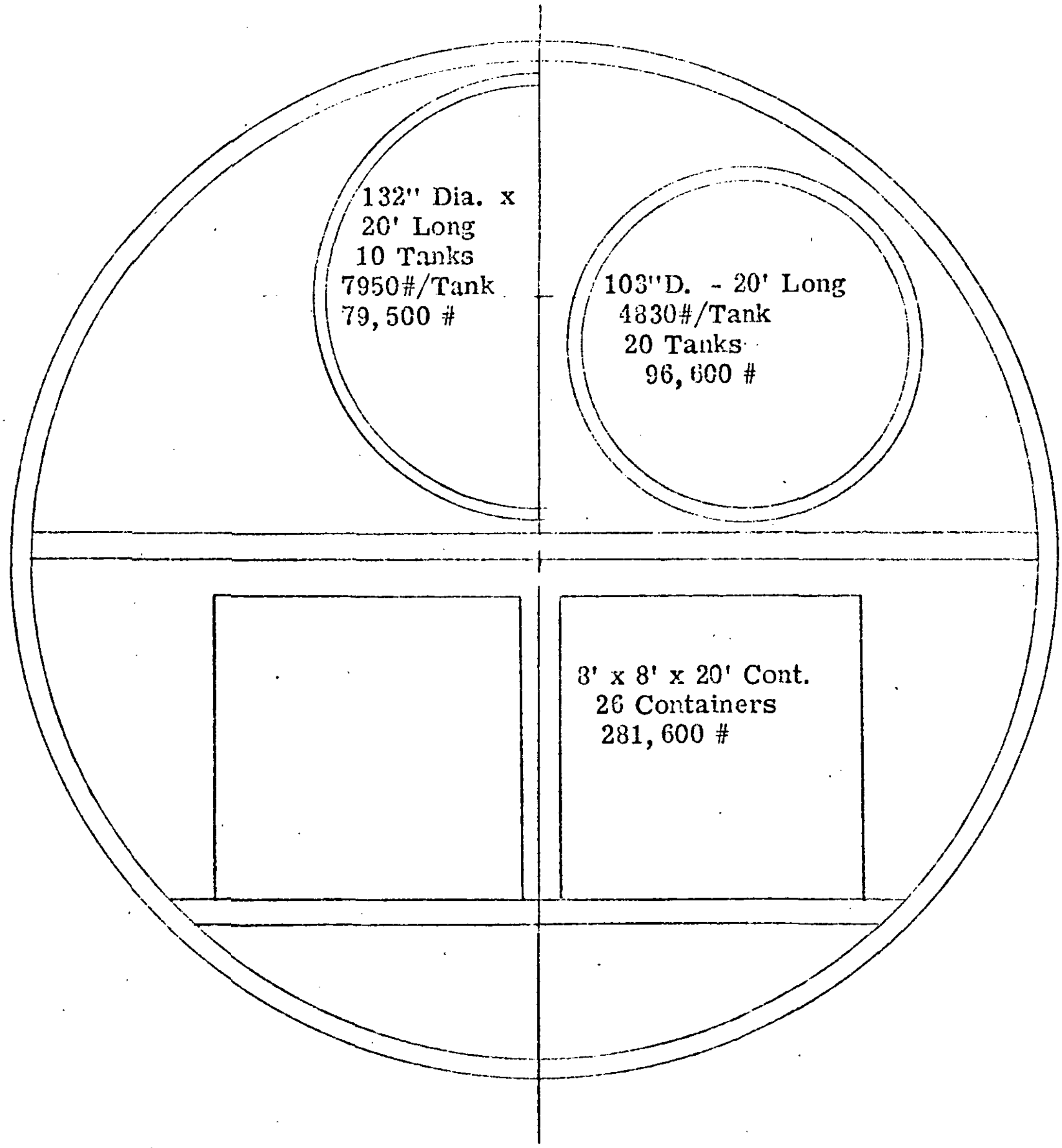
LH$_2$ TANK
AND
CARGO DISTRIBUTION

FIGURE 6



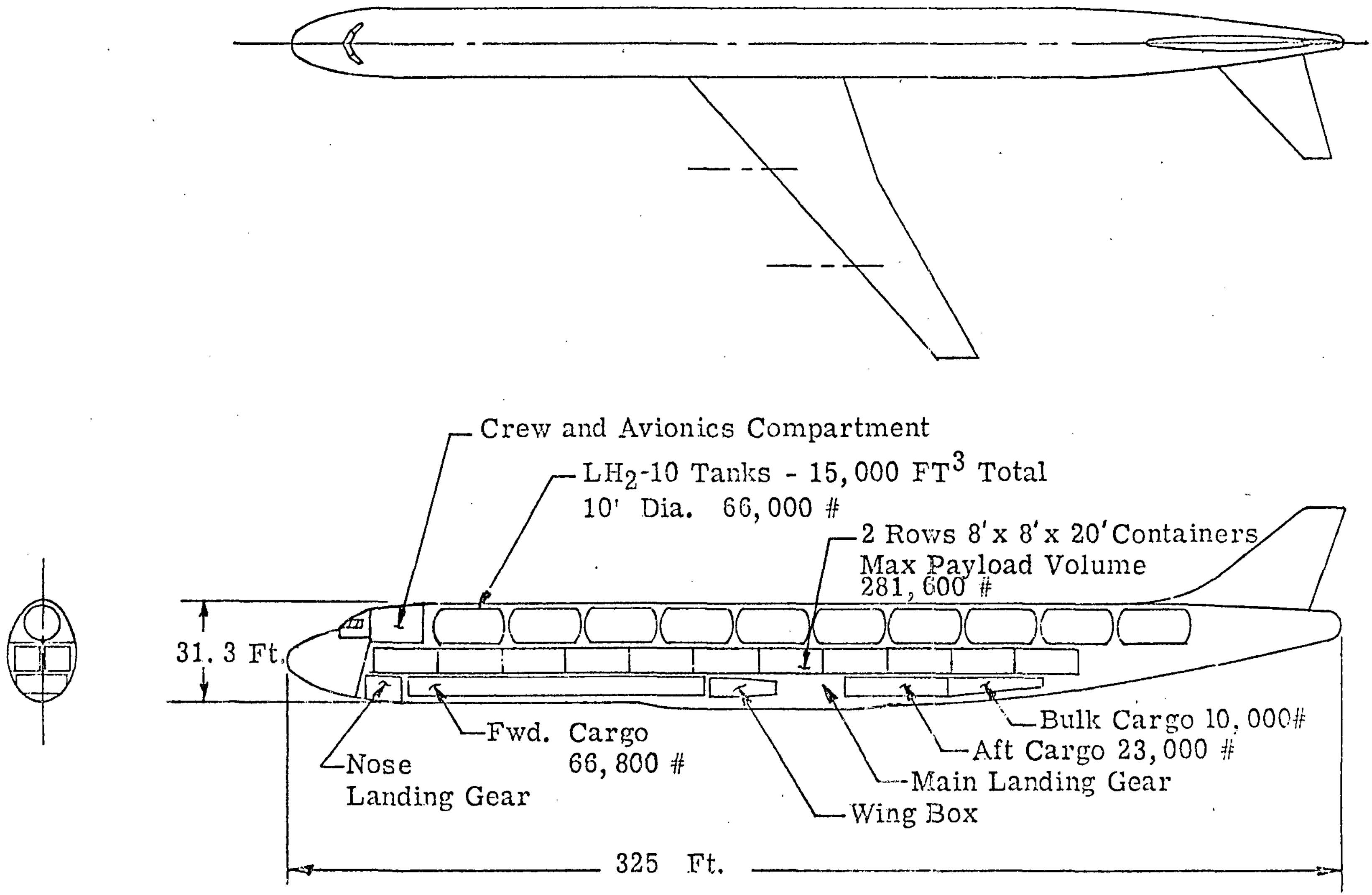
LH_2 TANK
AND
CARGO DISTRIBUTION

FIGURE 7



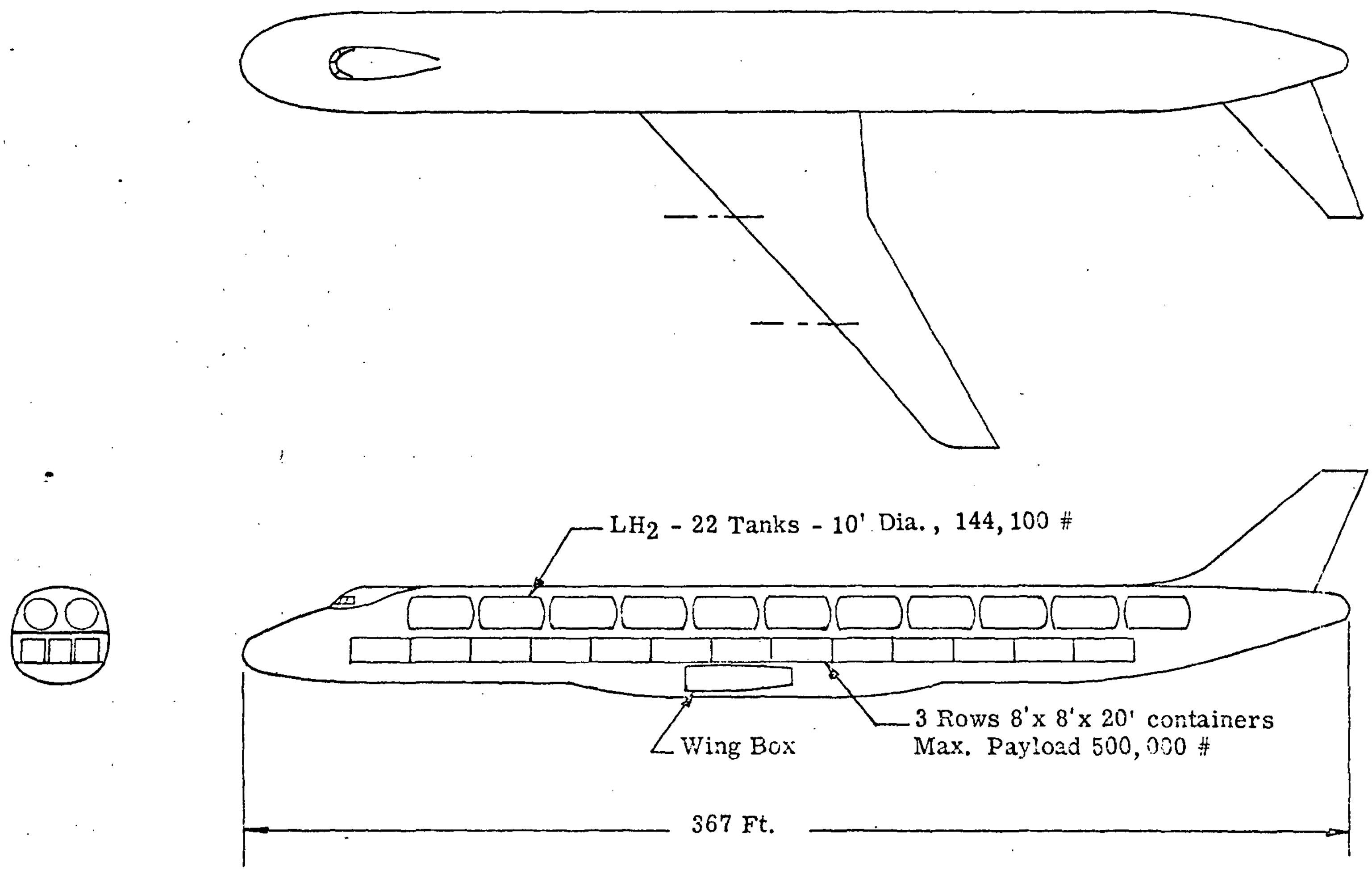
LH$_2$ TANK
AND
CARGO DISTRIBUTION

FIGURE 8



3000 NAUTICAL MILE RANGE
281,600 POUND CONTAINER CAPACITY

FIGURE 9



3000 NAUTICAL MILE RANGE
500,000 POUND CONTAINER CAPACITY

FIGURE 10

SUMMARY

SCALING EFFECTS ON STRUCTURE AND FUEL

ITEM DESCRIPTION	CONVENTIONAL & ADVANCED CARGO JP FUEL				ADVANCED CARGO HYDROGEN FUEL		GENERAL DYNAMICS	
	-1 Baseline CONVENTIONAL	-2 Baseline ATT	-3 Aluminum	-4 Cycled Comp. & ATT	-5 Aluminum	-6 Cycled Comp.	Baseline	(ATT)Cycled
Airframe Weight	210424	125535	463308	271007	359602	232654	94260	62980
Percent Wt. Savings		40.4		41.5		35.3		33.2
Mfgrs. Wt. Empty	327275	228912	640723	416876	519632	380280	156180	120571
Percent Wt. Savings		30.1		34.9		26.8		22.8
Operating Weight	355422	257042	646377	421474	521963	382594	163554	127935
Percent Wt. Savings		27.7		34.8		26.7		21.8
Design Gross Wt.	710000	550000	1500000	1130000	915000	753000	304800	247432
Percent Wt. Savings		22.5		24.7		17.7		18.8
Mission Fuel	277908	216288	588623	443526	128037	105406	100281	78687
Percent Wt. Savings		22.2		24.7		17.7		21.5
Payload	76670	76670	265000	265000	265000	265000	40000	40000
Cruise Mach No.	.85	.85	.85	.85	.85	.85	.32	.90
Range - Naut. Mi.	5070	5070	5070	5070	5070	5070	3000	3000

TABLE I

APPENDIX
STRESS ANALYSIS
LH_2 FUSELAGE TANKS

Stress analysis of the liquid hydrogen (LH_2) fuel tanks was made for the 1.5 million pound TOGW cargo aircraft. The purpose was to estimate an equivalent "smear" shell thickness to be used for weight estimates. The smeared thickness, not including the internal support frames near each tank end, was estimated to be .10 inch.

Tank construction was assumed to be of 2219-T81 integrally stiffened aluminum welded together longitudinally and circumferentially at sufficiently thickened weld lands. Internal intermediate frames with 1 foot spacing provide tank stability and fuel baffling. A heavier internal frame at each dome to cylinder joint provide the distribution of the tank support loads. These loads are assumed to be distributed into the fuselage by bulkheads and a longitudinal shear tie into the floor. Consideration for thermal contraction at the low temperatures is assumed. For example, one of the two tank supports must have a sliding joint.

The design criteria used for this analysis is as summarized on Page 23. Two conditions were checked. The first, an emergency condition combines a 15 psi design ultimate burst pressure (5 x 2 x 1.5) with the 9 g ultimate forward inertia load. The second condition is a flight condition and combines the 15 psi design ultimate burst pressure with the pressure resulting from a positive 5.88 g inertia load. This was determined by averaging the 3.75 g at the airplane c.g. and the 8 g for the most aft tank. Pages 24 and 25 include the calculations used to estimate a typical skin thickness. The resulting skin thickness is considered near minimum gage. The last two pages contain the estimates leading to the .10 inch smear thickness.

LH_2 TANKS

DESIGN CRITERIA

LOADS

OPERATING DIFFERENTIAL PRESS = 5 psi TENSION

= 1 psi COLLAPSING

INERTIAS (ULT.) REF. FAR 25

FLIGHT (Zero Pitch Accel.)	3.75 g down* 1.50 g up 1.50 g fwd 1.50 g side
EMERGENCY (Acting separately)	4.50 g down 2.00 g up 9.00 g fwd 1.50 g side

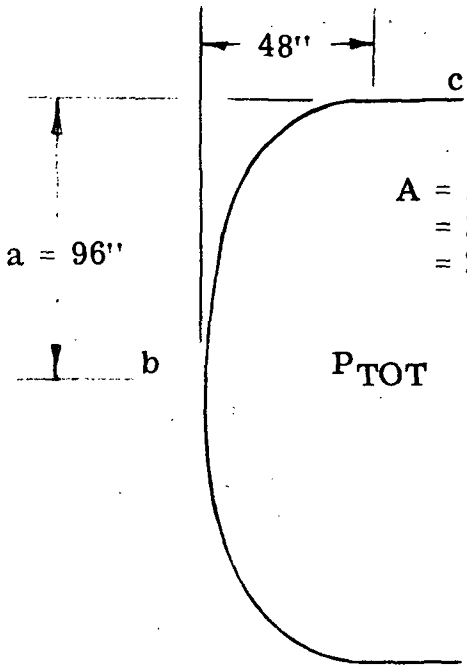
FACTORS

LIMIT TANK PRESS	2.00
ULTIMATE	1.50

* Assume 8 g down and 5 g up for aft tanks to include effect of pitching acceleration.

EMERGENCY CONDITION

FWD. BULKHEAD (ELLIPTICAL)



$A = .785(16)^2$
$= 201 \text{ ft}^2$
$= 28,950 \text{ in}^2$

LH_2 Density = 4.425 #/ft^3
Vol_{Tank} = 4488 ft^3

W = 19900#

g = 9 fwd. ult.

Wg = 179,000 # ult.

Pi_{ult} = 6.18 psi inertia

Pv_{ult} = 5 x 3 = 15 psi vapor

P_{Total} = 21.18 psi ult.

Mat = 2219-T81 Aluminum
Ftu = 62KSI
Fty = 47KSI
Ftall = 62/1.5 = 44.3KSI

Stress conc. factor = 1.5

Nϕ = MERIDIONAL LOAD

Nθ = HOOP LOAD

ptb Nϕ/pa = Nθ/pa = 1

No/ = Nθ = 21.2(96) = 2040#/in.

$t_{skin} = \dfrac{2040}{44,300} = .046"$ Not incl. stiff. and baffles

ptc Nϕ/pa = .5 Nθ/pa = 1 t_{skin} = .046" cylinder
(Discontinuity stresses increase
t_s locally)

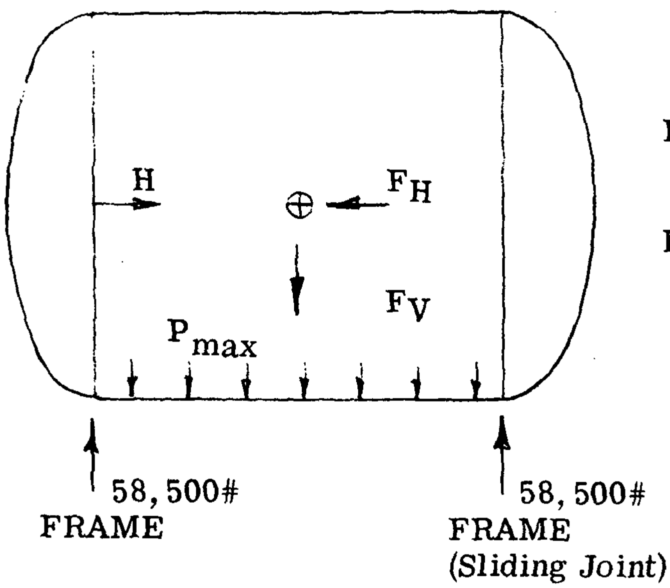
Aft Bulkhead

P_{TOT} 15 psi

t_s 15/21.2(.046) = .033"

FLIGHT COND.

$$M_Z = \frac{3.75 + 8.00}{2} = 5.88 \text{ Avg. for all Tanks}$$



$$F_H = 19900\ (1.5)$$
$$= 28,800 \text{ lbs. ult.}$$

$$F_V = 19900\ (5.88)$$
$$= 117,000 \text{ lbs. ult.}$$

P_{vapor} = 5 x 3 = 15 psi ult.

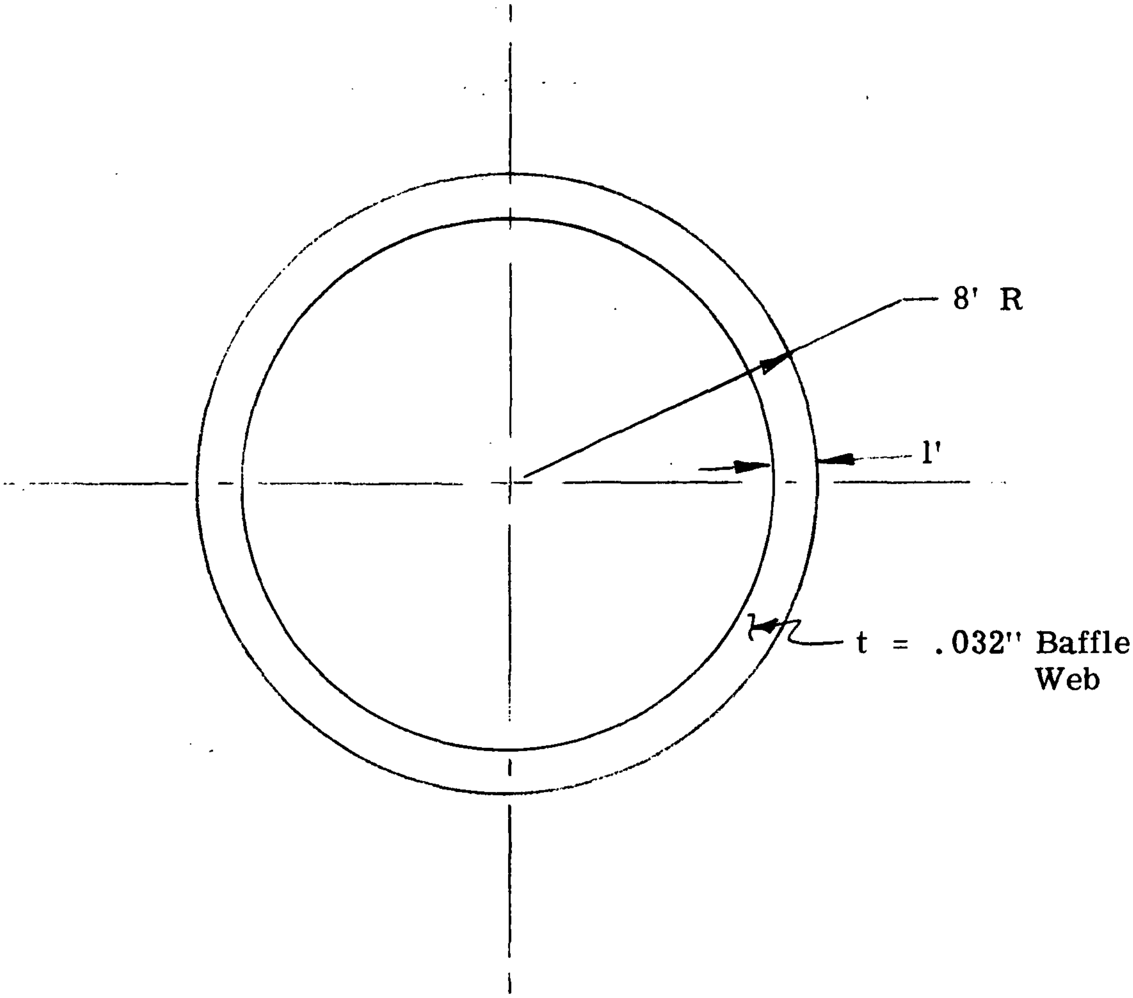
$$P_{inertia} = whg = \frac{4.425}{1728}\,(16)(12)(5.88) = 2.89 \text{ psi ult.}$$

P_{TOT} = 17.89 psi ult. at bottom

P_{TOT} = 15.00 psi ult. at top

INTERMEDIATE FRAMES

ASSUME RINGS SPACED 1' APART



This increases $\bar{t}$ approximately .032"

LH_2 TANKS

EFFECTIVE SMEAR THICKNESS

t_s		=	.046"
t_{stiff}	= 1.0" x .05" @ 6" spacing	=	.008" (Light)
t_{baffle}		=	.032
			.086"

Assume $\bar{t}$ = .10" Does not include tank support frames.

REFERENCES

1. Jack S. Esgar, Cryogenic Fuels for Aircraft, NASA SP-259

2. Study of the Application of Advanced Technologies to Long-Range Transport Aircraft, General Dynamics, NASA CR 112090, Volume I, (Classified) dated 8 May 1972.