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HYDROGEN AIRCRAFT CONCEPTS & GROUND SUPPORT

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ABSTRACT

As worldwide petroleum supplies diminish and prices escalate, the aviation industry will be forced to consider relying on energy resources other than kerosene for its aviation fuel needs. Additionally, there is growing environmental concern regarding greenhouse emissions particularly as aircraft cause pollution in sensitive layers of the atmosphere. These are serious implications necessitating prudence in seeking alternative fuels sooner rather than later.

Liquid Hydrogen (LH₂) combustion produces zero CO₂ emissions, very little NO_x, and water providing a solution to sustain air traffic growth whilst preventing further atmospheric pollution. Hydrogen itself is abundant and can be produced from renewable sources meaning worldwide availability and sustainability permitting sustainable growth of aviation at high rates (typically 4-5% per year).

Despite these major advantages, there are compromises to be made. The low density fuel means ingenuity must be exercised to design an aircraft configuration which will accommodate a fuel volume more than *four times* that which would normally be required. Practical *unconventional* aircraft conceptual designs providing solutions to this problem are presented including estimates of performance, mass, and relative cost- and energy-effectiveness.

To provide a means to produce, store and transport the fuel safely and efficiently, ground support operations have been systematically checked and the required airport infrastructure defined.

Technical issues such as safety, airworthiness certification, environmental issues and system synergies are also discussed, and an outline plan is presented providing the R&D necessary to introduce LH₂-fuelled civil aircraft into service.

This Thesis proves that LH₂ has sufficient long term promise to justify more substantial R&D offering possible improvement in performance and engine

reliability. The overall cost for a LH₂ aircraft are within reasonable values, and the requirement for new equipment to maintain and support LH₂-fuelled aircraft is not extensive. Importantly LH₂ is at least as safe.

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ABBREVIATIONS/NOMENCLATURE

A	AMPR (airframe unit weight), Aspect Ratio
a.c	Aerodynamic Centre
a/c	air conditioning
APU	Auxiliary Power Unit
AR	Aspect ratio
ATA	Air Transportation Association
A_{TF}	Judgement factor to account for advanced technology features
ATT	Judgment factor
BWB	Blended Wing Body
CO ₂	Carbon Dioxide
C_{DDTE}	Design, development, test and evaluation cost
C_{ACQ}	Acquisition Cost
C_{AMC}	Judgement factor for cost of advanced material relative to conventional metal designs
C_{OPER}	Operations and support cost
C_{DISP}	Disposal cost
C_{DSC}	Development support cost
C_{FTAR}	Cost of flight test operations
CH ₄	Methane
C_{PI}	Cost escalation factor
C_S	Cost factor
DOC	Direct Operating Costs
EAS	Equivalent Air Speed
E_{HD}	Total airframe engineering hours for development
E_{HP}	Total airframe engineering hours for production
E_{RATE}	Engineering hourly rate
ESAR	Equivalent Still Air Range
FC	First Class
FSW	Forward Swept Wing

GH ₂	Gaseous Hydrogen
GHe	Gaseous Helium
GN ₂	Gaseous Nitrogen
GSE	Ground Support Equipment
GWP	Global Warming Potential
IFE	In-flight Entertainment
IOC	Indirect Operating Costs
IR	Infrared
JAA	Joint Aviation Authority
JAR	Joint Airworthiness Regulations
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LE	Leading Edge
LH ₂	Liquid Hydrogen
LHR	London Heathrow
LN ₂	Liquid Nitrogen
mac	Mean Aerodynamic chord
M _{HD}	Manufacturing labour hours for development
M _{HP}	Manufacturing labour hours for production
M _{MAX}	Maximum Mach Number
MOE	Mass Operating Empty
MPAYLOAD	Mass Payload
MZF	Mass Zero-Fuel
MTOW	Maximum Take-off Weight
N ₂	Nitrogen
NG	Natural Gas
NO _x	Nitrous Oxide
O ₂	Oxygen
OPR	Overall Pressure Ratio
pax	Passengers
Psia	Pressure – pounds per square inch ambient

Q	Quantity of aircraft to be produced
R	Production rate (aircraft per month)
R&D	Research & Development
S	Maximum speed at best altitude
sfc	Specific Fuel Consumption
S _G	Ground Roll Distance
SO	Sulphuric Acid
SO ₂	Sulphur Dioxide
S _s	Distance to screen height
TB	Twin Boom
TE	Trailing Edge
TET	Turbine Exit Temperature
T_{HD}	Tooling hours for development
T_{HP}	Tooling hours for production
UV	Ultraviolet
V	Velocity
VTOL	Vertical Take Off and Landing
WE _{CT}	Weight empty of transport aircraft
YC	Economy Class

Notation

A	Aspect ratio	CTPROD	Production Tooling Cost
A_{exposed}	Exposed Area	CUA	Acquisition Unit Cost
a	Speed of sound	D	Diameter, Drag
b	Wing Span	e	Oswald Span Efficiency Factor
bf	Fuselage breadth	EHD	Engineering Hours for Development
B_h	Horizontal tail Span	EHP	Engineering Hours for Production
$\bar{C}$	Mean Aerodynamic Chord	ERATE	Engineering Labour Rate
C_{root}	Root Chord	f	Allowable Working Stress
cg	Centre of Gravity	F	Fuselage factor, Size factor
c	Specific Fuel Consumption	FF	Form factor
C_{ci}	Total circumferential length of wing halves	FHYR	Flight Hours per year
c_l	% of laminar flow	F_w	Fuselage Width at Tail section
C_{Do}	Zero Lift Drag component	g	Number of galleys
C_f	Skin friction Coefficient	i_w	Wing incidence
C_{fe}	Equivalent Skin friction Coefficient	K_y	Aircraft pitching radius of gyration ($=0.3L_t$)
$C_{HT/CVT}$	Horizontal/Vertical Tail Volume Coefficient	K_z	Aircraft yawing radius of gyration ($\approx 0.3 L_t$)
$C_{l\alpha}$	Wing lift curve slope	l, L	Length, Lift
CL	Lift Coefficient	L/D	Lift/Drag ratio
$C_{L\text{max}}$	Max Lift Coefficient,	l_f	Length of fuselage
$\Delta C_{L\text{max}}$	Increment to Max. lift coefficient	L_{HT}	Horizontal Tailplane Tail Arm
Cmo	Pitching moment coefficient	L_t	Tail arm
CRF	Recurring Flyaway Cost	L_{VT}	Vertical Tailplane Tail Arm

M	Mach Number (= ua)	QD	Quantity of Development Aircraft
M _{aircon}	Mass of air conditioning	QP	Quantity of Production Aircraft
M _{APU}	Mass of APU	QHD	Quality Hours for Development
M _{cri} /M _D	Critical Mach Number/Design Mach Number	QHP	Quality Hours for Production
M _{DEICE}	Mass of deicing system	ρ	density
M _{ELEC}	Mass of Electrics	r	radius
M _{eng}	Mass of engine	R	Reynolds number, Production rate per month, Wetted Area Factor
M _{FC}	Mass of flying controls	s	seat pitch
M _{fuel tank}	Mass of fuel tank	S	Wing Area/Maximum Speed at best altitude
M _{furnishings}	Mass of furnishings	S _a	Obstacle Clearance Distance
MGROSS	Gross Mass	S _e	Elevator Area
MHD	Manufacturing Labour Hours for Development	S _h /S _v	Horizontal/Tailplane Area
MHP	Manufacturing Labour Hours for Production	S _{ref}	Reference Area
M _{HYD}	Mass of hydraulics & pneumatics	S _{wet}	Wetted Area
M _{LG}	Mass of landing gear	t	Number of toilets, thickness
MOWE	Mass Operating Weight Empty	t/c	Thickness/chord ratio
MPAY	Payload Mass	T	Thrust, type factor
MZFW	Zero-fuel Mass	TFUEL	Total lbs of Fuel
NE	Number of Engines	THD	Tooling Hours for Development
n.p.	Neutral point	THP	Tooling Hours for Production
P	Number of passengers	T/O	Take –off
p	Number of seats across fuselage width, pressure	V (or U)	Forward Speed
p.m.	Pitching Moment	V	Volume
q	Dynamic pressure (= ½ ρV ²)	V _{approach}	Approach Speed
		V _{LOF}	Lift off speed

V_{md}	Minimum Drag Velocity	$\Lambda_{L.E.}$	Leading Edge Wing Sweep
VR	Rotation Speed		
V_{stall}	Stall Speed	$\Lambda_{H.L.}$	Sweep of wing at hinge line of high lift device
V_{TRANS}	Transition Speed		
w	Number of cross-aisles	μ	Coefficient of viscosity
W_e	Empty Weight	η_f	fuselage diameter/wing span ratio
W_f	Fuel Weight		
W_o	All-up Weight	σ	Relative Density
WAV	Weight of uninstalled avionics equipment		
$\left(\frac{x}{c}\right)_m$	Max thickness of aerofoil		
$\bar{Y}$	Spanwise Location of mac		
YS	Years of Service		
		Subscripts	
		HT	Horizontal Tailplane
		VT	Vertical tailplane
		f	fuselage
α_0	Zero Lift Angle of attack	APU	Auxiliary Power Unit
α_f	Angle of attack relative to fuselage centreline	DEICE	Deicing system
		ELEC	Electrics
β	Prandtl–Glauert compressibility factor, fuselage tail upsweep angle	eng	Engine
		FC	Flying Controls
		HYD	Hydraulics
ϵ_t	Wing Twist	LG	Landing Gear
ϕ	Shape factor	Wet	wetted
ϕ_w	Thickness correction factor	ref	reference
Γ	Dihedral		
λ	Taper ratio		
Λ	Wing Sweep		

Preface

This thesis is a result of the author's task in the CRYOPLANE Project which was an EU-funded project conducted from April 2000 – June 2002 and was a “*System analysis of a liquid hydrogen civil transport aircraft for the future*”. This project involved many contributors from industry and academia and was led by EADS.

The CRYOPLANE project was part of the 5th Framework Program of the European Commission. Thirty-four partners involving academia, industry and research establishments from 11 European countries were involved.

The objectives were to develop a conceptual basis for applicability, safety, and full environmental compatibility, and to investigate medium/long term scenarios for a smooth transition from kerosene to hydrogen in aviation. This included relevant technical, environmental, societal and strategic aspects to provide a sound basis for initiating larger scale activities preparing for the development and introduction of Liquid Hydrogen as an aviation fuel.

As part of this overall study, the authors' responsibility on behalf of Cranfield University was twofold:

- 1) The first task objective (as part of Work Package 1) was to identify liquid hydrogen fuelled aircraft configurations which met the requirements of efficient and safe operation in a particular aircraft category **and** which were *unconventional*.
- 2) The second task (as part of Work Package 7) was to evaluate the ground support requirements as well as the maintenance facilities necessary to support liquid hydrogen fuelled aircraft at an airport.

1.0 SCOPE OF THESIS

1.1 Thesis Chapter Content

As a useful and intuitive introduction into the nature of hydrogen as a fuel, **Chapter 2.0** begins with a brief history into the development of hydrogen as a fuel, its main properties including advantages and disadvantages and also its environmental effects. By that stage, we would have hopefully answered the question “*why would we want to introduce hydrogen fuel into service?*”.

The main and perhaps most interesting chapter, **Chapter 3.0**, covers the conceptual design of unconventional or novel medium range hydrogen aircraft. This chapter provides some background into unconventional aircraft designs. Subsequently, details are provided of the brainstorming activities which illustrate the means by which the novel concepts were initiated, and consequently analysed on a qualitative conceptual basis, finally resulting in a configuration that offers promise – a *Twin Tail-Boom*. This Twin Tail Boom is then subjected to conceptual design with estimates provided of the mass, size and performance.

Chapter 4.0 deals with hydrogen safety. Since safety is a vital issue it has been treated in its own chapter, although pertinent hazards and safety issues are highlighted throughout the thesis.

Chapter 5.0 deals with Aircraft Certification and identifies and highlights those regulations that may require change or those areas that are not adequately covered by existing regulations as a result of the change to LH₂ fuel. The Twin-Boom concept developed from Chapter 3.0 is used as a case-study for this chapter and subsequent chapters where necessary.

Ground operations and support (**Chapter 6.0**), such as pre- and post-flight checks, refuelling, manoeuvrability, parking, maintenance etc., conventional procedures and equipment have been systematically checked (again using the Twin-Boom aircraft

as a case-study) for changes becoming necessary in consequence to the use of LH₂ fuel.

Brief details are provided in **Chapter 7.0** of the development of production, transport and storage methods for the hydrogen fuel at airports. Airport infrastructure is essential to the successful introduction of hydrogen as an aviation fuel since only when there are a sufficient number of airports with means for distribution and supply, will LH₂ aircraft be possible.

Finally, **Chapter 8.0** includes a preliminary estimate of the Direct Operating Cost (DOC) for the LH₂-fuelled Twin-Boom aircraft. This chapter introduces the methods by which the Twin-Boom aircraft operating costs are estimated allowing comparisons to be made between the Twin-Boom (operating on liquid hydrogen fuel) and an equivalent aircraft operating on kerosene. Although assumptions are made, this provides a useful comparison in terms of the *relative* cost benefits of using LH₂ fuel over kerosene.

Chapters 9.0 and 10.0 provide a discussion of the results of the thesis as well as the overall conclusions and recommendations.

Appendix A provides an estimation of the net effect of the Twin Boom fuel tanks when compared against the lower weight of LH₂ fuel. **Appendix B** provides details of current ground operations including equipment and procedures that take place for conventionally aircraft fuelled on Kerosene. **Appendix C** includes useful background information on the environmental issues of renewable sources, and finally **Appendix D** provides details of system synergies i.e. those properties and characteristics of the liquid hydrogen fuel that offer potential alternative uses i.e. amalgamation of different LH₂ system function with other aircraft systems.

2.0 HYDROGEN FUEL

2.1 Introduction

In the design, manufacture and operation of transport aircraft, concerns of both the user *and* the public must be considered. The consumer is concerned with safety, cost, comfort etc. The public are increasingly concerned with conservation of resources as well as minimization of environmental impact, particularly since aircraft traffic is growing at approximately 4-5% per year (*Jenkinson, Simpkin, Rhodes, 1999*) and is likely to be the case for many decades. Worldwide mobility will continue to grow in respect of volume and quality particularly in economic growth areas such as China, India or South America. Limitation of this growth would be catastrophic for the aviation industry, as would political, legislative and financial measures to reduce CO₂ emissions. However, growth of air traffic can not feasibly continue under present conditions. Burning fuel depletes the limited resources that will be virtually exhausted in a few decades. Despite the improvement in fuel efficiency over the years, further potential for improvement is marginal and further progress is both slow and costly. Thus, the need to reduce both the consumption of fossil fuels and the emission of CO₂ is generally accepted as being the way forward. In December 1997, more than 160 nations met in Kyoto, Japan, to negotiate binding limitations on greenhouse gases for the developed nations, pursuant to the objectives of the Framework Convention on Climate Change of 1992. The outcome of the meeting was the Kyoto Protocol, in which the developed nations agreed to limit their greenhouse gas emissions relative to their 1990 emissions levels with an 8% target reduction for the European Union (or its individual member states) and a 7% reduction for the United States (*Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity, October 1998*).

2.2 Background

2.2.1 Renewable Energy

It is clear therefore, that in order to prolong fossil fuel resources, as well as reduce emissions of CO₂ and other pollutants and greenhouse gases, it is necessary to make a transition to renewable energy sources. There are already many renewable energy

sources in use today such as water, wind and solar power. Although renewable energy sources also utilise some fossil fuels and cause some degree of pollution in their extraction, processing and production, this is much less when compared to non-renewable energy sources.

Currently, all aircraft consume approximately 2-3% of the total of fossil fuels used worldwide (*Jenkinson, Simpkin, Rhodes, 1999*). This equates to 2.4% of the total CO₂ produced by all man-made sources. Technical progress in gas turbine engines and airframe efficiency have lead to a decrease in sfc, and hence CO₂ emissions, but air traffic increasing at a rate of 4-5% per year means **total** emissions are rising, expecting to rise to 7% by 2050 (*Jenkinson, Simpkin, Rhodes, 1999*). An example of the increase in demand of air travel and the increased air traffic that will result is illustrated by the decision to build a new Terminal 5 at London Heathrow, despite much opposition from environmental lobbyists and local residents. To make matters worse, the majority of aircraft pollution is emitted within sensitive layers of the atmosphere, having chemical and physical effects on its composition and global climate.

2.2.2 Environmental and Greenhouse Effect

When conventional aviation kerosene fuel, which is produced from crude oil, is burned, the primary combustion products produced include:

- CO₂
- Water
- Carbon monoxide (CO)
- Unburnt and partially burnt hydrocarbons
- NO_x
- Sulphuric acid (SO), and
- Soot

As well as being harmful to the local air quality, emissions also contribute to the global greenhouse effect. The greenhouse effect is the rise in temperature that the

Earth experiences because certain gases in the atmosphere (e.g. water vapour, CO₂, NO_x, and methane) trap energy from the sun. Without these gases, heat would escape back into space and the Earth's average temperature would be lower. Because of their effect on global warming, these gases are referred to as greenhouse gases (*Williams, 1980*).

Although CO₂ and water vapour are greenhouse gases, there are important differences between them regarding the effects they have on the atmosphere and the length of time they remain in the atmosphere i.e. their 'residence time'.

CO₂ remains in the atmosphere for a long time, approximately 100 years (*US DoE, Energy Efficiency and Renewable Energy*). Because of this long residence time and because CO₂ is independent of the altitude at which it is produced, it will accumulate.

Contrary to CO₂, water vapour depends strongly upon the altitude at which is emitted. In the troposphere (up to 11km), the natural water content is high and so the residence time of any additional water vapour is so short that the contribution to the greenhouse effect can be neglected. At higher altitudes, however, particularly at those altitudes at which aircraft tend to fly, such as the lower stratosphere (above 11km and up to 20km), the humidity of air is very low. This means that the residence time of water vapour created at these altitudes is of the order of 6 months (*US DoE, Energy Efficiency and Renewable Energy*). Although this is much shorter compared with hundreds of years for CO₂, the time is long enough that the water vapour will accumulate (and even more so as the volume of air traffic grows), thus their effects can not be ignored.

Water that is emitted with the engine exhaust jet can freeze into ice crystals under certain conditions and form condensation trails. There have been many studies into contrails recently that have highlighted the concentration of these contrails over airports and surrounding areas. As a temporary remedy, it has been suggested that aircraft are guided by air traffic control through flight paths outside

the concentration of contrails. In certain weather conditions, the condensation trails become persistent and form Cirrus clouds leading to an adverse greenhouse effect.

Thus, although the environmental impact of aviation is smaller than that of surface transport, if contamination is considered per passenger km, pollution caused by aircraft is high. Also, local pollution near airports is of the same order as ground traffic emissions (*Pohl, H.W. and Malychev, V.V. 1997*).

If a new fuel is to be introduced, it must be available universally without hazard of control, and meet requirements of economics, safety, performance, and environmental compatibility.

2.2.3 Candidate fuels

So what alternative fuels are available that aren't derived from fossil fuels and which of those are suitable to fuel aircraft, meet future aviation needs and minimise environmental pollution?

There are several possibilities but the ones that offer the most long-term promise are **Hydrogen** and **Methane**. The basic properties of Hydrogen and Methane compared with kerosene are shown below in Table 2-1 (*Brewer, 1991*).

	Hydrogen	Methane	Kerosene
Nominal composition	H ₂	CH ₄	CH _{1.93}
Molecular weight	2.016	16.04	≈168
Heat of combustion (low), k J/g	120	50	42.8
Liquid density, g/cm ³ at 283 K	0.071	0.423	≈0.811
Boiling point, K (at 1 atm)	20.27	112	440-539
Freezing point, K	14.4	91	233
Specific Heat, J/g K	9.69	3.50	1.98
Heat of vaporisation, J/g (at 1 atm)	446	510	360

Table 2-1 – Selected properties of Hydrogen, Methane and Kerosene fuels (*Brewer, 1991*)

Table 2-1 above shows that Hydrogen is 11.4 times less dense and Methane is 1.9 times less dense than kerosene. However, Hydrogen fuel is much more energetic with a much higher heat of combustion meaning that overall it has 2.8 times more energy per kg than kerosene. Methane on the other hand has 1.2 times more energy per kg than kerosene. Overall, Hydrogen requires 4.1 times more volume and Methane requires 1.6 times more volume. In addition, the much greater specific heat of hydrogen affords greater cooling capacity compared with Methane and Kerosene.

In that light, ***liquid hydrogen fuel*** is proposed as a very promising fuel resource for fulfilling the needs of all those concerned.

2.2.4 Characteristics of Hydrogen fuel

Having looked at the promising characteristics of liquid hydrogen as an aviation fuel, let us turn our attention to more specific properties of the fuel. Further properties of Hydrogen and kerosene can be seen in Table 2-2 below. A selection of the more important properties is compared graphically in Figure 2-1.

	Hydrogen	Kerosene
Nominal composition	H ₂	CH _{1.93}
Molecular weight	2.016	≈168
Heat of combustion (low), k J/g	120	42.8
Liquid density, g/cm ³ at 283 K	0.071	≈0.811
Boiling point, K (at 1 atm)	20.27	440-539
Freezing point, K	14.4	233
Specific Heat, J/g K	9.69	1.98
Heat of vaporisation, J/g (at 1 atm)	446	360
Diffusion velocity in air, cm/s	≤2.00	≤0.17
Buoyant velocity in air, m/s	1.2-9	Nonbuoyant
Flammability limits in air, vol%	4.0-75.0	0.6-4.7
Vaporisation rate without burning, cm/min (from liquid pool)	2.5-5.0	N/A
Min. ignition energy in air, mJ	0.02	0.25
Autoignition temperature, K	858	>500
Burning velocity In NTP air, cm/s	265-325	18
Flame temperature in air (stoichiometric), K	2318	2200
Thermal energy radiated to surroundings, %	17-25	30-42
Detonability limits in air, vol%	18-59	N/A

Table 2-2 - Comparison of selected properties of kerosene and hydrogen fuels
(Brewer, 1991)

Comparison of Properties - Liquid Hydrogen v Kerosene

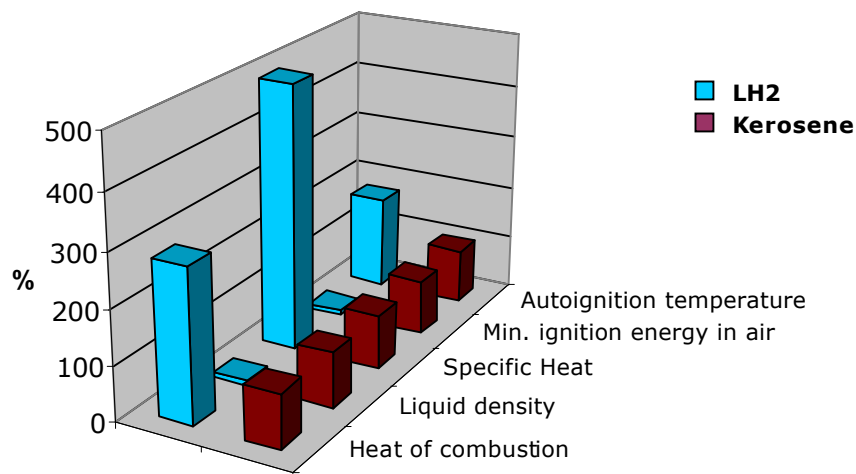


Figure 2-1 - Graphical representation of key properties and differences between hydrogen and kerosene fuel (kerosene values normalised to 100%)

So where does hydrogen come from? Hydrogen is the most plentiful substance in the universe, making up $\frac{3}{4}$ of universal matter (*Sanchez, 2001*). On earth it is the tenth most abundant element. Because it is a major constituent of the thin layer of water with which our planet is covered, it is quite accessible for use by mankind.

The first time hydrogen was used for aviation purposes was during the First World War. Tethered balloons were used as observation platforms, which subsequently led to numerous airships being built. Until helium was obtained in quantity from natural gas, hydrogen was the only gas used. In 1939, the Hindenburg accident gave Hydrogen the perhaps unjustified reputation of being a very dangerous substance. Public perception has been biased, perhaps unfairly, against hydrogen as a fuel. How the public perceive an aircraft, particularly in civil operations, is an important ‘design’ consideration even though this perception does affect the performance.

The largest user by far of LH_2 has been the space industry which uses LH_2 to fuel rocket and space launchers. Accidents involving liquid hydrogen, such as the “explosions” of space launchers (Challenger in 1986, Ariane 501 in 1996), are in fact the result of *combustion* (fireball) and not explosion. In these cases hydrogen reacted as a fuel but was not the primary cause of the accidents. Unlike the space industry that normally uses components once, aviation components must be designed to withstand shocks and stress of thousands of landings and flight loads for a much longer lifetime, and must also be accessible for inspection and maintenance.

In 1974, the ‘ H_2 indenburg’ society was created to promote the use of hydrogen as the fuel of the future. However, the goal of developing a substantial demonstration of the use of hydrogen power for a substantive portion of economy has not been achieved yet remains a major goal for the future.

At this present time, hydrogen fuel is more expensive to produce than kerosene. The actual cost depends on several factors including the method of liquefaction and production and processing methods, transportation, and storage as well as the cost

of the electricity used. This has meant that there is a varying range of potential costs of hydrogen as shown in Table 2-3 below. On average however, Hydrogen is **3.5** times more expensive to produce. This takes into account the cost of transporting to the airport, storage and delivery into the aircraft tanks.

	Liquefaction Method			
	Conventional		Advanced	
	\$/GJ	\$/10 ⁶ Btu	\$/GJ	\$/10 ⁶ Btu
NASA	10.45	11.01	8.70	9.15
Barstow Plant	7.76	8.18	6.01	6.34
Advanced Electrolysis Methods (Using Electric Power @ 20 mills/kWh)	12.70	13.39	10.95	11.54

Table 2-3 - Estimated costs of Liquid hydrogen (*Brewer, 1991*)

Hydrogen is thus currently far more expensive to produce; however, as normal fossil fuel reserves decrease, their cost will increase making hydrogen production much more economically viable. It is uncertain when this will be, but projected reserves of fossil fuels may stretch to another 50-60 years (*DoE, March 1995*). Until then, their price will gradually increase until a break-even point is reached whereby the costs of both fuels will be the same. Additionally, the cost of hydrogen production will decrease with new technologies and production methods.

2.2.4.1 Advantages of hydrogen

Examination of the hydrogen properties shown in Table 2-2 reveals that the mass of hydrogen fuel required to fly a certain range would be 2.8 times less (considering all other factors remain the same) when compared to a kerosene-fuelled aircraft, i.e. for the same mission, less fuel weight will be carried. Any overall weight saving would enable the use of smaller engines, and less wing area.

Based on operational experience with gas turbine engines fuelled with natural gas, it has been found that engine life is increased by about 25% (*Brewer, 1991*) and that engine maintenance is similarly reduced. This is because the fuel is clean and free of impurities to erode/corrode and very rapid diffusion and mixing promoting complete combustion and providing a uniform temperature profile thereby minimising thermal stresses in the combustor.

The low emissivity of the hydrogen/air flame reduces metal temperatures so combustor liners and turbine vanes and blades are subjected to less rigorous operating conditions. The high specific heat of LH₂, combined with its low temperature, permits the fuel to be used as a heat sink so that the engine can be cooled.

The buoyancy of hydrogen means that in the event of a hydrogen fire, the hydrogen will quickly rise. Therefore, the best course of action in the event of a hydrogen fire is to cut the source rather than using fire-fighting methods.

From an environmental perspective, hydrogen propulsion results in greatly reduced NO_x emission due to “lean” combustion. Emission of NO_x from a hydrogen engine can be reduced by a factor of 1/2 to 1/3 relative to an equivalent kerosene engine (*Brewer, 1991*). The only combustion by-products are a little NO_x and water.

2.2.4.2 Disadvantages of hydrogen

Despite these significant advantages of hydrogen, there are, as in most cases, compromises to be made. Liquid hydrogen fuelled aircraft design will be more challenging. The low density fuel means ingenuity must be exercised to design an aircraft configuration which will accommodate a fuel volume more than *four times* that which would normally be required. Conventional fuel storage in the wing is therefore not possible because of insufficient space but also because of the need to provide an acceptable surface-to-volume ratio to minimise heat leak and weight due

to tank structure and insulation (since liquid hydrogen is a cryogen). Ideally, LH₂ fuel tanks would be spherical which is difficult to achieve in practice, although compromises can be made. The need to contain the large volume and maintain the low temperature of the fuel means that large fuel tanks are required as is extra insulation leading to increased weight. This is in addition to a more complex and heavier fuelling system. An example of the net effect of the increase in fuel tank weight when compared with the lower fuel weight is demonstrated in **Appendix A**. Although this provides an approximation, there are many factors to consider, for example, consideration should be given to the large fuel tank volume which will cause an increase in drag and hence require more thrust and more fuel etc. There will be additional weight due to the increased complexity of the fuel system which will also require insulation.

Hydrogen-fuelled aircraft will have a lower L/D ratio because of the increase in wetted area of the large fuel tanks. Fuel tank weight will also increase because the low temperature of the fuel requires fuel tanks and pipelines be insulated to minimise heat leak and limit boil-off. The fuelling system will also be more complex and therefore heavier.

All contact of the air with any supercooled surfaces must be prevented since this would result in freezing. Special procedures must be followed when fuelling/defuelling a LH₂ tank and a different means of tank pressurisation must be provided.

There are unique safety issues that need addressing due to specific properties of hydrogen. This is set against negative public perception of hydrogen fuel.

2.2.4.3 Summary of LH₂ characteristics and effects on aircraft design

As the previous discussion has shown there are many advantages to liquid hydrogen as an aviation fuel. However, there are associated challenges which result either

directly or indirectly from the properties of the fuel. This has been summarised in Table 2-4.

Property	Effect (relative to jet fuel)
High heat of combustion	Fuel weight reduced by factor of 2.8
High specific heat	Fuel cools engine <ul style="list-style-type: none">◆ High TET and OPR◆ Further reduced sfc◆ Further weight saving
Low density	<ul style="list-style-type: none">◆ Requires over 4 x more volume◆ Large fuel tanks leading to lower L/D
Cryogenic	Requires <ul style="list-style-type: none">◆ Efficient insulation system◆ Heavy tank and fuel system◆ Special tank fill and vent procedures

Table 2-4 - Advantages/disadvantages of using LH₂ fuel for aircraft.

The properties of hydrogen have many far-reaching advantages not limited to just its specific properties. These are illustrated in Figure 2-2 below.

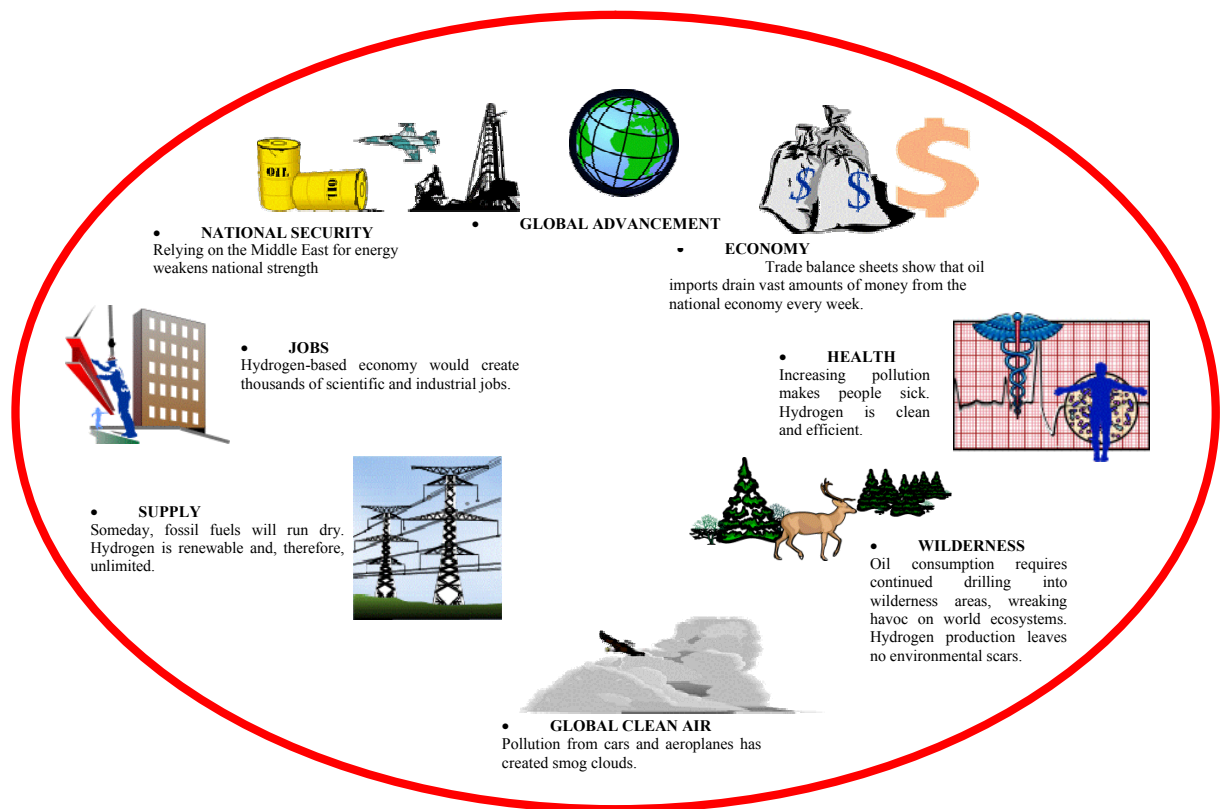


Figure 2-2 – Illustration of the advantages of hydrogen fuel.

As shown in Figure 2-2, switching over to using hydrogen fuel has far reaching advantages, some less quantifiable. Being able to rely on a country's own energy resources means that the economy is strengthened and dependence is not placed on another country for energy which would otherwise be in a position of power able to dictate policy. A hydrogen fuel economy would create a large number of jobs as the industry increases in size with more widespread use. The environmental advantages in switching to hydrogen are overwhelming since Hydrogen may be produced from renewable energy sources providing a sustainable energy source. Additionally, the reduced emissions in the use of hydrogen mean that pollution is significantly less.

2.3 Objectives

In light of the potential of hydrogen as an aviation fuel offering all the advantages previously described, the objective of this thesis is to:

“Develop a conceptual liquid hydrogen-fuelled aircraft design that is to include initial estimates of mass, size and performance. The infrastructure and ground support at an airport necessary to support such liquid hydrogen fuelled aircraft should be defined with those equipment and procedures requiring change to be identified. The safety of employing liquid hydrogen fuel in such an environment is to be addressed and the hazards identified. The Airworthiness regulations that would require change as a direct result of switching to liquid Hydrogen fuel are to be highlighted. Finally, estimates of the direct operating costs of a liquid hydrogen fuelled aircraft, relative to a kerosene fuelled equivalent, are to be presented.

The overall aim is to provide a basis for compatibility of liquid hydrogen as an aviation fuel thus establishing the technical feasibility and future promise of liquid hydrogen fuel”

More specifically, the aims are to:

- Design a viable (technically feasible) conceptual ‘*unconventional*’ medium-range civil transport aircraft *from the outset* to operate on hydrogen fuel. Attempt should be made to exploit properties of hydrogen to compound its benefits with that of the configuration itself. The conceptual design study will begin with a blank sheet of paper and determine layouts that are technically feasible and economically viable providing estimates of its mass, size and performance.
- Provide a breakdown of the economics of a liquid hydrogen fuelled aircraft, illustrating the likely Direct Operating Costs (DOC) of LH₂-fuelled aircraft when compared with an equivalent kerosene aircraft.
- Define the required airport ground operations including turnaround and maintenance procedures and equipment necessary to support the example liquid hydrogen fuelled aircraft.

- Identify operational and safety issues requiring change or implementation regarding procedures and equipment during the turnaround and maintenance operations. It is a fundamental requirement that LH₂ aircraft may be supported and maintained in a manner that is as safe and efficient as it is today for conventional aircraft. In line with this, issues regarding the production, storage and delivery of LH₂ fuel should be analysed to ensure uninterrupted availability at the airport, and to ensure that such a large-scale system is feasible. There are inherent safety and operational issues also associated with the infrastructure. In line with this the airport fuel supply, storage and delivery infrastructure has been defined. Aircraft specific safety aspects should be analysed and taken into account when defining aircraft concepts.
- The airworthiness regulations should be analysed and those regulations requiring modification, and those requiring development from new to address a specific characteristic of liquid hydrogen fuelled aircraft should be identified.

Achieving these objectives will not only provide an understanding into the conflicting requirements and improve the understanding of the technical issues and challenges faced but it is hoped that they will also excite interest and ingenuity.

Because of the very long lead time for development of production capability for alternate fuels, and the long cycle time between development, production and utilisation of the aircraft, serious effort is needed to provide suitable, and above all, safe aircraft and infrastructure. This thesis makes attempts to take a stride towards the design and operation of LH₂ fuelled aircraft and their ground support and provides a comprehensive analysis of some of the complex interrelated aspects as a basis for overall judgement into their feasibility.

3.0 UNCONVENTIONAL AIRCRAFT DESIGN

Now that the potential of hydrogen as an aviation fuel is understood, we can ask the question “*what will a LH₂-aircraft look like and how do we proceed designing one?*”, “*What will its mass and its performance be?*” These are some of the questions that are addressed in this chapter.

Before beginning the design process, it is beneficial to gain an understanding into the development of the passenger jet as it is today and also to look at past research into unconventional configurations.

3.1 *Development of passenger jet configurations – Challenges faced by designers*

Many challenges faced by the aeronautical community in its infancy included:

- ◆ the ability to construct an aircraft capable of safe and sustained controlled flight
- ◆ the development of aircraft that can be flown easily whilst carrying a useful payload
- ◆ development of lightweight materials and manufacturing techniques
- ◆ advancement of aerodynamics and propulsion technology
- ◆ development and integration of electronics and avionics

Many of these issues, although somewhat advanced since then, still remain challenging and equally pertinent. Furthermore, there are the additional challenges in dealing with the environmental issues associated with the operation of aircraft. There is growing concern over the depletion of fossil fuels which will soon (≈ 50 -60 years) cease to be available. Atmospheric pollution is also a serious issue and encompasses pollution due to emissions, ozone formation, CO₂, and water vapour. Aircraft noise, especially in the vicinity of airports has been an issue ever since the rapid development of jet powered commercial aircraft. The rise in commercial

aviation has been dependent on the availability of cheap fuel and so alternative fuels (and configurations) for the future are being sought.

The search for solutions to both present and forthcoming challenges has led to proposals for various novel configurations. Novel configurations proposed in the past few decades have not led to widespread use even though they were backed up by substantial research effort.

3.2 *What drives a unique configuration?*

Since the introduction of the passenger jet, considerable improvements have been made in terms of aerodynamics, structures, propulsion and aircraft systems. Additionally, manufacturing materials and techniques have advanced greatly. Although the classic exterior design of the first Boeing 707 configuration has remained mostly unchanged, things are very different internally.

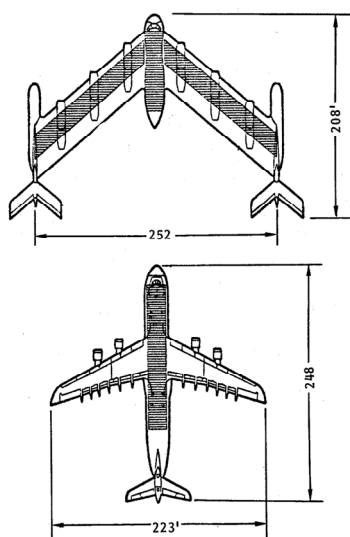
Once limits have been reached of the classic configuration (arguably now), other designs of aircraft must be looked at. Whilst much improvement has been made in terms of safety, comfort, efficiency and performance, the overall layout of these aircraft has remained essentially the same. It is becoming increasingly difficult and expensive to gain any performance improvements from the classical design. Currently, there exists the challenge of meeting increased passenger demand combined with increasing concern over pollution, airport congestion and noise, all of which become more critical as time passes. Arguably, the solution to most of these problems is seen as larger aircraft with much improved efficiency and performance. However, there are many problems with continually stretching a fuselage to provide a larger aircraft, and the predicted efficiency, economic and indeed safety enhancements may not be sufficient to meet these future demands.

Unconventional design concepts based upon the potential benefits to be derived from aerodynamic or structural principles must be subjected to the preliminary design system study process to determine if potential benefit still remains when the

aircraft design is optimised. There is also the problem in that although methods can be used to determine the weight and performance of these unconventional designs, generally there is a lack of statistical or experimental data to validate the performance estimates.

When a designer tries to meet certain extreme or unique design requirements with a “conventional” configuration, it may be that a satisfactory design solution can not be found. In such a case, the result may very well be a ‘unique’ aeroplane configuration. Here we highlight some of the main configurations which have been studied in the past along with their claimed advantages and disadvantages.

3.2.1 *Very Large Aircraft*



One interesting very large aircraft design is the span-distributed loading design in which the payload/cargo is carried in the wing shown in Figure 3-1. By distributing the payload along the wingspan, the structural weight of the wing is reduced due to the reduced bending moment. Pioneering work by Lockheed in 1979 led to the spanloader configuration shown here.

Figure 3-1 - Conventional passenger aircraft and very large spanloader configuration (*Roskam, 1988*)

The spanloader aircraft configuration will require very wide runways and taxiways. To counter this problem, the spanloader employs an unconventional air cushion landing system located at each wing tip and also at the centrebody.

Benefits of the concept compared to conventional designs are shown below in Figure 3-2 and claim to possess 12% lower DOC, 8% lower fuel consumption and 10% lower gross weight. However, there are operational difficulties such as passenger loading, and emergency egress.

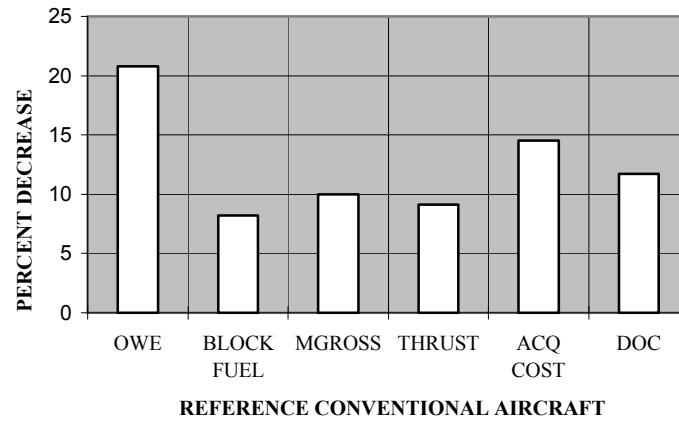


Figure 3-2 - Estimated percentage decrease in aircraft weight, fuel usage, thrust requirements and cost of spanloader aircraft (*Roskam, 1988*).

Boeing also came up with a similar design of a span-distributed load freighter (Figure 3-3) claiming a 50% reduction in DOC compared to an equivalent conventional freighter.

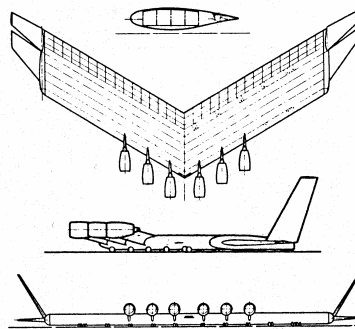


Figure 3-3 - Span-distributed freighter aircraft (*Roskam, 1988*).

3.2.2 Multi-Body Concept

An interesting and much studied alternative to the spanloader design concept is the

multi-body concept where the payload is carried in separate bodies located on the wing as shown below in Figure 3-4.

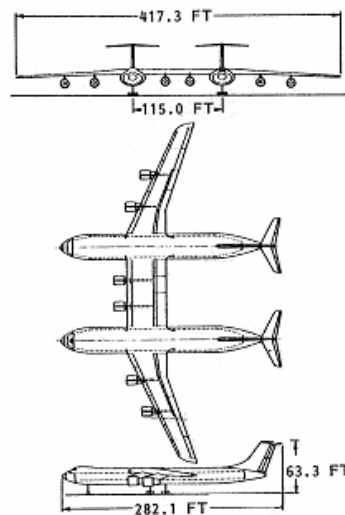


Figure 3-4 - The multi-body aircraft configuration concept (*McMasters J.H., Kroo, October 1996*)

Similar to the spanloader design, the basic advantage of the multibody concept is the reduction in wing root bending moments and the cumulative effects on the performance of the aircraft. The American mustang F-82 had twin fuselages and had almost double the range, a significant increase in payload, and better takeoff performance. For twin-fuselage aircraft the bending moment alleviation allows the use of significantly higher aspect ratio wings aircraft than on an aircraft with single fuselage resulting in an improved in the L/D ratio (which is proportional to $AR^{1/2}$).

In addition, it is expected that faster loading and unloading of the two fuselages is possible when compared to one large fuselage.

The variation of wing bending moments from root to tip is shown in Figure 3-5 below and illustrates that a reduction in wing root bending moment of $\approx 51\%$ can be achieved for a twin-fuselage concept at the cruise condition.

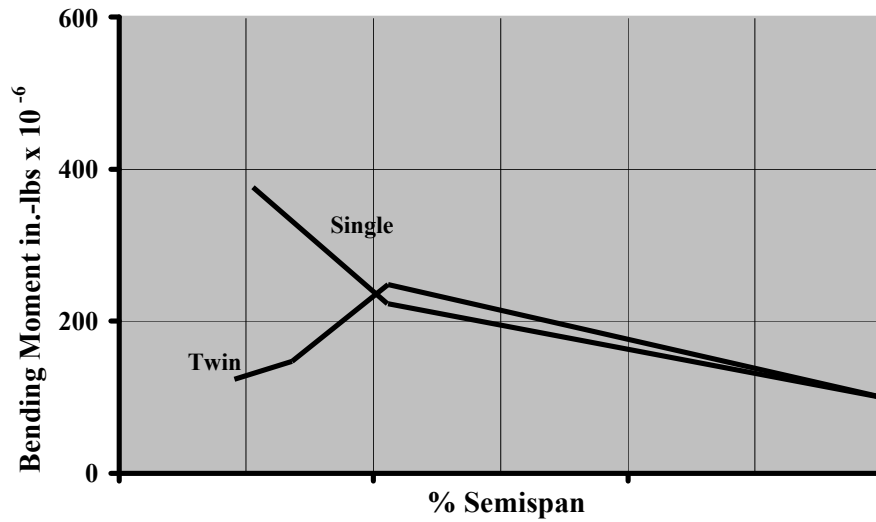


Figure 3-5 – Bending Moment relief offered by the multi-body aircraft configuration concept (*McMasters J.H., Kroo, October 1996*)

The synergistic effects of the reduction in a multibody aircraft weight as compared to the singlebody aircraft is shown in the bar chart in Figure 3-6 below and includes a reduction of 8% in operating weight, 10% in aircraft unit cost, and 11% in DOC.

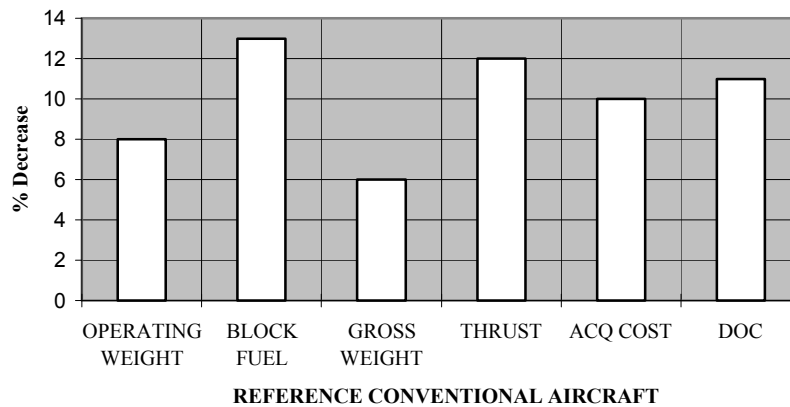


Figure 3-6 – Percent decrease in the weight and cost of the multi-body aircraft configuration concept (*McMasters J.H., Kroo, October 1996*)

If the number of passengers is in the range of 200-400, it is claimed that the use of a twin-fuselage will always yield a smaller wetted surface area. These results have not considered the elimination of the second cockpit and using that space for passengers or cargo which would improve performance and revenue potential further. It is claimed that narrowbodies weight less in terms of fuselage weight than widebodies with the same capacity.

Fuselage spacing is a trade-off between the desire for large separation to aid in load alleviation and several other factors. Four considerations call for less separation

1. adverse yaw due to engine out (assuming fuselage mounted engines)
2. landing gear spacing.
3. minimising rolling moment of inertia
4. minimising excessive dynamic fuselage behaviour

Consideration of all these effects indicates that a fuselage separation distance, centreline to centreline, of about 35% of the wing span is a good choice.

Even with the compromises that these problems bring, it is claimed that the net gains in seat miles per gallon should still be significant, since the total fuselage weight, thrust requirements, wing and tail size, and fuel weight are less.

3.2.3 Oblique wing

This concept enables different configurations for efficient performance over a wide range of flight conditions. At supersonic speeds, wave drag and sonic booms associated with supersonic transports are reduced. The oblique-wing is claimed to be lighter, quieter, and more fuel efficient than a symmetrical swept wing configuration designed for the same mission. Boeing performed a design study (Figure 3-7) for NASA to assess the performance and economic potential of oblique wing transports operating at subsonic speeds. The wing is pivoted to a sweep of 45° for the cruise, and is pivoted back to the unswept position for takeoff and landing.

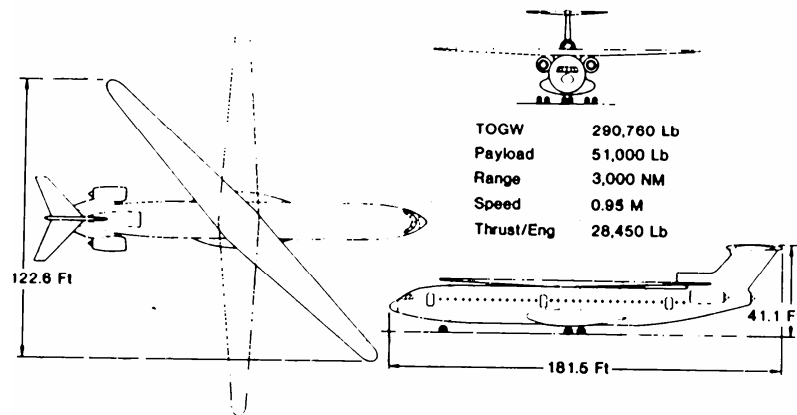


Figure 3-7 - Boeing designed oblique-wing aircraft (*Roskam, 1988*).

The claimed advantages are shown in Table 3-1.

	Oblique wing	Conventional	% Change
Take-Off Gross Weight - lb	307,411	330,238	-7
DOC - ¢/seat mile	2,267	2,386	-5
Thrust/Eng – lb	91,206	101,464	-10
Block Fuel –lb	78,196	83,935	-7
Noise footprint area 90 EPNdB – sq. miles	3.5	7.4	-55

Table 3-1 - Advantages of oblique wing design concept compared with that for fixed swept wing counterpart (*Roskam, 1988*).

Additional advantages of the oblique wing aircraft include efficient operation of multi-mode military operations such as high speed dash compared with low speed reconnaissance.

3.2.4 Transonic biplane

The biplane design is a closed rectangular lifting system having fins connecting the wing tips producing the smallest possible induced drag for a given span and height. Drag reductions of as much as 50% of the monoplane induced drag are predicted for

a vertical separation between the wings equal to the semispan. As an extension of the NASA/Industry Advanced Transport Technology (ATT) program completed in 1972, reconsideration was given to the concept of a transonic biplane (Figure 3-8) as proposed by the Lockheed-Georgia Company.

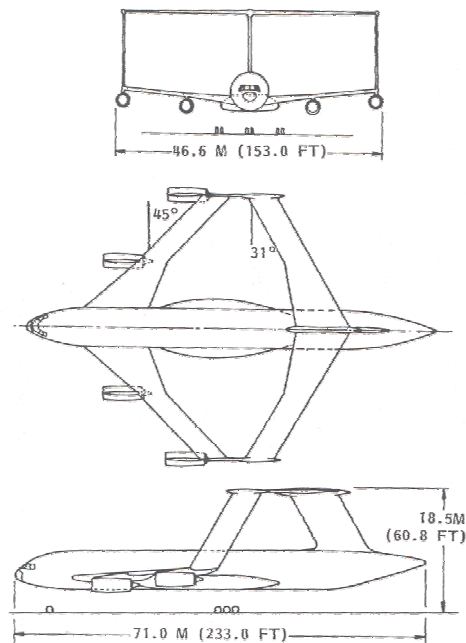


Figure 3-8 - Transonic biplane concept (*Cahill, Stead, 1954*).

In the transonic biplane concept shown above, the two primary lifting surfaces are a swept-back wing attached to the lower part of the forward fuselage and a swept-forward wing attached to the top of the vertical tail at the rear of the fuselage. The data in Table 3-2 shows the principal results of low-speed wind tunnel tests.

Item	Biplane (lb)	Monoplane (lb)
Forward wing	13,060	48,284
Aft wing	13,570	-
Tip fins	9,033	-
Horizontal tail	-	4,105
vertical tail	14,079	3,212
Fuselage	58,970	54,125
Operating weight	281,392	282,377
Passenger payload	84,800	84,800
Mission fuel	298,704	299,248
Ramp Gross Weight	664,896	666,425

Table 3-2 - Component weights of biplane concept compared with conventional monoplane (*Cahill, Stead, 1954*).

The table shows that the weight and fuel required for the biplane concept are approximately the same as those for the monoplane design of the ATT study. However, the biplane incurred flutter instabilities at speeds well below those required for transport aircraft cruising at M0.95. The flutter motions are extremely complex and no single feature of the configuration was isolated as the source of the instabilities.

3.2.5 Joined Wing

The joined wing aeroplane may be defined as one that incorporates tandem wings arranged to form diamond shapes in both plan and front views. Claimed advantages for the joined wing include a lightweight structure, high stiffness, low induced drag, good transonic area distribution, high trimmed C_{Lmax} , reduced wetted area and parasite drag, direct lift control capability, direct sideforce control capability, and good stability and control.

These claims have been supported by independent analyses, design studies and wind tunnel tests. Joined wings are not invariably lighter than aerodynamically equivalent conventional wing-plus tail systems.

Locating the interwing joint inboard provides a lighter wing system than joining the wings at their tips; however, the tip-jointed arrangement has aerodynamic advantages such as higher span efficiency, suitability for winglets, and greater trimming moments. Generally, joint locations from 60-100% of the span may be considered optimum.

The front and rear wings of a joined wing pair both lift upward unlike a conventional wing-plus-tail system with the tail applying a trimming downward force. The net result is that the fuselage bending moments produced by a joined wing are smaller than those produced by a wing-plus-tail arrangement. Lateral and torsional fuselage loads may also be reduced since the joined wing provides additional load paths to withstand rolling and yawing moments applied by gusts or control surfaces.

The savings in fuselage structural weight obtainable through the joined wing depend on the extent to which the fuselage is designed by pressurisation loads as opposed to airloads. However, for many fuselages, significant weight can be saved. Experimental data shows that the joined wing has good stability and control in normal flight and at the stall, and can also provide reductions in parasite drag through smaller lifting surface areas, reduced wing-fuselage interference, and suitability for thin aerofoils. These beneficial effects offset the effects of lower wing Reynolds numbers.

3.2.6 Multirole Global Range Transport

The notable feature of this aircraft is the ability to carry large payloads for very long ranges, $\approx 10,000$ nm, unrefuelled. Excellent reliability and maintainability are required for the long flight times involved.

Design studies show that laminar flow control aircraft tend toward high aspect ratio wings which also provide a reduction in induced drag. The high aspect ratio wings require active controls for gust and manoeuvre load alleviation and flutter suppression and to provide satisfactory flying qualities. The system studies indicate significant acquisition cost savings of about 20% which can be achieved by use of a single multi-purpose aircraft capable of satisfying the several mission requirements.

3.2.7 Forward Swept Wing and application in high aspect ratio aircraft configurations

The benefits of using FSW on aircraft include reduced lift-induced-drag, and improved high angle of attack performance. The lack of adequate material and structural technology in the past, to cope with the FSW aeroelastic divergence problem prevented any serious exploitation of these benefits. With advances in composite material structures, active controls, and improving knowledge of the favourable aerodynamic interferences, e.g. canard effects, the FSW concept can be exploited.

3.3 Aircraft Configuration Design

So, what if we try to combine the possible advantages of a unique, novel and unconventional configuration with the known advantages of hydrogen fuel? This defines the objective which is *to explore a “practical” unconventional configuration as required for a long term change of commercial aviation to hydrogen.*

A practical configuration means a principal arrangement of the aircraft such that typical performance and handling requirements of everyday airline operation can be met without undue need for infrastructure and ground equipment/procedures inconsistent with current aviation. The aim was to design a civil aircraft from the outset to incorporate the large LH₂ fuel volume with minimum penalty and optimum performance benefits.

Ideally, when analysing any configuration, a range of aircraft categories would be studied since it is possible that different configurations have relatively greater/lesser benefits for smaller/larger sizes of aircraft. However, in order to provide more meaningful results, effort was concentrated on a **medium range** aircraft since in this case it was deemed representative of the other aircraft categories.

The first step was to select promising *unconventional* configurations. So how did these configurations evolve? The starting point was to gather or brainstorm ideas which involved many contributors including leading experts and experienced participants. To illustrate and provide some background behind the evolution of these concepts, the procedure adopted for the brainstorming session is briefly described here.

3.3.1 Brainstorming

Brainstorming is used to generate new ideas between a group of people helping to focus and combine efforts with the aim to innovate, and can be composed of the elements shown in Figure 3-9 which lists the main reasons why brainstorming is an effective tool used by many industries, including aerospace.

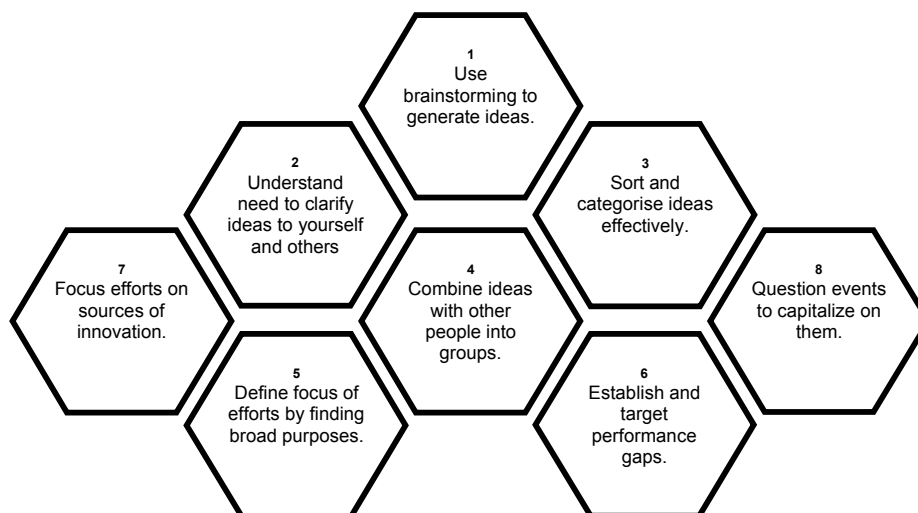


Figure 3-9 – Elements and purpose of Brainstorming.

As described, Brainstorming is commonly used in industry and is effective in generating new ideas. It is on this basis that a Brainstorming session was used to generate ideas for a Liquid Hydrogen fuelled aircraft. As such, on the 12th and 13th September 2005 a Brainstorming session was organised and held at Cranfield University. This session involved the attendees in Table 3-3.

Name	Institute
Professor T Van Holten	Delft University of Technology
Ronald Slingerland	Delft University of Technology
Jeroen Krijnen	Delft University of Technology
Manuel Astaburuaga	Delft University of Technology
Fredrik Svensson	FFA, Sweden
Hans Bjornstrom	FFA, Sweden
Wilhelm Oelkers	DASA
Eric Prenzel	DASA
Hans-Peter Gfell	Dornier
Prof J P Fielding	Cranfield University, College of Aeronautics
Dr Robert I Jones	Cranfield University, College of Aeronautics
Michael Sefain	Cranfield University, College of Aeronautics

Table 3-3 - Brainstorming session attendees.

The specific process that was adopted in the Brainstorming session was broken down and simplified into three processes as shown in the Figure 3-10.

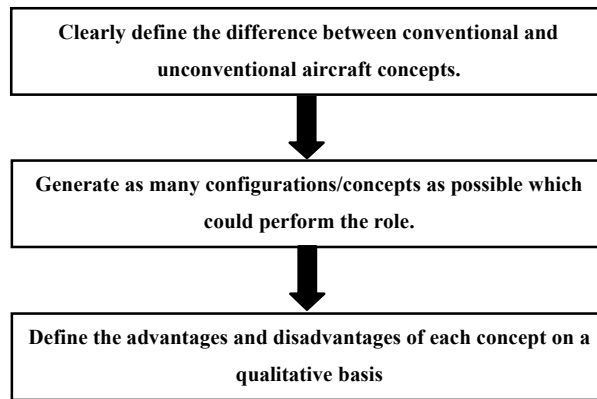


Figure 3-10 – Brainstorming session process.

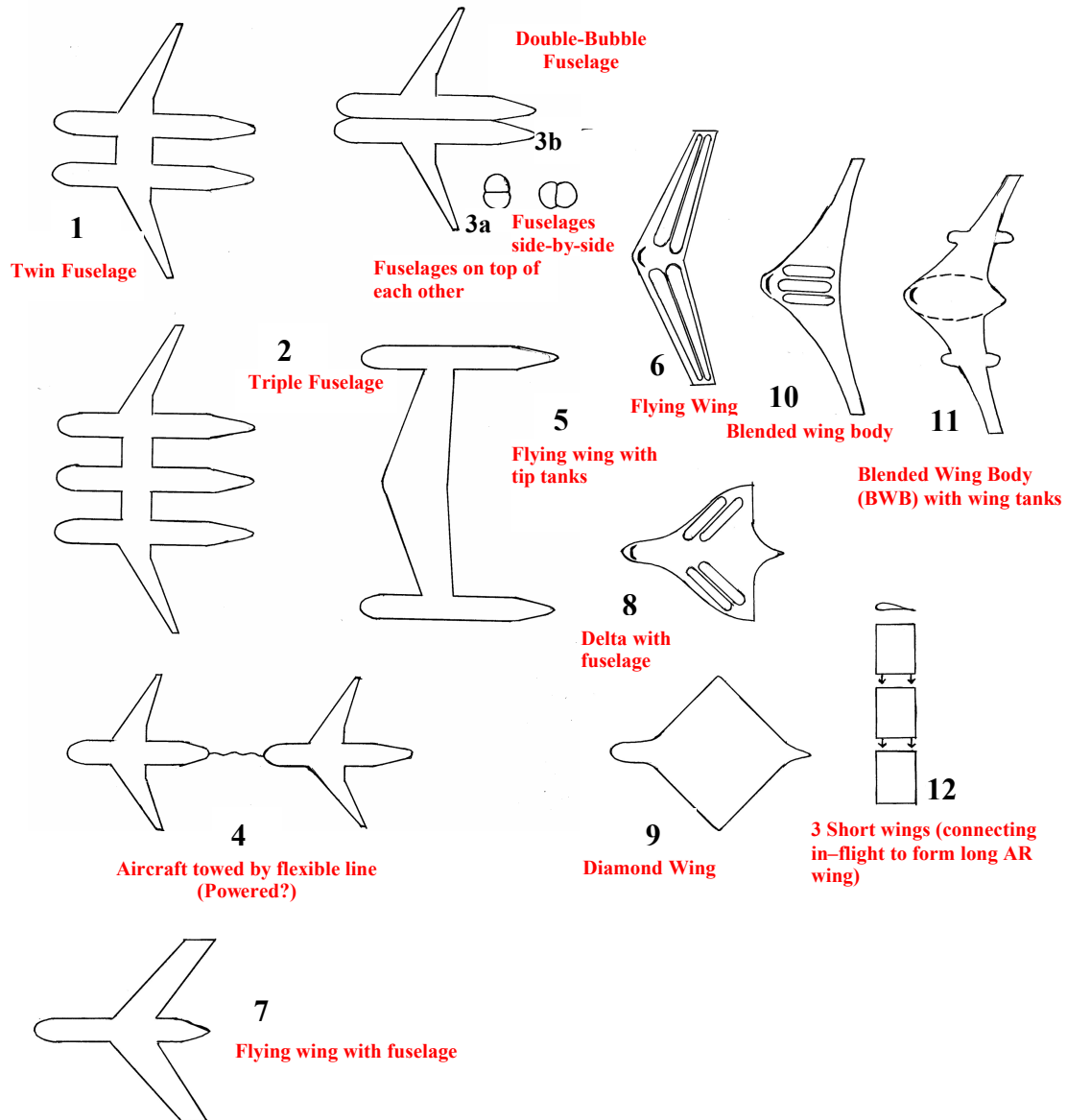
Parameters such as passenger fuselage, hydrogen fuel tanks etc. were varied in shape and location to generate the unconventional configurations according to the following constraints:

- *Concepts only for subsonic civil passenger jet aircraft*
- *No supersonic or military aircraft*
- *No lighter than air vehicles - only fixed wing.*

The constraints were deliberately removed as far as possible to enable new and more innovative ideas to be thought of away from those well known concepts. This extended as far as declaring that all the configurations were not applicable to liquid hydrogen fuelled aircraft but that they be generic.

As a result of the Brainstorming, 20 concepts were generated (Figure 3-11) shown as sketches below.

3.3.2 Results of Brainstorming Session – Configurations



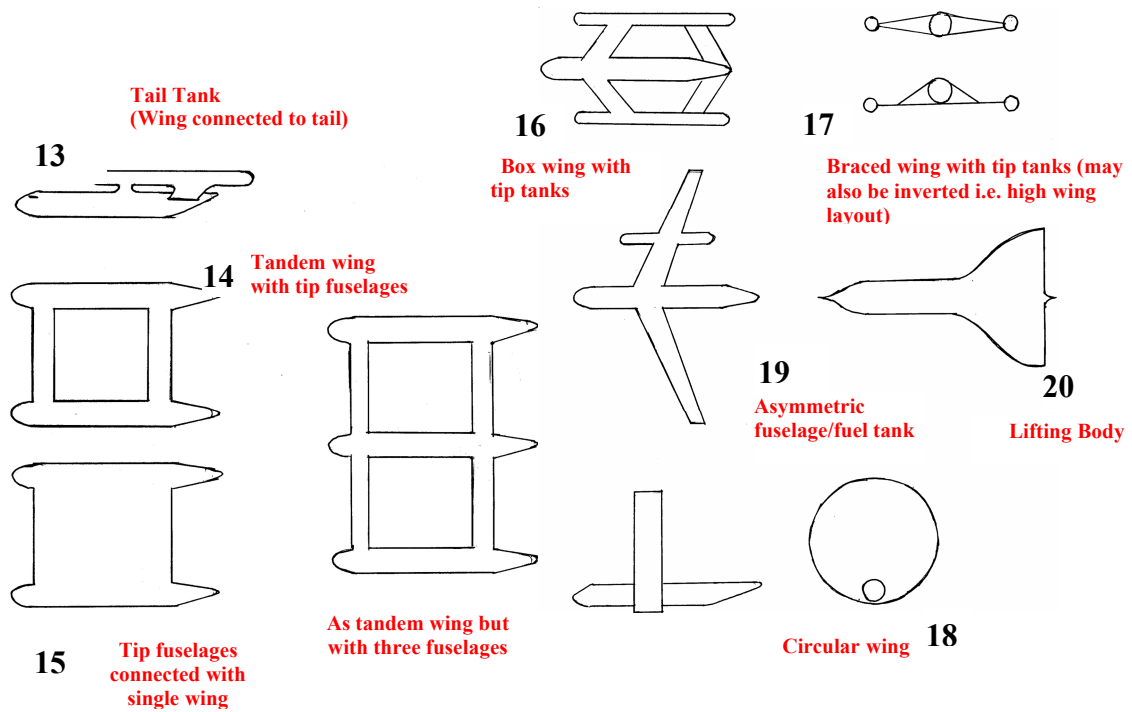


Figure 3-11 – Sketches representing configurations evolving from the Brainstorming session.

The specific aim of the brainstorming session was to generate unconventional configurations that were not specifically applicable to liquid hydrogen fuel but that they be generic. This meant that some of the configurations would not be particularly advantageous to a hydrogen fuelled aircraft. Therefore, to provide a means of further configuration down-selection, the complex relationships and interaction among the concepts were discussed in detail and evaluated by all the participants in order to provide an understanding of the overall behaviour of the system, leading to the perceived principal advantages and disadvantages of each concept as shown in Table 3-4 and Table 3-5. These are listed alongside each configuration and are a combination of aerodynamic, structural or otherwise.

CONFIGURATION	1	2	3a	3b	4	5	6	7	8	9
Fuel pax separation	+	+			+	+		+		
Minimum change	+	+	+	+						
Bending relief	+	+				+	+	+	+	
Family concept	+	+	+	+	+			+	+	
Centre wing (useful volume)	+	+								
Cargo flexibility	+	+	+	+	+					
Commonality			+	+					+	
Performance					-	+	+	+		
Potential volume efficiency						+	+	+	+	
Noise shielding						+	+	+		
Turnaround	-	-	-	-		-	-			
Taxiing (runway size)	-	-				-	-	-		
Pilot position	-	+/-								
Passenger comfort	-	+/-				-	-			
Emergency evacuation	-	-/+	-	-		-	-	-		
Roll inertia	-	-				-	-			
Trim balance	-					-	-			
Undercarriage configuration	-	-				-				
Dynamics	-	-				-				
Drag	-	-		-						
Very unconventional					-	-	-	-		
Landing					-				-	
Fuelling										
Maintenance							-		-	-
Produceability							-			
Family	-	-					-		-	-

+ advantage

- disadvantage

+/- advantage/disadvantage? - depends on specific location of passengers and fuel

Table 3-4 - Advantages/disadvantages for brainstorming configurations 1- 9.

CONFIGURATION	10	11	12	13	14	15	16	17	18	19	20
Fuel pax separation		+		+	+		+	+		+	
Minimum change		+		+							
Bending relief	+	+									
Family concept		+	+	+			+			-	
Centre wing (useful volume)	+					+					
Cargo flexibility		+			+	+					
Commonality											
Performance	+						+			+	
Potential volume efficiency											+
Noise shielding	+										
Turnaround		-			-	-					
Taxiing (runway size)		-	-		-	-					
Pilot position		+/-			-	-					
Passenger comfort		+/-									
Emergency evacuation	-	-/+									
Roll Inertia		-			-	-	-				
Trim balance											
Undercarriage configuration		-	-		-	-					
Dynamics											
Drag				-				-			
Very unconventional		-	-						-		
Landing		-									
Fuelling				-							
Maintenance				-					-		
Produce ability									-		
Family	-				-	-					

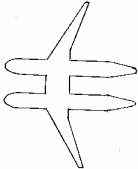
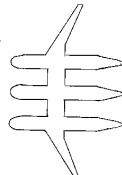
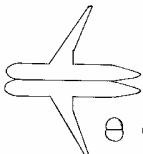
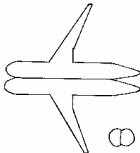
+ advantage

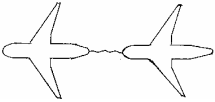
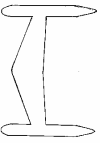
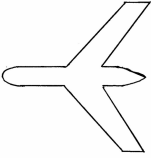
- disadvantage

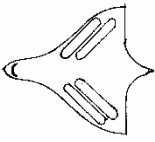
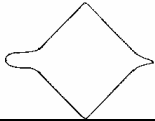
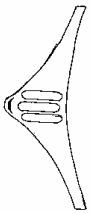
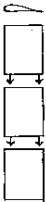
+/- advantage/disadvantage? - depends on specific location of passengers and fuel

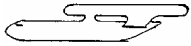
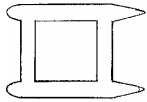
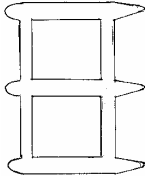
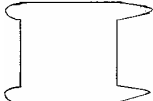
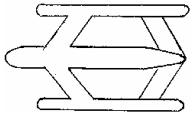
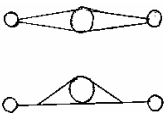
Table 3-5 - Advantages/disadvantages for brainstorming configurations 10-20.

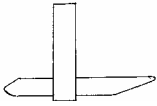
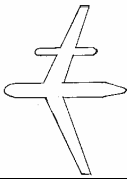
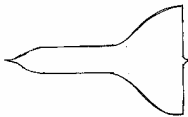
The second day of the Brainstorming session (13th September 2005) was a discussion of the configurations which had evolved. The following data provides the results of that discussion of each concept and provides a brief summary of the main characteristics and features.

Configuration	Characteristics/Main features
1 	<p>Defined by two fuselages separated by part of wing structure.</p> <p>Which fuselage holds passengers and which holds fuel is undetermined i.e. there may be both passengers and tanks in each of the fuselages, or one fuselage dedicated to passengers only and the other one to tanks. Both would be feasible.</p>
<p>Comments</p> <p>Configuration 1 is a variation on configuration 19, particularly when realistic fuel tank sizes are used. Thus, they can be combined into a single configuration whose main features are a single or double passenger fuselage with an external or internal tank respectively.</p> <p>Configuration 1 is also a variation of configurations 3b and 5.</p> <p>This is the first configuration that will be further considered.</p> <p style="text-align: right;">Retained (Combined with configuration 19)</p>	
2 	<p>This is a variation of configuration 1, but defined by three fuselages. Here also, the question of passenger/fuel location is undecided, and provides even more flexibility than configuration 1.</p>
<p>Comments</p> <p>The configuration possesses many disadvantages. Also, as the tanks approach a realistic size, this configuration approaches a “conventional” wing tank concept. For these reasons it will be discarded.</p> <p style="text-align: right;">Rejected</p>	
3a 	<p>This is characterised by two fuselages, one on top of the other, with no separating structure.</p>
<p>Comments</p> <p>This is a “conventional” double-bubble fuselage, and therefore not within the scope of unconventional configurations.</p> <p style="text-align: right;">Rejected</p>	
3b 	<p>This is similar to configuration 3a, except the fuselages are now side-by-side, as in a “double-bubble” design.</p>

Comments This configuration has strong disadvantages, especially in terms of fuel/pax separation – both from safety and structural points of view.		Rejected
4 	This is defined by an aircraft towed by a flexible line. There are questions of whether the towed aircraft is powered or not, and again of passenger/fuel location.	
Comments Far too unconventional and impractical.		Rejected
5 	This is characterised by a main flying wing with two external fuselages/tanks.	
Comments Tends to and is thus a variation of configurations 2 and 11.		Rejected
6 	Configuration 6 is also characterised by a flying wing except this time with internal fuel tanks.	
Comments This configuration possesses similar features to configurations 7, 8, 10, 11, and as such are a variation on a theme. The theme here is a main “flying wing”, possibly with a partially extending fuselage to form a blended wing body. Hence, a blended wing body will be taken as a single concept which is representative of all of these concepts combined, i.e.		
		Retained (combined with configurations 7, 8, 10, 11)
7 	Configuration 7 also consists of a main flying wing but with an extended fuselage.	

Comments <div>See configuration 6.</div>	
8 	A delta wing with a fuselage and internal fuel tanks.
Comments <div>See configuration 6.</div>	
9 	A diamond wing
Comments <p>This is just a special case of and offers no additional advantages over a normal delta wing, i.e. configuration 8.</p> <div>Rejected</div>	
10 	A blended wing body with internal fuel tanks.
Comments <div>See configuration 6.</div>	
11 	A blended wing body with external wing tanks.
Comments <div>See configuration 6.</div>	
12 	Configuration 12 is comprised of three separable short wings, which each take off separately and join in the air to form a “flying wing“ with a longer aspect ratio.

Comments This has obvious impracticalities and is a very unconventional design.		Rejected
13 	The defining feature of this configuration is that the fuel tank is located above the fuselage, but separated by a connecting structure.	
Comments This has potential benefits.		Retained
14 	Configuration 14 is a tandem wing with tip fuselages.	
Comments This will be considered further.		
14a 	Configuration 14a is variation of the tandem wing (configuration 14) but with three fuselages. The joining wings may incorporate sweep rather than the straight edges shown.	
Comments In reality, this is more likely to tend a configuration such as 16 , particularly at the higher subsonic speeds.		See configuration 16
15 	Configuration 15 is also a variation of the tandem wing (configuration 14) but with a single connecting wing.	
Comments This is likely to tend to configuration 1 , and will thus be initially combined.		See configuration 1
16 	This is a box wing with wing tip fuselages/tanks	
Comments There have been previous studies of this type of configuration and the results seem promising.		Retained
17 	Structurally braced wing with tip tanks. The concept may also be inverted i.e. high wing layout.	

Comments Only suitable for low speed and its advantages are few		Rejected
18 	Circular wing	
Comments Offers no advantages, either in performance or in the use of hydrogen		Rejected
19 	Configuration 19 is an asymmetric design defined by a more central fuselage (although not necessarily on the centreline) and a more outboard tank.	
Comments		See configuration 1.
20 	The main characteristic defining this concept is a main lifting body with a small wing.	
Comments Only suitable for high speed, with no real advantages.		Rejected

3.3.3 Configuration assessment

As a consequence of this analysis **six** configurations emerged. To reduce this number further, an “assessment matrix” was used to compare the configurations against important attributes. The details of this process can vary but in general, involves defining the important attributes required for the successful operation of the aircraft, ranking each of the candidate options against these attributes based on quantitative, if available, or qualitative considerations, and then summing the scores of each option to find out which scored the highest. Thus, a meeting was held on the 29th March 2001 and involved participating members (Table 3-6) from Cranfield University.

Name	Institute
Professor D Howe	Cranfield University, College of Aeronautics (retired)
Prof J P Fielding	Cranfield University, College of Aeronautics
Dr Robert I Jones	Cranfield University, College of Aeronautics
Frank Taylor	Cranfield University, College of Air Transport
Michael Sefain	Cranfield University, College of Aeronautics

Table 3-6 – Configuration assessment attendees.

In an attempt to remove as much subjectivity as possible and maximise confidence in the process, the following approach was adopted.

1. Firstly, the specification document was reviewed to produce a limited but inclusive list of general attributes (Table 3-7) to be possessed by the aircraft.
2. This list was then considered by the “customer” to define the relative importance placed on each attribute. (In this case, the customer was represented by a team of leading experts in the field of aircraft design).

3.3.4 Design attributes

The following attributes (Table 3-7) were decided to be important when ranking each configuration, and chosen on the basis that they provided the most important features of a new design yielding economic and performance advantages. However, as some attributes are more important than others, a “weighting” factor was used. This is shown as the Weighting column in Table 3-7.

Attribute		Notes	Weighting
1	Undercarriage configuration	Includes general difficulties of locating/storing undercarriage, any extra complexities, costs introduced etc. Is undercarriage location very difficult?	2/10
2	Engine location	Considerations of where the engines may be located, proximity to fuel tanks (possibly leading to reduced fuel system weight and complexity) etc. Also consider noise, and safety implications.	4/10
3	Fuel volume efficiency/tank config.	The ability of the concept to store the increased fuel volume whilst maintaining the aerodynamic, weight etc. penalty to a minimum. For example, thermal efficiency of insulation is included here.	10/10
4	Safety	Does the configuration provide more/fewer safety advantages, e.g. in terms of fuel/passenger separation, emergency evacuation, etc. which may be effected by different configurations. Also includes other passenger safety aspects. Since the aircraft must be certificated, the real question is that of <i>relative</i> safety. Again, if it's very unsafe then the configuration can be disregarded.	8/10
5	Passenger/payload considerations	Analysis of how well or efficiently the available volume is utilised to contain the passengers and payload - again whilst maintaining the aerodynamic, weight etc. penalty to a minimum. This also includes airport compatibility, and passenger appeal.	5/10
6	Performance	Since this can cover many aspects which are all inter-related, drag is initially used as a measure of the configurations' performance, e.g. less drag = less thrust required = less weight = less cost, etc. Although it is possible that a measure of performance can also be defined from other aspects, e.g. take-off length, range etc.	6/10
7	Weight	This too is also linked to performance, however, it is believed to be an important attribute in itself since it is also linked with DOC.	6/10
8	Maintainability/Reliability	This includes consideration of such features as accessibility, complexity, likely systems failure, etc. For the LH ₂ aircraft, the cooling ability of the liquid hydrogen may help in certain cases.	4/10
9	Stability & Control	This covers aeroelastic effects which may prove more of a problem because of the possibility of large external tanks or unconventional configurations.	5/10

Table 3-7 - Attributes used to rank final brainstorming configurations.

Each concept was ranked by its ease of meeting, or suitability to meet, each attribute, some of which are more specific to the change to hydrogen fuel. Ideally, the ranking of designs for suitability would occur with no knowledge of the weighting factors to prevent any possibility of influencing the concept scores. However, in practice, this is

not easy to achieve as it is often possible to guess the customers' biases even when they are not known from previous experience.

The total scores were evaluated by multiplying the *attribute scores* by their *weighting*. The selection of these configurations was based on qualitative data. Ideally, selection should be based on quantitative data but due to the unconventional nature of the configurations and the large number of them meant that this was not feasible. This is a common problem in industry. Instead, a group of leading experts in the aerospace industry and aircraft design assembled to fully evaluate each concept on an individual basis lending experience, forethought and insight into the benefits of each.

3.3.5 *Final concepts*

Subsequently, after all the brainstorming and analysis, two configurations emerged (Figure 3-12):

1. A Twin-Boom configuration was thought of whereby external slender booms were utilised as hydrogen fuel tanks and also as structural booms interconnecting the wing and tail surfaces together.
2. A Tail-Tank configuration whereby a tank was placed above the fuselage but physically separated from it, apart from being interconnected by an above-fuselage pylon and the tailplane.

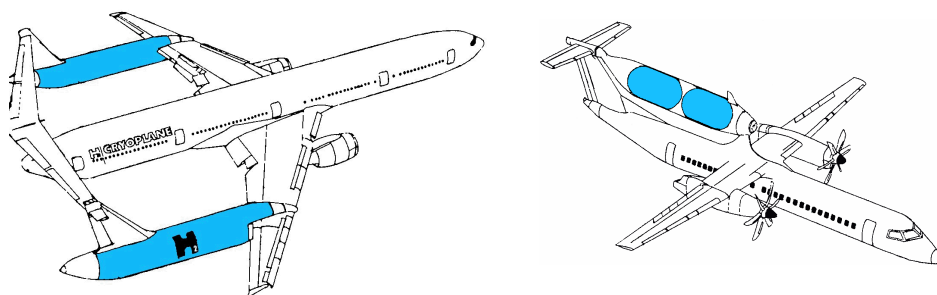


Figure 3-12 - Twin Tail-Boom and Tail-Tank concepts.

Although the Tail-Tank concept scored highly it was deemed too “conventional”. Since the study focused on unconventional designs, this concept was discarded. It is worthy to note that the tail tank configuration scored particularly highly due to it being “minimum change”.

Aircraft Design process

Having reduced the number of configurations to a more manageable number i.e. two, a preliminary design may be conducted. There are many aircraft design processes, but all involve a significant amount of iteration. With an aircraft specification outlining the requirements (detailed in the following section), the aim was to arrive at an optimum solution, normally leading to detailed design, and subsequent manufacture. Estimates and assumptions are used to start the process since much can be achieved with a simple approach whereas as the design matures it is progressively refined.

The complete design process consists of three usually distinguishable phases comprising the following:

- ◆ overall systems study
- ◆ project design phase
- ◆ detailed design phase

The aim here is to progress to a baseline design by synthesising all the requirements resulting in an initial configuration being derived giving an indication of the likely performance benefits. The following conceptual design has predominantly been obtained from equations and formulae from the *Cranfield Conceptual Aircraft design Course, 2000*, *Raymer, 1989* and *Torenbeek, 1982* which all adopt similar processes to that shown in Figure 3-13.

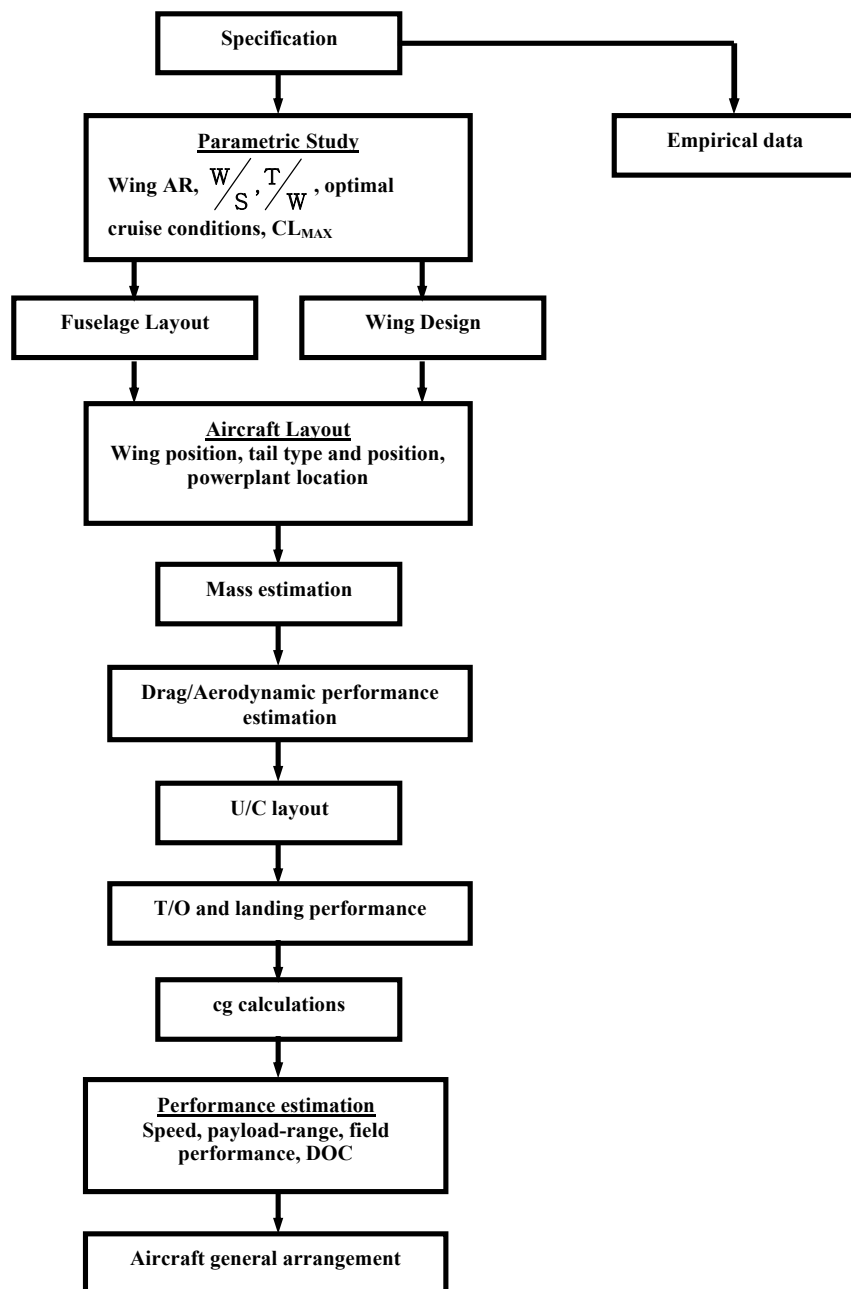


Figure 3-13 - Schematic flow diagram of conceptual design process (Fielding, 1999).

The first task is to obtain rough estimates of the mass and size. The mass depends on payload, range, speed, operating altitude etc., which are stated in the requirement specification. Past experience or knowledge of similar types plays a very large part in the project design phase and herein lies the difficulty with the unconventional aircraft under analysis. Any data or information is very scarce and that which is available is very specific to the configuration under review. Therefore, the initiation of the project

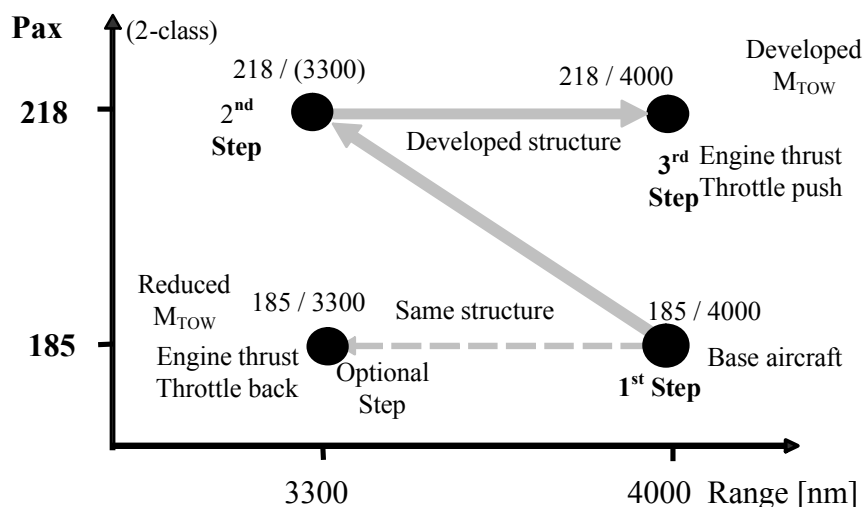
design process requires many assumptions. In all cases, however, the optimum design layout is only achieved after an investigation into the influence of all the parameters and their sensitivity to changes. Achievement of the optimum solution is based on minimising mass, since mass is closely related to cost, although not directly proportional (since it is often possible to reduce mass by employing relatively costly materials).

3.4 Conceptual Design

3.4.1 *Medium-Range Aircraft Specification* (JAR/FAR 25)

The following specification was produced during the CRYOPLANE project (*CRYOPLANE, 2000*) and developed by EADS Airbus. The specification is representative of the future requirements of a medium-range civil transport aircraft based on introducing hydrogen in ≈ 2015 providing an excellent and *realistic* basis on which to base the proposed aircraft design.

<i>Category/Type</i>	Commercial jet aircraft
<i>Basic capacity:</i>	180 seats medium range for 2 Class layout – with 10% FC
<i>Family</i>	A nominal range of family members should be achievable without using auxiliary tanks.
<i>Range:</i>	4 000 nm defines basic engine size/thrust
<i>Technology Level</i>	2010 design standard. Defined improvements vs 1990 includes:
	Aerodynamics L/D 4% better
	Weights MWE 7.5% better
	Engines sfc 10% better



Tank capacity of variants should permit 100% of design range at reduced payload.

Flight crew 2 + 1 observer. Standardisation for 90% US male 2010.

Cabin Crew Special attendant seats located near doors. No extra rest facilities.

	FC	YC
Pass/attendant	10	50

Lavatories

	FC	YC
Pass/lavatory	10	50

Catering

	FC	YC
meals/passenger	7	1.7

Comfort

	First Class	Economy Class
Seat pitch	36 in	32 in
Seat depth	27.5 in	26 in
Seat recline	7 in	5 in
Leg room	22 in	20 in

	First Class	Economy/High Density
Head clearance	> 5"	> 1"
Seats' width		
Double	54"	41.5"
Single	27"	22"
Triple	-	62"
Luggage (hatracks)	Baggage size 22" x 8.7"	

Interior noise OASPL < 80 dB (A)

SIL < 70 dB

Pressure differentiation 8.13 lb/in² (560 hPa)

WC Fluid/Waste 1.2kg/pax

Fuel Liquid Hydrogen

	Kerosene	Hydrogen
Density for performance	803 kg/m ³	71 kg/m ³
Heating Value	18600 Btu/lb	52000 Btu/lb

<i>Fluids for Engines</i>	Oil for engines: no. of engines x thrust/1000		
<i>Unusable fuel</i>	10% of maximum fuel capacity.		
	<u>First Class</u>	<u>Economy Class</u>	
<i>Fixed Equipment</i>	1.5 kg/pax	0.4 kg/pax	
<i>Catering</i>	15 kg/pax	6 kg/pax	
<i>Passenger seats</i>	32 kg/seat	14 kg/seat (including life vests)	
<i>Loading Devices</i>	Container LD3 – 46W	65kg/unit	
<i>Standard Equipment</i>	Aircraft documents	19kg	
<i>Emergency equip</i>	Aircraft dependent	15 kg/aircraft	
	Passenger dependent	0.3 kg/pax	
<i>Geometry</i>	General 54 m x 54 m box to be observed		
<i>Flight Physics</i>	Equal or better than existing aircraft (e.g. A320)		
<i>Structures/Systems</i>	According to regulations and requirements		
<i>Propulsion</i>	2 engines minimum		
<i>Weight</i>	Standard passenger weight	75.0 kg	
	Luggage	15.7 kg	
<i>Flight performance</i>	Cruise speed	0.80 mach	
	Approach speed	< 135 kts	
	Max. operating speed	0.84 mach	350 kts (CAS)
	Max. operating altitude	41 000 ft	
	One engine out ceiling	16 000 ft (97% M _{TOW} , ISA)	
	Community noise	- 30 EPN dB (cumulative)	
<i>Field performance</i>	Take/off landing length	< 7 000ft	
<i>Pavement strength</i>	CAN < 45, Flex, cat B		
<i>Economics</i>	Typical block distance	2000nm	
	Utilisation	850 trips/year	

3.4.2 Twin-Boom Conceptual design

The design process begins by collating a database of information relating to historical and in-service aircraft and with which we can use to support assumptions or provide initial estimates. The following tables (

Table 3-8, Table 3-9, and Table 3-10) provide various data for the Airbus A310-300, and Boeings 707-320C and 757-200. These aircraft have been selected because they are similar (in terms of passenger load and range) to the specification for the proposed Twin Boom aircraft.

Manufacturer Type Model	AIRBUS A310- 300	BOEING 707- 320C	BOEING 757- 200
Initial service date	1983	1962	1982
In service (ordered)			
Africa	11	53	8
Middle East/Asia/Pacific	69(5)	31	65(5)
Europe & CIS	87(1)	9	181(20)
North & South America	57	25	551(61)
Total aircraft	224(6)	120	805(86)
Engine Manufacturer	P&W	P&W	R-R
Model / Type	4152	JT3D-7	RB211-535E4B
No. of engines	2	4	2
Static thrust (kN)	231.0	84.5	191.3
Operational Items:			
Accommodation:			
Max. seats (single class)	280	219	239
Two class seating	218	147	186
Three class seating	187	-	-
No. abreast	9	6	6
Hold volume (m ³)	79.90	50.27	50.69
Volume per passenger	0.29	0.23	0.21
Mass (Weight) (kg):			
Ramp	150900	152405	116360
Max. take-off	150000	151315	115900
Max. landing	123000	112037	95450
Zero-fuel	113000	104330	84550
Max. payload	33300	38100	25690
Max. fuel payload	21500	12852	22610
Design payload	20710	13965	17670
Design fuel load	49624	71126	40190
Operational empty	79666	66224	58040
Weight Ratios:			
Ops empty/Max. T/O	0.531	0.438	0.501
Max. payload/Max. T/O	0.222	0.252	0.222
Max. fuel/Max. T/O	0.322	0.471	0.290
Max. landing/Max. T/O	0.820	0.740	0.824
Fuel (litres):			
Standard	61100	90299	42597
Optional	68300		

Table 3-8 - Engine details, Mass, Weight Ratio and fuel volumes for Airbus A310-300, Boeing 707-320C, and Boeing 757-200 (*Simpkin, Rhodes, Jenkinson, Aircraft Data Set*)

Manufacturer/Type/Model	AIRBUS A310- 300	BOEING 707- 320C	BOEING 757- 200
DIMENSIONS			
<i>Fuselage:</i>			
Length (m)	45.13	44.35	46.96
Height (m)	5.64	3.76	4.10
Width (m)	5.64	3.76	4.00
Finess Ratio	8.00	7.30	11.74
<i>Wing:</i>			
Area (m ²)	219.00	283.40	185.25
Span (m)	43.89	44.42	38.05
MAC (m)	5.89	7.36	5.64
Aspect Ratio	8.80	6.96	7.82
Taper Ratio	0.283	0.259	0.243
Average (t/c) %	11.80	10.00	
1/4 Chord Sweep (°)	28.00	35.00	25.00
<i>High Lift Devices:</i>			
Trailing Edge Flaps Type	F1	F1	S2
Flap Span/Wing Span	0.840	0.670	0.757
Area (m ²)	36.68	44.22	30.380
Leading Edge Flaps Type	slats	flaps	slats
Area (m ²)	28.54		18.39
<i>Vertical Tail:</i>			
Area (m ²)	45.20	30.47	34.37
Height (m)	8.10	7.20	7.33
Aspect Ratio	1.45	1.70	1.56
Taper Ratio	0.395	0.410	0.35
1/4 Chord Sweep (°)	40.00	30.00	39.000
Tail Arm (m)	20.20	21.00	18.97
S_v/S	0.206	0.108	0.19
$S_v L_v/S_b$	0.095	0.051	0.092
<i>Horizontal Tail:</i>			
Area (m ²)	64.00	58.06	50.35
Span (m)	16.26	13.95	15.21
Aspect Ratio	4.13	3.35	4.59
Taper Ratio	0.417	0.400	0.33
1/4 Chord Sweep (°)	34.00	36.00	27.500
Tail Arm (m)	22.50	20.50	19.85
S_h/S	0.292	0.205	0.27
$S_h L_h/S_c$	1.116	0.571	0.957
<i>Undercarriage:</i>			
Track (m)	9.60	6.73	7.32
Wheelbase (m)	15.21	17.98	18.29
Turning radius (m)	31.40		36.60
No. of wheels (nose;main)	2;8	2;8	2;8
Main Wheel diameter (m)	1.168	1.117	
Main Wheel width (m)	0.406	0.406	
<i>Nacelle:</i>			
Length (m)	6.30	6.00	5.2
Max. width (m)	2.70	1.60	2.60
Spanwise location	0.352	0.44/0.71	0.34

Table 3-9 - Fuselage, Wing, Tail and Undercarriage dimensions for Airbus A310-300, Boeing 707-320C, and Boeing 757-200 (*Simpkin, Rhodes, Jenkinson, Aircraft Data Set*).

Manufacturer Type Model	AIRBUS A310- 300	BOEING 707- 320C	BOEING 757- 200
PERFORMANCE			
Loadings:			
Max. power load	324.68	447.47	302.93
Max. wing load (kg/m ²)	684.93	533.93	625.64
Thrust/Weight Ratio	0.3140	0.2278	0.3365
Take-off (m):			
ISA sea level	2290	3054	2226
ISA +20°C SL.	2450		2682
ISA 5000ft	2950		
ISA +20°C 5000ft	3660		
Landing (m):			
ISA sea level.	1490	1905	1564
ISA +20°C SL.	1490		1564
ISA 5000ft	1686		1774
ISA +20°C 5000ft	1686		1774
Speeds (kt/Mach):			
V_2	156		150
V_{app}	138	135	137
V_{no}/M_{mo}	360/M0.84	383/M0.90	350/M0.86
V_{ne}/M_{me}	420/M0.90	425/M0.95	
C_{Lmax} (T/O)	2.45		2.42
C_{Lmax} (L/D @ MLM)	3.02	2.22	2.81
Max. cruise :			
Speed (kt)	484	521	513
Altitude (ft)	35000	25000	31000
Fuel consumption	4690		5039
Long range cruise:			
Speed (kt)	458	478	459
Altitude (ft)	37000		39000
Fuel consumption	3730		3470
Range (nm):			
Max. payload	3645	3150	3812
Design range	4300		4000
Max. fuel (+ payload)	5076	5000	4265
Ferry range			
Design Parameters:			
W/SC_{Lmax}	2227.23	2360.53	2185.60
W/SC_{LtoST}	2702.77	3947.87	2474.59
Fuel/pax/nm (kg)	0.0529		0.0540
Seats x Range	937400		744000

Table 3-10 - Performance data for Airbus A310-300, Boeing 707-320C, and Boeing 757-200 (*Simpkin, Rhodes, Jenkinson, Aircraft Data Set*).

Aspect Ratio

In the first instance we begin by selecting a representative Aspect Ratio (A) for the medium-range Twin Boom aircraft. Normally at a later stage in the design process, the aspect ratio is determined by a trade-off study in which the aerodynamic advantages of a higher aspect ratio are balanced against the increased weight. For our initial layout, we can use the following values:

<i>Phase</i>	<i>Equation</i>	<i>Parameters</i>	<i>Reference</i>
Aspect ratio	$\text{Aspect ratio} = AM_{\max}^c$		Table 4.1, RAYMER, 1989
		A 7.50	Table 4.1, RAYMER, 1989
		C 0	Table 4.1, RAYMER, 1989
		$M_{\max}$	Specification, 3.4.1

Table 3-11 - Initial estimate for aspect ratio.

T/W

Next we can calculate an initial value for the Thrust to Weight (T/W) ratio. The Thrust/Weight ratio directly affects the performance of any aircraft. An aircraft with a higher T/W will accelerate more quickly, climb more rapidly, reach a higher maximum speed and sustain higher turn rates. On the other hand, the larger engine will consume more fuel increasing aircraft weight. T/W varies since the weight of the aircraft varies during flight as fuel is burned. In addition, the engine's thrust varies with altitude.

<i>Phase</i>	<i>Equation</i>	<i>Parameters</i>	<i>Reference</i>
Thrust Weight Ratio	$T/W_o = AM_{\max}^c$		Table 5.3, Raymer, 1989
		A 0.267	Table 5.3, Raymer, 1989
		C 0.363	Table 5.3, Raymer, 1989
		$M_{\max}$ 0.84	Specification, 3.4.1

Table 3-12 - Estimate for Thrust Weight Ratio (T/W).

W/S

The wing loading (W/S) is the weight of the aircraft divided by the wing area. The quoted W/S normally refers to take-off but can also be related to other flight conditions. W/S affects stall speed, climb rate, take-off and landing distances, and

turn performance. It is the wing loading that determines the design lift coefficient, and also impacts drag (through its effect upon wetted area and wing span). More importantly, wing loading has sizeable effect upon aircraft weight, since if wing loading is reduced the wing is larger. Although a larger wing may improve performance it will also lead to additional drag and empty weight.

We can make an initial estimate of wing loading by equating stall and approach speed.

<i>Phase</i>	<i>Equation</i>	<i>Parameters</i>	<i>Reference</i>
Wing Loading (STALL)	$W/S = q_o C_{LMAX}$		
		$q_o = \text{dynamic pressure} = \frac{1}{2} \rho V^2$	
		$\rho = 0.0023769 \text{ sl/ft}^3 \text{ at sea level}$	<i>ISA Tables</i>
		$C_{LMAX} = 2.3 \text{ assuming Fowler flaps}$	<i>Fig 5.3, Raymer, 1989</i>
		$V_{\text{approach}} = 135 \text{ kts (228.5 ft/s)}$	<i>Specification, 3.4.1</i>
		$1.2V_{\text{stall}} = V_{\text{approach}}$ $V_{\text{stall}} = 190.4 \text{ ft/sec}$	<i>Raymer, 1989</i>

Table 3-13 - Estimate for Wing Loading (W/S) - Stall

W/S - Landing

The landing distance can be used to estimate the maximum wing loading. In this case, it is a useful starting point since the maximum landing distance is defined in the specification (section 3.4.1).

For aircraft with thrust reversers (as in most modern passenger aircraft), the landing distance is reduced. To reflect this the first term in equation 5.11 (Raymer, 1989) and shown in Table 3-14 is multiplied by 0.66 (*RAYMER*). Furthermore, for commercial (FAR 25) aircraft, the total landing distance is multiplied by 1.67 to provide the required safety margin.

Phase	Equation	Parameters	Reference
Wing Loading (LANDING)	$S_{landing} = 80 \left(\frac{W}{S} \right) \left(\frac{1}{\sigma C_{L_{MAX}}} \right) + S_a$		<i>Eq 5.11, Raymer, 1989</i>
		$S_{landing} = 7000\text{ft}$	<i>Specification, 3.4.1</i>
		S_a = obstacle clearance distance = 1000 (for airliner and 3 deg glide slope)	<i>Raymer, 1989</i>
		$C_{L_{MAX}} = 2.3$	<i>Table 3-13</i>
		$\sigma = 1$ (sea level)	<i>ISA Tables</i>

Table 3-14 - Estimate for Wing Loading (W/S) – Landing.

W/S - Cruise

To maximise range during cruise, the wing loading should be selected to provide a high L/D at cruise conditions. As mentioned, during cruise, the aircraft weight reduces due to the fuel burned, so the wing loading also reduces. Thus, in order to maintain optimum cruise efficiency despite the reducing wing loading the dynamic pressure should be reduced by the same amount. The dynamic pressure can be reduced in either of two ways: by reducing the velocity, which is undesirable, or by climbing to a higher altitude (lower air density). The second method is the method usually employed and is known as *cruise-climb*. A jet aircraft flying a cruise-climb will obtain maximum range by flying at a wing loading such that the parasite drag is 3 times the induced drag.

Phase	Equation	Reference
Wing Loading (CRUISE)	$\frac{W}{S} = q \sqrt{\frac{\pi A e C_{D_0}}{3}}$ (Maximum Jet Range)	Eq. 5.14, Raymer, 1989
	Parameters	Reference
	At 35,000ft cruise altitude	
	a 973.1ft/sec	ISA Tables
	ρ 0.0007382sl/ft ³	ISA Tables
	M 0.8	Specification, 3.4.1
	u = Ma 778.5 ft/sec	
	q 223.69	
	A Aspect ratio	Table 3-11
	C _{fe} 0.003	Table 12.3, Raymer, 1989
	$C_{D_0} \quad C_{f_e} \frac{S_{wet}}{S_{ref}} = 0.012$	Eq. 12.23, Raymer, 1989
	S _{wet} /S _{ref} 4	Raymer, 1989
	$e = 4.61 \left(1 - 0.045 A^{0.68} \right) \left(\cos \Lambda_{LE} \right)^{0.15} - 3.1$	Eq. 12.50, Raymer, 1989
	Λ _{LE} 30°	Assumption – Jenkinson, Simpkin, Rhodes, Aircraft Data Set

Table 3-15 - Estimate for Wing Loading (W/S) – Cruise.

Mission Segment Weight Fractions

The take-off weight is calculated by summing the crew, payload, fuel, and empty weights which are all expressed as fractions of take-off weight. An initial guess is used to determine a calculated take-off weight, and the solution is iterated until the two are approximately equal. Thus empty weight fraction may be estimated.

Phase	Equation	Parameters	Reference
$\frac{W_e}{W_o}$	$\frac{W_e}{W_o} = A + BW_0^{C1} A^{C2} (T/W_0)^{C3} (W_0/S)^{C4} M_{\max}^{C5} K_{VS}$	A 0.32	Table 6.1, Raymer, 1989
		B 0.66	
		C1 -0.13	
		C2 0.3	
		C3 0.06	
		C4 0.05	
		C5 0.05	
		K _{VS} 1.00 (fixed sweep)	
		Results in ... $\frac{W_e}{W_o} = 0.32 + 0.548W_0^{-0.13}$	

Table 3-16 - Estimate of empty weight fraction for calculation of mission segment weights

The methods used for estimating the mission-segment weight fractions i.e. Engine Start, Taxi and Take-off, Climb, Cruise, Descent and Landing, are a combination of analytical and statistical methods.

Phase	Equation	Parameters	Reference
Warmup and Take-off	W_1/W_0	W_1/W_0 0.97-0.99	<i>Eq. 6.8 Raymer, 1989</i>
Climb	$W_2/W_1 = 0.991 - 0.007M - 0.01M^2$		<i>Eq 6.9, Raymer, 1989</i>
		M 0.8 (Cruise Mach)	<i>Specification, 3.4.1</i>
Cruise	$\frac{W_3}{W_2} = e^{\left[\frac{-RC}{V \left(\frac{L}{D} \right)} \right]}$		<i>Eq 6.11, Raymer, 1989</i>
		At 35,000ft (cruise altitude),	<i>ISA Tables</i>
		a 973.1 ft/s	
		V = Ma 778.48 ft/s	<i>ISA Tables</i>
		ρ 0.0007382 sl/ft ³	<i>ISA Tables</i>
		q_0 223.69	
		R 4000 nm	<i>Specification, 3.4.1</i>
		c 0.5502	<i>CRYOPLANE, 2000</i>
		W/S $W/S_{(cruise)} \times W_1/W_0 \times W_2/W_1$	<i>Raymer, 1989</i>
		A 7.5	<i>Table 3-11</i>
		C_{do} 0.012	<i>Table 3-15</i>
		e	<i>Table 3-15</i>
		$\frac{L}{D} = \frac{1}{\frac{qC_{D_O}}{W/S} + \frac{W}{S} \frac{1}{q\pi Ae}} = 14.6$	<i>Eq 6.13, Raymer, 1989</i>
Descent for Landing	$W_4/W_3 = 0.99-0.995$	W_{i+1}/W_i	<i>Eq 6.22, Raymer, 1989</i>
Landing and Taxi back	$W_5/W_4 = 0.992-0.997$		<i>Eq 6.23, Raymer, 1989</i>
Total Mission Weight Fraction $W_5/W_0 = (W_1/W_0) \times (W_2/W_1) \times (W_3/W_2) \times (W_4/W_3) \times (W_5/W_4)$			

Table 3-17 - Calculation of Total Mission Weight Fraction

The specific fuel consumption (sfc) is obtained from Unconventional engines, (*CRYOPLANE, 2000*) and has been increased by 10% to account for installation

losses (*Raymer, 1989*) and then reduced by 10% to account for advanced technology (*Specification, 3.4.1*).

During cruise (and loiter), the lift equals the weight, so the Lift to Drag ratio (L/D) can be expressed as the inverse of the drag divided by the weight. Furthermore, since all weight lost must be due to fuel used, and allowing a 10% allowance (*Specification, 3.4.1*) of fuel for ullage (and also excess volume for pressure relief), the total fuel fraction can be calculated.

$$\frac{W_f}{W_0} = 1.10 \left(1 - \frac{W_s}{W_0} \right) = 0.33 \quad \text{Eq. 3.11, Raymer, 1989}$$

As previously stated, the iteration for takeoff weight (W_0) begins with an initial guess for W_0 (e.g. using historical data), and then the aircraft weight is calculated throughout the mission until the estimated and calculated weight converge to give values that are the same (approximately).

Weight Estimation

Initial Guess $W_0 = 3\,000\,000$ lb

The mass of the payload, $M_{PAY} = (\text{No. of pass} + \text{crew}) \times \text{pass. Weight} + (\text{No. of cargo containers} \times \text{weight per container}) = 40257$ lb (using details from the *Specification, Section 3.4.1*).

Empty Weight, $W_e = 127\,920$ lb (from Table 3-16)

For the iterative calculation, the calculated empty weight is given by the following equation derived using *Eq 19.13, Raymer, 1989*.

$$W_e = 127\,920 \left(\frac{W_0}{300\,000} \right)^{1+c}$$

Where $c = -0.06$

Fig 3.1, Raymer, 1989

The mass iteration can be seen below in Table 3-18.

W ₀ lbs	W _F lbs	W _E lbs	W ₀ (CALCULATED) lbs
300000	106812.84	127920	274989.72
274989.7	97908.11	117869	256034.67
256034.7	91159.30	110216	241632.42
241632.4	86031.48	104378	230666.79
230666.8	82127.25	99919	222303.78
222303.8	79149.66	96510	215917.14
215917.1	76875.74	93902	211034.65
211034.7	75137.37	91904	207298.94
207298.9	73807.29	90374	204438.78
204438.8	72788.95	89202	202247.85
202247.8	72008.89	88303	200568.90
200568.9	71411.11	87613	199281.89
199281.9	70952.88	87085	198295.09
198295.1	70601.54	86679	197538.34
197538.3	70332.10	86368	196957.92
196957.9	70125.45	86130	196512.70
196512.7	69966.93	85947	196171.16
196171.2	69845.33	85806	195909.13
195909.1	69752.03	85699	195708.10
195708.1	69680.46	85616	195553.85
195553.9	69625.54	85553	195435.51
195435.5	69583.40	85504	195344.70
195344.7	69551.07	85467	195275.03
195275	69526.27	85438	195221.56
195221.6	69507.23	85416	195180.54
195180.5	69492.62	85399	195149.06
195149.1	69481.42	85386	195124.91
195124.9	69472.82	85376	195106.37
195106.4	69466.22	85369	195092.15
195092.2	69461.15	85363	195081.24
195081.2	69457.27	85358	195072.87
195072.9	69454.29	85355	195066.44
195066.4	69452.00	85352	195061.51
195061.5	69450.24	85350	195057.72
195057.7	69448.90	85349	195054.82
195054.8	69447.86	85347	195052.59
195052.6	69447.07	85346	195050.88
195050.9	69446.46	85346	195049.57
195049.6	69445.99	85345	195048.57
195048.6	69445.64	85345	195047.79
195047.8	69445.36	85344	195047.20
195047.2	69445.15	85344	195046.75
195046.7	69444.99	85344	195046.40
195046.4	69444.86	85344	195046.13
195046.1	69444.77	85344	195045.92
195045.9	69444.70	85344	195045.77
195045.8	69444.64	85344	195045.64
195045.6	69444.60	85344	195045.55
195045.6	69444.56	85344	195045.48
195045.5	69444.54	85344	195045.43
195045.4	69444.52	85344	195045.38
195045.4	69444.50	85343	195045.35
195045.4	69444.49	85343	195045.33
195045.3	69444.48	85343	195045.31

Table 3-18 - Iterative calculation of total, empty and fuel weights.

Therefore $W_o = 195045 \text{ lb}$ (approximately).

This estimated take-off weight enables the fuselage, wing and tails to be sized.

SIZING

Fuselage Layout

The fuselage fulfils several functions. In the majority of aircraft, these include the provision of volume and overall structural integrity. Once the fundamental configuration of the aircraft has been determined it is possible to propose a layout for the fuselage with only secondary reference to other aspects of the design. This is therefore the starting point that has been adopted in sizing the Twin-Boom.

There are a number of primary considerations that have an impact upon the layout including payload, pressurisation, powerplant location etc. In establishing the outside shape of the fuselage, the aerodynamic aim is to achieve a reasonably streamlined form together with the minimum surface area consistent with the required volume. This is achieved by giving consideration to the cross-section, nose and tail shapes and lengths, the wing fuselage junction and the overall length. Whilst the fuselage drag may be a theoretical minimum for a streamlined shape having a length/diameter ratio of less than four, this is rarely practicable. Consideration of volume utilisation, overall centre of gravity location and the moment arm required for stabilising/control surfaces usually results in the overall length to effective diameter ratio being at least 6. A value nearer 10 is more typical with 14 for a 'stretched' design.

The shape of the cross-section may be determined by primary consideration such as the need for pressurisation (although this is not too critical aerodynamically). As a general rule the nose and tail shapes should not be unduly bluff. For most subsonic aircraft the nose shape is relatively short having a length of 1 to 2 effective diameters. Typically, the tail section has a length of 2.5 to 3.5 effective diameters. The tail upsweep angle is largely determined by the clearance required upon rotation during take-off. The shape of the region where the wing intersects the fuselage is always

significant and is another area that demands careful detail design to minimise the interference drag.

The Fuselage and cabin lengths can be calculated by determining the number of passengers, the seat pitch, the number of rows and the number of toilets and galleys that must be provided – all of which is available in the design specification (Section 3.4.1).

Phase	Equation	Parameters	Reference
Cabin Length	$cabin\ length = \left(\frac{P}{p} + g \right) s + t + 0.8w$		<i>Conceptual Aircraft Design, 2000</i>
		P no. of passengers	<i>Specification, 3.4.1</i>
		g no. of galleys	<i>Specification, 3.4.1</i>
		p no. of seats across width	<i>Jenkinson, Simpkin, Rhodes, Aircraft Data Set</i>
		s seat pitch (m)	<i>Specification, 3.4.1</i>
		t no. of toilets	<i>Specification, 3.4.1</i>
		w no. of cross-aisles	<i>Historical Data</i>

Table 3-19 – Fuselage Cabin length.

The external cross section length may be determined by adding to the dimensions given for the fuselage width to allow for trim and structure. This is typically 0.2 to 0.3 m (the larger value being for larger aircraft).

Phase	Equation	Parameters	Reference
Nose Length	1.2 D	D Fuselage Diameter	<i>Conceptual Aircraft Design, 2000</i>
Tail Length	3D		

Table 3-20 – Fuselage nose and tail lengths.

Wing

Now that we have an initial estimate of the take-off weight and wing loading we can calculate the basic wing parameters e.g. aspect ratio, taper ratio, sweep dihedral and thickness/chord ratio. The Wing Area can be determined simply as the take-off weight divided by the wing loading.

Phase	Equation	Parameters	Reference
Wing Leading Particulars	$b = \sqrt{AS}$	b Wing Span	<i>Eq. 7.5, Raymer, 1989</i>
	$C_{root} = \frac{2S}{b(1+\lambda)}$	A Aspect Ratio S Wing Area	<i>Eq. 7.6, Raymer, 1989</i>
	$C_{tip} = \lambda C_{root}$	λ Taper Ratio C_{root} Root Chord	<i>Eq. 7.7, Raymer, 1989</i>
	$\bar{C} = \left(\frac{2}{3}\right) \frac{1+\lambda+\lambda^2}{1+\lambda}$	$\bar{C}$ mac $\bar{Y}$ spanwise location of mac	<i>Eq. 7.8, Raymer, 1989</i>
	$\bar{Y} = \left(\frac{b}{6}\right) \left(\frac{1+2\lambda}{1+\lambda}\right)$		<i>Eq. 7.9, Raymer, 1989</i>

Table 3-21 – Wing Leading Particulars

Tails

For the initial layout, a historical approach is used for estimation of the tail size. The effectiveness of a tail in generating a moment about the centre of gravity is proportional to the lift produced by the tail and the tail moment arm. The force due to tail lift is directly proportional to the tail area which leads to the tail volume coefficients.

Phase	Equation	Parameters	Reference
Tail Leading Particulars	$S_{HT} = c_{HT} \bar{C} \frac{S_W}{L_{HT}}$ $S_{VT} = c_{VT} b_w \frac{S_W}{L_{VT}}$		<i>Eq. 6.28, Raymer, 1989</i>
			<i>Eq 6.29, Raymer, 1989</i>
		b _w Wing span	<i>Table 3-21</i>
		$\bar{C}$ Wing mac	<i>Table 3-21</i>
		C _{HT} 1	<i>Table 6.4, Raymer, 1989</i>
		C _{VT} 0.09	<i>Table 6.4, Raymer, 1989</i>
		L _{HT} Tail arm = 55% of fuselage length (assume L _{HT} = L _{VT})	<i>Raymer, 1989</i>

Table 3-22 – Tail Leading Particulars

To calculate tail size, the moment arm is estimated. For an aircraft with the engines on the wings, the tail arm is approximately 55% of the fuselage length (*Raymer, 1989*). No reduction in tail area has been included for the Twin-Boom to account for a computerised “active” flight control system.

Engines

The thrust required can be calculated from the weight divided by the Thrust to Weight ratio, and the engine dimensions may be scaled from those supplied for the unconventional LH₂ engines (*CRYOPLANE, 2000*).

Phase	Equation	Parameters	Reference
Engine Thrust and dimensions	$T = \left(\frac{T}{W_0} \right) W_0$	T Thrust	<i>Table 3-12</i>
		T/W ₀ Thrust to Weight Ratio	
		L Length	<i>Unconventional Engines- CRYOPLANE, 2000</i>
		D Depth	
		W Width	

Table 3-23 – Engine Thrust and dimensions

Landing gear

A conventional tricycle landing gear layout is adopted with two four-wheel bogeys (8 main wheels) plus two nose wheels to retain control in case of a flat nose wheel tyre. The optimum range for the percent of the aircraft's weight which is carried by the nose wheel is about 8-15%. This provides adequate nose wheel steering whilst enabling take-off rotation to be performed more easily.

Phase	Equation	Parameters	Reference
Landing Gear Tyre Sizing	Tyre Width or Diameter $= AW_W^B$	W_W weight-on-wheels (90% of W_0 for main wheels)	<i>Raymer, 1989</i>
		<u>Diameter</u>	
		A 1.63	<i>Table 11.1, Raymer, 1989</i>
		B 0.315	<i>Table 11.1, Raymer, 1989</i>
		<u>Width</u>	
		A 0.1043	<i>Table 11.1, Raymer, 1989</i>
		B 0.480	<i>Table 11.1, Raymer, 1989</i>

Table 3-24 – Landing Gear tyre sizing

Fuel Tanks (Twin Boom)

Knowing the fuel required (from our mission weights) and the fuel density we can calculate the fuel volume required. We can also calculate the size of the fuel tank (booms) by assuming a length to diameter ratio to give good aerodynamic performance i.e. using the same approach as that adopted for the fuselage. The wetted area and structural mass may then be estimated using the same formulae as that for fuselages (since both fuselages and the fuel tanks booms are pressurised cylindrical vessels). The fuel tank insulation mass can then finally be estimated using a known insulation material (with known density) and a given thickness.

Phase	Equation	Reference
Fuel Tank Sizing (Twin Booms)	$M_{fuel\ tank} = \left[1 + (4.12 - 0.354D) \frac{2f}{(1+f)} \right] \left[3.56 \frac{p}{f^{0.75}} S_{fuel\ tank} D \right]$	<i>Conceptual Aircraft Design, 2000</i>
	Parameters	Reference
	ρ_{LH2} 71kg/m ³	<i>Specification, 3.4.1</i>
	L Length	<i>Conceptual Aircraft Design, 2000</i>
	D Diameter	
	L/D 7	
	p 1.1 bar	<i>Brewer, 1991</i>
	M _f	<i>Table 3-18</i>
	M _{LH2 fuel}	<i>2.8 times less than M_{fuel} (based on specific energy)</i>
	Add 10% to volume ($V = \frac{m}{\rho}$) to allow for ullage/unusable fuel	<i>Specification, 3.4.1</i>
	$S_{fuel\ tank} = 2\pi r L + 4\pi r^2$ (i.e. cylinder + half spheres on each end)	
	f 1.0	<i>Conceptual Aircraft Design, 2000</i>

Table 3-25 – Twin Boom fuel tanks sizing

Using insulation such as Polymethacrylimide and assuming a thickness of 5 in (*Brewer, 1991*) we can calculate the mass of the insulation knowing the volume and density.

Phase	Equation	Parameters	Reference
Fuel Tank Insulation mass	$M = \rho V$	Volume $\pi r^2 L + \frac{4}{3} \pi r^3$	
		r fuel tank radius	Table 3-25
		ρ 2.2lb/ft ³	(Colozza, 2002)
		t thickness, 5 in	Brewer, 1991
		$S_{\text{fuel tank}}$	Table 3-25

Table 3-26 – Twin Boom fuel tank insulation mass

DRAG

The Aircraft net wetted area must be calculated for drag estimation and includes the area that extends through the fuselage section. The flat plate skin friction coefficient depends upon the Reynolds, number, Mach number, and skin roughness. The most important factor affecting skin-friction drag is the extent to which the aircraft has laminar flow over its surfaces.

Parasite (zero-lift) drag

Two methods for the estimation of the parasite drag (C_{D0}) can be used. The first is based on the fact that a well-designed aircraft in subsonic cruise will have a parasite drag that is mostly skin friction drag plus a small pressure drag. The latter is a fairly consistent percentage of the skin-friction drag for different classes of aircraft. This leads to the concept of an “equivalent skin friction coefficient”, C_{fe} which includes both skin-friction and pressure drag. C_{fe} is multiplied by the aircrafts wetted area to obtain an initial estimate of parasite drag which is suitable for initial conceptual studies.

Another method involves estimating the subsonic parasite drag of each component of the aircraft using a flat plate skin friction coefficient CF and a component form factor (FF) that estimates the pressure drag. Then the interference effects on the component drag are estimated as a factor “ Q ” and the total component drag is determined as a

product of the wetted areas, C_f , FF and Q. Miscellaneous drag e.g. flaps, undercarriage etc. are also estimated and then added along with estimated contributions from protuberances and excrescences.

Aerofoil

The NACA 64-210 aerofoil was chosen because of its good high speed performance and low speed characteristics. The characteristics are shown in Table 3-27 below

α_0	C_{mo}	Alrad	$C_{l\alpha}/\text{deg}$	C_{lmax}	section c_d at C_{lmax}
-1.6	-0.04	6.3	0.11	1.35	0.0118

Table 3-27 – NACA 64-210 Aerofoil characteristics (*Raymer, 1989, Rasicz, Stanley, 1952*)

The wing wetted area can be approximated from their planforms and is estimated by multiplying the planform area (A_{exposed}) by a factor based upon the wing or tail thickness ratio.

Phase	Equation	Parameters	Reference
Wing wetted area	$S_{wet} = A_{\text{exposed}} \left[1.977 + 0.52 \left(\frac{t}{c} \right) \right]$		<i>Eq 7.11, Raymer, 1989</i>
		$A_{\text{exposed}} = S_w + (c_{\text{root}} + D)$	<i>Raymer, 1989</i>
		S_w Wing Area	<i>Table 3-21</i>
		C_{root} Wing root chord	<i>Table 3-21</i>
		D Fuselage diameter	

Table 3-28 – Wing wetted area

Phase	Equation	Parameters	Reference
Wing Profile Drag, C_{D0}	$C_{D0} = \frac{S_{wet} C_f FF}{S_w}$		<i>Raymer, 1989</i>
		<i>At 35,000 ft cruise altitude</i>	
		$R = \frac{\rho V l}{\mu}$	
		ρ 0.0007382	<i>ISA Tables</i>
		a 973.1 ft/s	<i>ISA Tables</i>
		M 0.8	<i>Specification, 3.4.1</i>
		u = Ma	
		$C_f = \frac{0.455}{(\log_{10} R)^{2.58} (1 + 0.144 M^2)^{0.65}}$	<i>Eq. 12.27, Raymer, 1989</i>
		$\left(\frac{x}{c}\right)_m$ Maximum thickness of aerofoil = 0.5	<i>RAYMER, 1989 for high speed aerofoils</i>
		$FF = \left(1 + \frac{0.6}{\left(\frac{x}{c}\right)_m} \left(\frac{t}{c}\right) + 100 \left(\frac{t}{c}\right)^4\right) \left(1.34 M^{0.18} (\cos \Lambda_m)^{0.28}\right)$	<i>Eq. 12.30, Raymer, 1989</i>
		S_w Wing Area	Table 3-21
		S_{wet} Wing wetted area	Table 3-28

Table 3-29 – Wing Profile Drag

Vortex Drag

Drag due to wing twist

The basic lift distribution of the twisted wing causes vortex induced drag at zero lift. For a near elliptical lift distribution (first approximation) we can use the following table.

Phase	Equation	Parameters	Reference
Drag due to wing twist	$\Delta \epsilon C_{D_v} = 3.75 \times 10^{-5} \epsilon_t^2$	ϵ_t Wing twist = -1°	<i>Torenbeek, 1982</i> <i>Approximation</i> <i>(Torenbeek, 1982)</i>

Table 3-30 – Drag due to wing twist

Vortex drag induced by fuselage

Lift and vortex-induced drag of bodies are much more sensitive to the viscous effects than those of a wing and can be calculated based on experimental data.

The main interference effects are:-

- the lift on the nose (in upwash) which is counteracted partly by download on the rear fuselage (in downwash)
- fuselage crossflow induces increased effective angles of attack - particularly near the wing/fuselage junction

Because there is wing lift carry over into the body, the vertical displacement of the wing relative to the fuselage alters the flow pattern in a +ve sense for a low wing and a -ve sense for a high wing.

Phase	Equation	Parameters	Reference
Vortex Drag induced by fuselage	$C_D S = 0.15 \alpha_f^2 V_f^{2/3}$	V_f Fuselage Volume $V_f = \pi \left(\frac{D}{2} \right)^2 l_{cabin} + \frac{\pi}{2} \left(\frac{D}{2} \right)^2 (l_{nose} + l_{tail})$ l_{cabin} Fuselage cabin length l_{nose} Fuselage nose length l_{tail} Fuselage tail length	<i>Torenbeek, 1982</i> <i>Conceptual Aircraft Design, 2000</i> <i>Table 3-19</i> <i>Table 3-20</i> <i>Table 3-20</i>
		$\alpha_f = \frac{C_L - C_{L_0}}{C_{L_\alpha}}$ $C_L = \frac{0.1 c_{root} D}{A_{exposed}}$ c_{root} Wing root tip chord D Fuselage Diameter $A_{exposed}$ Wing Exposed Area $C_{L_0} = C_{L_{\alpha_{wf}}} \left((\alpha_f - \alpha_{01} \epsilon_t) + \left(\frac{K_I}{K_{II}} \right) (i_w - \alpha_{LO_r}) \right) + C_L$ $C_{L_{\alpha_{wf}}} = K_I C_{mo}$ C_{mo} $K_I = \left(1 + 2.15 \frac{D}{b} \right) \frac{A_{exposed}}{S} + \frac{\pi}{2 C_{L_{w\alpha}}} \left(\frac{D^2}{S} \right)$ $K_{II} = \left(1 + 0.7 \frac{D}{b} \right) \frac{A_{exposed}}{S}$ b Wing span S Wing Area $C_{L_{w\alpha}}$ (Lift curve slope of the wing) α_f Fuselage AoA (assume 0) α_{01} $4/3\pi$ ϵ_t Wing twist	<i>Torenbeek, 1982</i> <i>Torenbeek, 1982</i> <i>Table 3-21</i> <i>Table 3-28</i> <i>Torenbeek</i> <i>Torenbeek</i> <i>NACA 64-210, Table 3-27</i> <i>Torenbeek, 1982</i> <i>Torenbeek, 1982</i> <i>Table 3-21</i> <i>Table 3-21</i> <i>NACA 64-210, Table 3-27</i> <i>Torenbeek, 1982</i> <i>Torenbeek, 1982</i> <i>Table 3-30</i>

		$i_w = \alpha_{Lor} = \alpha_{lor} + \alpha_{01} \epsilon_t$ $\alpha_{lor} \quad -1.6^\circ$	<i>Torenbeek, 1982</i> <i>NACA 64-210, Table</i>
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Table 3-31 – Vortex Drag induced by fuselage

Horizontal Tailplane contribution

For isolated horizontal tailplane, drag can be obtained as for wing (ignoring twist)

Phase	Equation	Parameters	Reference
Horizontal Tailplane Contribution to Drag	$C_D S = 1.02 C_{L_h}^2 \frac{S_h}{\pi A_h}$		<i>Torenbeek, 1982</i>
		C_{L_h} Assume same aerofoil as wing (i.e. NACA 64-210) set at 1° to horizontal	<i>Torenbeek, 1982</i>
		A_h Tailplane Aspect Ratio S_h Tailplane Area	<i>Jenkinson, Simpkin, Rhodes, Aircraft Data Set</i>

Table 3-32 – Horizontal tailplane Contribution to Drag

PROFILE DRAG

Wing- minimum drag

The Reynolds number is calculated at cruise conditions i.e. 35,000ft.

Phase	Equation	Parameters	Reference	
Wing- Minimum Drag	$C_{d_{p\min}} = 2C_F(1 + \phi_w)$		<i>Torenbeek, 1982</i>	
		C_F <i>Skin friction Coefficient</i>	<i>Torenbeek, 1982</i>	
		$C_F = \frac{0.455}{\ln R^{2.58}}$		
		<i>At 35,000 ft cruise altitude</i>		
		$R = \frac{\rho V l}{\mu}$		
		l mac		<i>Table 3-21</i>
		ρ 0.0007382		<i>ISA Tables</i>
		a 973.1 ft/s		<i>ISA Tables</i>
		M 0.8		<i>Specification, 3.4.1</i>
		V = Ma		
	ϕ_w <i>Thickness correction factor</i>	<i>Torenbeek, 1982</i>		
	$\phi_w = 2.7 \frac{t}{c} + 100 \left(\frac{t}{c} \right)^4$			
t/c <i>Thickness chord ratio Wing</i>	<i>Historical data, Jenkinson, Simpkin, and Rhodes, Aircraft Data Set</i>			

Table 3-33 – Wing Minimum Drag

ϕ_w is the thickness correction factor that accounts for the aerodynamic effect of the thickness and also for the difference between the circumference and twice the projected length of the wing.

Wing - Incremental Drag

Phase	Equation	Parameters	Reference
Wing-incremental Drag	$\Delta C_{d_p} = 0.01 c_{l_{\max}} - 0.046 \left(1 + 2.75 \frac{t}{c} \right)$	$c_{l_{\max}}$	<i>Torenbeek, 1982</i> <i>NACA 64-210, Table 3-27</i>
		t/c <i>Wing thickness/ chord ratio</i>	<i>Table 3-33</i>

Table 3-34 – Wing Incremental Drag

Fuselage - Basic Drag

Phase	Equation	Parameters	Reference
Fuselage Basic Drag	$C_D S = C_f FF \frac{S_{wet}}{S_{ref}}$		<i>Raymer, 1989</i>
		$C_f = \frac{0.455}{(\log_{10} R)^{2.58} (1 + 0.144 M^2)^{0.65}}$	<i>Eq 12.27 Raymer, 1989</i>
		<p><i>At 35,000 ft cruise altitude</i></p> $R = \frac{\rho V l}{\mu}$ <p>l Fuselage length</p> <p>ρ 0.0007382</p> <p>a 973.1 ft/s</p> <p>M 0.8</p> <p>V = Ma</p>	<p><i>Table 3-19+Table 3-20</i></p> <p><i>ISA Tables</i></p> <p><i>ISA Tables</i></p> <p><i>Specification, 3.4.1</i></p>
		$FF = \left(1 + \frac{60}{f^3} + \frac{f}{400} \right)$ $f = \frac{L}{D}$ <p>D fuselage diameter</p> <p>S_{wet} Fuselage Wetted Area</p> $S_{wet} = 3.13 D^2 \left(\frac{L}{D} - 1.5 \right)$ <p>S_{ref} Wing Area</p>	<p><i>Eq 12.31 Raymer, 1989</i></p> <p><i>Conceptual Aircraft Design, 2000</i></p> <p><i>Table 3-21</i></p>

Table 3-35 – Fuselage Basic Drag

Fuselage- Upsweep and incidence effects

Phase	Equation	Parameters	Reference
Fuselage Upsweep and Incidence Effects	$C_D S = \Delta\alpha\beta(C_D S) + C_D S_{basic}$		
		$\Delta\alpha\beta(C_D S) = A_I \sin^3 \alpha_f + \frac{A_{II} \sin^3 (\alpha - \beta)}{\cos \beta}$	Torenbeek, 1982
		$A_I = A_{II} = lD + l_{nose} \frac{D}{2} + l_{tail} \frac{D}{2}$ = planform fuselage areas	Torenbeek, 1982
		l cabin length	Table 3-19
		l_{nose} nose length	Table 3-20
		l_{tail} tail length	Table 3-20
		D fuselage diameter	
		α_f 15°	Torenbeek, 1982
		β 10°	Torenbeek, 1982
		$C_D S_{basic} = C_f S_{wet} (1 + \phi_f)$	Torenbeek, 1982
		$C_f = \frac{0.455}{(\ln R^{2.58})}$	Torenbeek, 1982
		At 35,000 ft cruise altitude	
		$R = \frac{\rho V l}{\mu}$	
		l Fuselage length	Table 3-35
		ρ 0.0007382	ISA Tables
		a 973.1 ft/s	ISA Tables
		M 0.8	Specification, 3.4.1
		V = Ma	
		S_{wet} Fuselage wetted area	Table 3-35
		ϕ_f 0.15	Torenbeek, 1982

Table 3-36 – Fuselage Upsweep and Incidence effects

Tailbooms

The basic profile drag of the external fuel tanks can also be calculated in the same way as the fuselage drag, since they are of a very similar shape and a similar

slenderness ratio (for aerodynamic reasons) resulting in a minimum drag for a given volume.

Phase	Equation	Parameters	Reference
Tailboom Drag	$C_D S_{basic} = C_F S_{wet} ((1 + \phi_f))$		<i>Torenbeek, 1982</i>
		$C_f = \frac{0.455}{(\ln R^{2.58})}$ <p><i>At 35,000 ft cruise altitude</i></p> $R = \frac{\rho V l}{\mu}$	<i>Torenbeek, 1982</i>
		l Tailboom length	<i>Table 3-25</i>
		ρ 0.0007382 sl/ft ³	<i>ISA Tables</i>
		a 973.1 ft/s	<i>ISA Tables</i>
		μ 3.7762 x 10 ⁻⁵	<i>ISA Tables</i>
		M 0.8	<i>Specification, 3.4.1</i>
		V = Ma	
		S_{wet} Tailboom wetted area	<i>Table 3-25</i>
		ϕ_f 0.15 (As for fuselage)	<i>Torenbeek, 1982</i>

Table 3-37 – Tailboom Drag

Engine Nacelles

In preliminary design, the nacelle drag is frequently assumed to be independent of C_L although interference effects can be quite appreciable. Internal friction losses of the inlet diffuser are not accounted for - these are included in the installed engine thrust determination.

The fan cowl drag area = friction drag + afterbody pressure drag

Phase	Equation	Parameters	Reference
Engine Nacelles	$C_D S = 1.25 C_F S_{wet}$		<i>Torenbeek, 1982</i>
		$C_f = \frac{0.455}{(\ln R^{2.58})}$	<i>Torenbeek, 1982</i>
		<i>At 35,000 ft cruise altitude</i>	
		$R = \frac{\rho V l}{\mu}$	
		<i>l</i> Nacelle length <i>ρ</i> 0.0007382 sl/ft ³ <i>a</i> 973.1 ft/s <i>μ</i> 3.7762 x 10 ⁻⁵ <i>M</i> 0.8 <i>V</i> = Ma	<i>UnconvEngines, CRYOPLANE, 2000</i> <i>ISA Tables</i> <i>ISA Tables</i> <i>Specification, 3.4.1</i>
		<i>S_{wet} Nacelle wetted area</i>	

Table 3-38 – Engine Nacelle Drag

Horizontal and Vertical Tailplane drag

Phase	Equation	Parameters	Reference
Horizontal and Vertical Tailplane Drag	$C_{D_0} = \frac{S_{wet} C_f FF}{S_w}$		<i>Raymer, 1989</i>
		<i>At 35,000 ft cruise altitude</i>	
		$R = \frac{\rho V l}{\mu}$	
		<p>ρ 0.0007382</p> <p>a 973.1 ft/s</p> <p>μ 3.7762×10^{-5}</p> <p>M 0.8</p> <p>u = Ma</p>	<p><i>ISA Tables</i></p> <p><i>ISA Tables</i></p> <p><i>ISA Tables</i></p> <p><i>Specification, 3.4.1</i></p>
		$C_f = \frac{0.455}{(\log_{10} R)^{2.58} (1 + 0.144 M^2)^{0.65}}$	<p><i>Eq 12.27</i></p> <p><i>Raymer, 1989</i></p>
		$\left(\frac{x}{c}\right)_m$ Maximum thickness of aerofoil = 0.5	<i>Raymer, 1989</i>
		$FF = \left(1 + \frac{0.6}{\left(\frac{x}{c}\right)_m} \left(\frac{t}{c}\right) + 100 \left(\frac{t}{c}\right)^4\right) \left(1.34 M^{0.18} (\cos \Lambda_m)^{0.28}\right)$	<p><i>Eq 12.30</i></p> <p><i>Raymer, 1989</i></p>
		S_{wet} <i>Wing Wetted Area</i>	<i>Table 3-28</i>
		S_w <i>Horizontal/Vertical Tailplane Wetted Area</i>	<i>Table 3-22</i>

Table 3-39 – Horizontal and Vertical Tailplane Drag

INTERFERENCE CORRECTIONS

Wing/Fuselage - Vortex Drag

The wing induces an upwash in front and downwash aft of the wing/fuselage junction, hence the nose of the aircraft will experience a lift increment and the afterbody a lift decrement. In addition, the fuselage cross-flow component leads to increased effective angles of attack near the wing/body junction. The combination of both of these effects is of the same order of magnitude.

Phase	Equation	Parameters	Reference
Wing/Fuselage – Vortex Drag	$\Delta_i C_{D_v} = \left(\frac{0.55 \eta_f}{(1 + \lambda)} \right) \left(\frac{(2 - \pi \eta_f) C_{L_0}^2}{\pi A} \right)$		<i>Torenbeek, 1982</i>
		η_f fuselage diameter/wing span ratio	
		C_{L_0} λ A	<i>Table 3-31</i> <i>Historical data,</i> <i>Jenkinson,</i> <i>Simpkin, Rhodes,</i> <i>Aircraft Data Set</i> <i>Table 3-11</i>

Table 3-40 – Wing/Fuselage – Vortex Drag

- *Viscous interference drag*

Near the intersections of the wing and fuselage contours there is a thickening of the boundary layers and an increase in the local flow velocity - both of these effects increase profile drag.

Phase	Equation	Parameters	Reference
Wing/Fuselage – Viscous Interference Drag	$\Delta i (C_D S)_p = 1.5 C_f t_r C_{ci} \cos^2 \Lambda$		<i>Torenbeek, 1982</i>
		C_f fuselage skin friction	<i>Table 3-35</i>
		t_r wing root chord thickness	<i>Table 3-21</i>
		C_{ci} total length (circumferential) of wing halves $= 4.5 C_{root}$	<i>Torenbeek, 1982</i>
		Λ Wing sweep	<i>Jenkinson,</i> <i>Simpkin,</i> <i>Rhodes, Aircraft</i> <i>Data Set</i>

Table 3-41 – Wing/Fuselage – Viscous Interference Drag

- *Lift effect on fuselage drag*

For the conceptual design stage the Lift effect on fuselage drag can be approximated as equal to the drag due to fuselage upsweep and incidence effects.

Phase	Equation	Parameters	Reference
Wing/Fuselage – Lift effect on fuselage drag	$C_{DS} = \Delta\alpha\beta(C_{DS}) = A_I \sin^3 \alpha_f + \frac{A_{II} \sin^3(\alpha - \beta)}{\cos \beta}$		Table 3-36

Table 3-42 – Wing/Fuselage – Lift effect on Fuselage Drag

Nacelle/Airframe

The Jet engine pods and jet efflux interact with the flow in a number of complex ways. For wing-mounted engine nacelles as in the Twin-Boom case, the determining factors are the nacelle fore and aft position, and the distance between nacelle and wing chord. However, at this stage in the conceptual design we can assume 7 drag counts for a high bypass engine.

Phase	Equation	Parameters	Reference
Nacelle/Airframe Interference drag	7 Drag counts		Torenbeek, 1982

Table 3-43 – Nacelle/Airframe Interference Drag

Wing/Tailboom

For our purposes and to simplify the analysis, the tailbooms are assumed to be the same shape as the fuselage which they are to a large extent. In reality, however, there will be local design differences.

In a similar fashion to the fuselage, there will be adverse interference effects between the wing and the tailboom. The determination of the magnitude and effect of this interference will most likely be determined by a combination of Computational Fluid Dynamics (CFD) analysis combined with wind tunnel testing. Even estimating the interference drag effects is not simple since there is no statistical data for such an unconventional configuration and if there were it is very likely that it would be

proprietary. However, as a useful starting point, it is assumed that all those interference effects that exist between the fuselage and wing (i.e. Wing/Fuselage – vortex drag, viscous interference drag, lift effect on fuselage drag) are equally applicable to the tail booms. As a result, the same formulae used for the calculation of the wing/fuselage vortex, viscous interference drag and lift effect are used to calculate the wing/tailboom drag replacing the fuselage dimensions and skin friction coefficients with those for the Twin-Boom.

Phase	Equation	Parameters	Reference
Wing/Tailboom Interference drag	Wing/tailboom - Vortex drag $\Delta_i C_{D_v} = \left(\frac{0.55 \eta_f}{(1 + \lambda)} \right) \left(\frac{(2 - \pi \eta_f) C_{L_0}^2}{\pi A} \right)$	η_f	Table 3-40
		Tailboom diameter/wing span ratio	
		C_{L_0}	Table 3-31
		λ	Table 3-40
		A	Table 3-11
	- Viscous interference drag $\Delta i(C_D S)_p = 1.5 C_f t_r C_{c_i} \cos^2 \Lambda$		Table 3-41
		C_f tailboom skin friction	Table 3-37
		t_r wing root chord thick.	Table 3-21
		C_{ci} length of wing halves	Torenbeek, 1982
		$= 4.5 C_{root}$	
	- lift effect on tailboom drag $\Delta \alpha \beta (C_D S) = A_I \sin^3 \alpha_f + \frac{A_{II} \sin^3 (\alpha - \beta)}{\cos \beta}$	Λ Wing sweep	Table 3-41
		$A_I = A_{II}$	
		$= lD + l_{nose} \frac{D}{2} + l_{tail} \frac{D}{2}$	
		= planform tailboom areas	
		l tailboom length	Table 3-25
		l_{nose} tailboom nose length	Table 3-25
		l_{tail} tailboom tail length	Table 3-25
		D tailboom diameter	Table 3-25
		α_f 15°	Table 3-36
		β 10°	Table 3-36

Table 3-44 – Wing/Tailboom Interference Drag

PROTRUBERANCES, SURFACE IMPERFECTIONS AND MISCELLANEOUS DRAG

Flight Deck Windows

If the windshields are well faired to the fuselage nose and sharp corners are avoided, then C_D can be limited to 2.5% of the fuselage drag.

Phase	Equation	Parameters	Reference
Flight Deck Windows	Assume 2.5% of fuselage drag		<i>Torenbeek, 1982</i>

Table 3-45 – Flight Deck Window Drag

External Drag – Engine Air Intakes/Spillage Drag

The forces exerted on the airframe (externally and internally) by the airflow passing through the jet engine are already included in the Nacelle Drag. However, other installation drag components may include:

- external drag, e.g. cooling system intake swoops
- internal drag, e.g. drag due to pressure losses in oil cooling systems
- jet interference, important for wing mounted engines.

Phase	Equation	Parameters	Reference
External Drag – Engine Air Intakes/Spillage Drag	$C_D S = 0.025 \times \text{intake area}$		<i>Torenbeek, 1982</i>

Table 3-46 – External Drag – Engine Air Intakes/Spillage Drag

Thrust Reverse Drag

Phase	Equation	Parameters	Reference
Thrust reverser Drag	Assume 4% of nacelle drag		<i>Torenbeek, 1982</i>

Table 3-47 – Thrust Reverser Drag

Cooling Drag

The cooling drag caused by the ventilation/cooling of space between the hot engine sections and the surrounding structure can be approximated as 5% of the nacelle drag.

Phase	Equation	Parameters	Reference
Cooling Drag	Assume 5% of nacelle drag		<i>Torenbeek, 1982</i>

Table 3-48 – Cooling Drag

External drag - Engine air intakes/spillage

- Engine air outlets/reversers

- oil coolers/radiators

Excrescences, surface imperfections, other extras

The representative weight breakdown of excrescence drag (*Torenbeek, 1982*) at cruise for typical subsonic transport aircraft and approximated for the Twin-Boom can be seen in the Table below.

	Drag Counts
WING	
flap, slat, and spoiler gaps	1.9
aileron gaps	1.1
flap linkages and tracks	0.3
aileron linkages	0.2
fasteners double joints	0.6
EMPENNAGE	
linkages fasteners	0.3
rudder gaps	0.85
root gaps	0.7
elevator gaps	1.85
FUSELAGE	
doors, windows	0.2
windscreen wipers	0.8
NACELLES	
doublers, joins	1.4
doors, fasteners	0.6
miscellaneous	0.6
SYSTEMS	
anti-icing	0.4
instrumentation	0.55
APU	0.6
fuel system	0.75
aerials	0.8
air.con	1.9

Table 3-49 – *Excrescences, surface imperfections, and miscellaneous drag*

LIFT

Wing Lift Curve Slope

The lift-curve slope is need for three reasons. Firstly, it is used to correctly set the wing incidence angle whereby the floor remains level during cruise. Also, the wing incidence angle influences the required fuselage angle of attack during take-off and landing, which affects the aft fuselage upsweep and/or landing gear length. Secondly

is used to calculate the drag due to lift and finally, is it used in longitudinal stability analysis.

Phase	Equation	Parameters	Reference
Wing Lift curve slope	$C_{L_\alpha} = \frac{2\pi A}{2 + \sqrt{4 + \frac{A^2 \beta^2}{\eta^2} \left(1 + \frac{\tan^2 \Lambda_{\max t}}{\beta}\right)}} \frac{S_{\text{exposed}}}{S_{\text{ref}}} F$		<i>Eq 12.6, Raymer, 1989</i>
		$\beta^2 = 1 - M^2$	<i>Eq 12.7, Raymer, 1989</i>
		$\eta = \frac{C_{l_\alpha}}{2\pi/\beta}$	<i>Eq 12.8, Raymer, 1989</i>
		F Fuselage Factor	
		$F = 1.07(1 + d/b)^2$	<i>Eq 12.9, Raymer, 1989</i>
		S _{exposed} Exposed wing area	<i>Table 3-28</i>
		S _{ref} wing area	<i>Table 3-21</i>
		A wing aspect ratio	<i>Table 3-11</i>
		Λ wing sweep	<i>Table 3-41</i>

Table 3-50 – Wing Lift curve slope

Maximum Lift (Clean)

The maximum lift coefficient of the wing will usually determine the wing area. This in turn will have a great influence upon the cruise drag which strongly affects the aircraft takeoff weight to perform the design mission.

For high aspect ratio wings with moderate sweep, the maximum lift depends mostly on the aerofoil characteristics. The maximum lift coefficient of the clean wing (i.e. without flaps and other high lift devices) will usually be about 90% of the aerofoil maximum lift coefficient as determined from the 2-D data.weeping the wing reduces the maximum lift.

Phase	Equation	Parameters	Reference
Maximum Lift (clean wing)	$C_{L_{max}} = C_{l_{max}} \left(\frac{C_{L_{max}}}{C_{l_{max}}} \right) + \Delta C_{L_{max}}$		<i>Eq 12.16, Raymer, 1989</i>
		$\frac{C_{L_{max}}}{C_{l_{max}}}$	<i>Fig 12.8, Raymer, 1989</i>
		$C_{l_{max}}$ Aerofoil max. lift coeff. $\Delta C_{L_{max}} = 0$ (for clean wing)	<i>NACA 64-210, Table 3-27</i>

Table 3-51 – Maximum Lift (Clean Wing)

Maximum Lift

Since the lift coefficient is reference to the original wing area, not the extended wing area, the effective slope of the lift curve for an extending flap is increased by approximately the ratio of the total extended wing area to the original wing area. Leading edge device alone do little to improve little for take-off and landing because they are effective only at fairly high angles of attack, however, they are very useful when used in combination with trailing edge flaps because they prevent premature airflow separation caused by the flaps.

Thus the maximum lift is simply equal to the lift of the clean wing plus the increment due to high lift devices. For the Twin Boom, Fowler flaps and Krueger flaps are used to augment the lift during low speed flight e.g. take-off and landing.

Phase	Equation	Parameters	Reference
Maximum Lift	$\Delta C_{L_{\max}} = \Delta C_{l_{\max}} \left(\frac{S_{flapped}}{S_{ref}} \right) \cos \Lambda_{H.L.}$		<i>Eq 12.21, Raymer, 1989</i>
		$\Delta C_{l_{\max}}$ lift contribution due to high lift device $S_{flapped}$ total area of wing occupied by high lift device $= S_{flapped} = \frac{flap span}{wing span} \times wing area$ S_{ref} wing area $\Lambda_{H.L.}$ Sweep of wing at hinge line of high lift device	<i>Table 12.2, Raymer, 1989</i> <i>Jenkinson, Simpkin, Rhodes, Aircraft Data set</i> <i>Table 3-21 Approximation</i>

Table 3-52 – Maximum Lift

WEIGHTS AND MASS BREAKDOWN

The following equations provide reasonable estimates of the group weights. When the component weights have been estimated, they are summed to determine the empty weight.

Component	Equation	Reference
Wing	$W_{wing} = 0.0051(W_{dg} N_z)^{0.557} S_w^{0.649} A^{0.5} (t/c)^{-0.4} (1 + \lambda)^{0.1} (\cos \Lambda)^{-1} S_{csw}^{0.1}$	<i>Eq 15.25, Raymer, 1989</i>
	W _{dg} Design Gross Weight	<i>Table 3-18</i>
	N _z Ultimate load factor = 1.5 x limit load factor	<i>Table 14.2, Raymer, 1989</i>
	S _w Wing Area	<i>Table 3-21</i>
	A Aspect Ratio	<i>Table 3-11</i>
	t/c Thickness/Chord Ratio	<i>Table 3-33</i>
	λ Taper Ratio	<i>Table 3-40</i>
	Λ Sweep	<i>Table 3-41</i>
	S _{csw} Control Surface Area	<i>Jenkinson, Simpkin, Rhodes, Aircraft Data Set</i>
Horizontal Tail	$W_{ht} = 0.0379 K_{uht} (1 + F_w/B_h)^{-0.25} W_{dg}^{0.639} N_z^{0.1} S_{ht}^{0.75} L_t^{-1} K_y^{0.704} (\cos \Lambda_{ht})^{-1} A_h^{0.166} (1 + S_e/S_{ht})^{0.1}$	<i>Eq 15.26, Raymer, 1989</i>
	K _{uht} 1.0 for Horizontal Tail	<i>Raymer, 1989</i>
	F _w Fuselage Width at Tail section	<i>Approximately 70% of Max. fuselage diameter</i>
	B _h Horizontal Tail Span	<i>Table 3-22</i>
	S _{ht} Horizontal Tail Area	<i>Table 3-22</i>

	L_t Tail Length K_y Aircraft pitching radius of gyration ($\approx 0.3L_t$) Λ_{ht} Horizontal Tail Sweep A_h Horizontal Tail Aspect Ratio S_e Elevator Area	Table 3-22 Raymer, 1989 Jenkinson, Simpkin, Rhodes, Aircraft Data Set Jenkinson, Simpkin, Rhodes, Aircraft Data Set Approx. 20% of S_{HT}
Vertical tail	$W_{vt} = 0.0026(1 + H_t/H_v)^{0.225} W_{dg}^{0.556} N_z^{0.536} L_t^{-0.5} S_{vt}^{0.5} K_z^{0.875} (\cos \Lambda_{vt})^{-1} A_v^{0.35} (t/c)_{root}^{-0.5}$ H_t Horizontal tail height above fuselage H_v Vertical tail height above fuselage S_{vt} Vertical tail Area K_z Aircraft yawing radius of gyration ($\approx 0.3 L_t$) A_v Vertical Tail Aspect ratio t/c Thickness/chord ratio	Eq 15.27, Raymer, 1989 Raymer, 1989 Raymer, 1989 Table 3-22 Raymer, 1989 Table 3-22 Jenkinson, Simpkin, Rhodes, Aircraft Data Set
Fuselage	$W_{fuselage} = 0.3280 K_{door} K_{Lg} (W_{dg} N_z)^{0.5} L^{0.25} S_{fwet}^{0.302} (1 + K_{ws})^{0.04} (L/D)^{0.10}$ K_{door} 1.0 (no cargo door) K_{Lg} 1.0 (wing mounted landing gear) L Fuselage Length S_{fwet} Fuselage Wetted area D Fuselage Diameter	Eq 15.28, Raymer, 1989 Raymer, 1989 Raymer, 1989 Table 3-19 + Table 3-20 Table 3-35
Landing Gear	$W_{LG} = C_3 W_l$ W_l 85% M_{TOW}	Conceptual Aircraft Design, 2000
Powerplant	$M_{eng} = 2499 \text{ kg (each)}$	From Unconventional Engines, CRYOPLANE, 2000

<i>Nacelle/Engine Structure</i>	$M_{Nacelle/Engine\ Struc} = 0.17 M_{eng}$	<i>Conceptual Aircraft Design, 2000</i>
<i>Flying Controls</i>	$M_{FC} = 0.11 M_{TOW}^{0.8}$	<i>Conceptual Aircraft Design, 2000</i>
<i>Hydraulics and Pneumatics</i>	$M_{HYD} = 3.2 M_{TOW}^{0.5}$ <i>This has then been increased by 25% to allow for the increased fuel system mass due to extra complexity and the need for insulation.</i>	<i>Conceptual Aircraft Design, 2000</i>
<i>Electrics</i>	$M_{ELEC} = 0.75 M_{TOW}^{0.67}$	<i>Conceptual Aircraft Design, 2000</i>
<i>Accessory Drives and APU</i>	$M_{APU} = 300kg$	<i>Conceptual Aircraft Design, 2000</i>
<i>Air conditioning, pressurisation and Oxygen</i>	$M_{air\ con} = 0.035 M_{TOW}^{0.88}$	<i>Conceptual Aircraft Design, 2000</i>
<i>De-icing</i>	$M_{DEICE} = 0.16 M_{TOW}^{0.7}$	<i>Conceptual Aircraft Design, 2000</i>
<i>Furnishings</i>	$M_{furnishings}$	<i>Specification, 3.4.1</i>
<i>Twin Fuel Booms</i>	$M_{fuel\ tan\ k} = \left[1 + (4.12 - 0.354D) \frac{2f}{(1+f)} \right] \left[3.56 \frac{P}{f^{0.75}} S_{fuel\ tan\ k} D \right]$ <p>f Allowable Working Stress D Fuel tank diameter P fuel tank pressure S_{fuel tank} fuel tank wetted area</p>	<i>Conceptual Aircraft Design, 2000</i> <i>(same equation formula as for fuselage)</i> <i>Conceptual Aircraft Design, 2000</i> <i>Table 3-25</i> <i>Brewer, 1991</i> <i>Table 3-25</i>
<i>W₀ = Sum of above component weight</i>		

Table 3-53 – Component Weight Breakdown

PAYLOAD-RANGE

The loading options for the aircraft are often shown in the form of a payload-range diagram, which illustrates the varying proportions of fuel mass and payload in terms of range. Extended range i.e. ferry requirements are not considered for this stage of the conceptual design.

Phase	Equation	Parameters	Reference
Range	$Range = \log_e \left(\frac{W_i}{W_f} \right) \frac{L}{D} \frac{V}{c}$		<i>Conceptual Aircraft Design, 2000</i>
		L/D Lift to Drag ratio	<i>Table 3-17</i>
		W _i aircraft weight at start of mission	<i>Table 3-18</i>
		W _f fuel weight	<i>Table 3-18</i>
		<i>At 35,000 ft cruise altitude</i>	
		a 973.1 ft/s	<i>ISA Tables</i>
		M 0.8	<i>Specification, 3.4.1</i>
		V = Ma	
		c specific fuel consumption	<i>Unconventional Engines, CRYOPLANE, 2000</i>

Table 3-54 – Payload Range

Take-off Distance

The take-off distance (assuming all engines operating) can be defined as the distance from brakes release to the point of rotation plus one third of the airborne distance from rotation to a point 10.7 m (35ft) i.e. the screen height. This distance must then be multiplied by 1.15 to provide an adequate safety margin.

Phase	Equation	Parameters	Reference
Take-off Distance	$S_G + S_S$ $S_G = \frac{1}{(2gK_A)} \ln \left[\left(\frac{K_T + K_A V_{LOF}^2}{K_T} \right) \right]$ $S_S = \left[(r + h_s)^2 - r^2 \right]^{0.5}$	$g \quad 9.81 \text{ ms}^{-2}$ $K_T = \left(\frac{T}{W} \right) - \mu$ $T \quad \text{Thrust}$ $W \quad \text{Weight}$ $\mu \quad \text{Coefficient of friction} \quad (=0.02 \text{ for paved runway})$ $K_A = \rho \left(\frac{2W}{S} \right) \left(\mu C_L - a - b C_L^2 \right)$ $S \quad \text{Wing Area}$ $C_L \quad 0.7$ $a \quad \text{zero-lift drag coefficient}$	<p><i>Jenkinson, L.R., Simpkin, P, Rhodes, D, 1999</i></p> <p><i>Jenkinson, L.R., Simpkin, P, Rhodes, D, 1999</i></p> <p><i>Jenkinson, L.R. Simpkin, P, Rhodes, D, 1999</i></p> <p><i>Table 3-23</i></p> <p><i>Table 3-53</i></p> <p><i>Jenkinson, L.R., Simpkin, P, Rhodes, D, 1999</i></p> <p><i>Jenkinson, L.R., Simpkin, P, Rhodes, D, 1999</i></p> <p><i>Table 3-21</i></p> <p><i>Jenkinson, L.R., Simpkin, P, Rhodes, D, 1999</i></p>

		<p>b lift-dependent drag coefficient ($C_D = a + b C_L^2$)</p> <p>$V_{LOF} = 1.11 V_{stall}$</p> <p>$V_{stall} = \left(\frac{W}{\frac{1}{2} \rho S C_{L_{max}}} \right)^{0.5}$</p> <p>$C_{L_{max}}$ Max. Lift Coefficient</p> <p>ρ 1.225 kg/m³</p> <p>r radius of climb $r = \frac{V_{TRANS}^2}{g(n-1)}$</p> <p>$n$ load factor $n = \frac{L}{Mg}$</p> <p>$L = \frac{1}{2} \rho V_{TRANS}^2 S (0.9 C_{L_{max}})$</p> <p>$h_s$ screen height (10.7m)</p>	<p>Table 3-56</p> <p>Table 3-56</p> <p>Jenkinson L.R.,Simpkin, P, Rhodes, D, 1999</p> <p>Jenkinson L.R.,Simpkin, P, Rhodes, D, 1999</p> <p>Table 3-52</p> <p>ISA Tables</p> <p>Jenkinson L.R.,Simpkin, P, Rhodes, D, 1999</p> <p>Jenkinson L.R.,Simpkin, P, Rhodes, D, 1999</p>

Table 3-55 – Take-off distance

DRAG POLAR

Phase	Equation	Parameters	Reference
Drag Profile	$Drag\ Profile = (C_{D_f} + C_{D_w}) + (K_V + C_{D_{L_V}}) C_L^2$		<i>Conceptual Aircraft Design, 2000</i>
	Incompressible zero-lift drag coefficient, C_{D_f}	$C_{D_f} = R \times F \times T \times C_f$	<i>Conceptual Aircraft Design, 2000</i>
	Incompressible drag coefficient due to lift, $C_{D_{L_V}}$	R Wetted Area Factor -5.5 for Jet airliners (increased to 15 for Twin Boom because of near threefold increased wetted area of tail booms)	<i>Conceptual Aircraft Design, 2000</i>
		T Type Factor – 1.1 for airliners	<i>Conceptual Aircraft Design, 2000</i>
		F Size Factor = $1 + 0.1 \left(\frac{20}{S} \right)^{0.5}$	<i>Conceptual Aircraft Design, 2000</i>
		$C_f = 0.0048 - 0.0006 \log_e (10.7S) (1 - 0.2M) \left(1 - 2 \frac{c_l}{R} \right)$	<i>Conceptual Aircraft Design, 2000</i>
		c_l % of laminar flow (assumed zero for worst case).	
		S Wing Area	<i>Table 3-21</i>
		M Cruise Mach Number	<i>Specification, 3.4.1</i>
		$C_{D_w} = \left(\left(\frac{0.12 C_{D_f}}{1 - 0.2M} \right) \left(\frac{(M \cos \Lambda)^{0.5}}{A_f - t/c} \right)^{20} \right)$	<i>Conceptual Aircraft Design, 2000</i>
		Λ Wing Sweep	<i>Table 3-41</i>
		A_f Aerofoil Design Standard = 0.5 (Advanced Aerofoil)	<i>Conceptual Aircraft Design, 2000</i>

		t/c <i>Thickness/chord ratio</i> $K_v = 1 + \left((0.142 + 0.0062A) \frac{(10t/c)^{0.33}}{\cos \Lambda} \right) + \left(\frac{0.1}{(4 + A)^{0.8}} \right)$ A <i>Aspect Ratio</i>	<i>Table 3-33</i> <i>Conceptual Aircraft Design, 2000</i> <i>Table 3-11</i>
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Table 3-56 – Drag Polar

WEIGHT & BALANCE

There is a 2-2 seating arrangement for the first class section of the cabin and a 3-3 seating arrangement for economy class.

The order of loading is as follows: the 16 first class passengers are loaded first, and then the remaining 168 economy class passengers are loaded two-by-two in the aisle first until that is full, then the centre seat until that is full and finally the window seat until all passengers are loaded. Then the reverse occurs whereby the window seats are loaded followed by the centre seats and the aisle seats and then finally the first class. This is what produces the ‘loops’. Once all the passengers are loaded the fuel is added.

The following table shows an example of the required inputs.

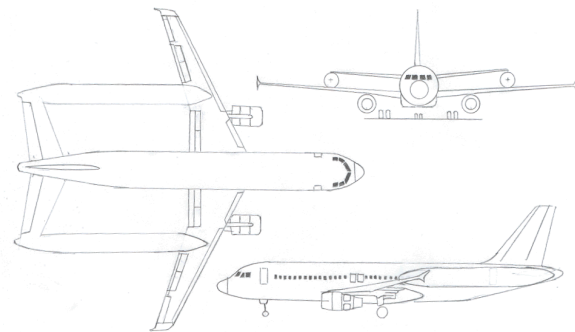
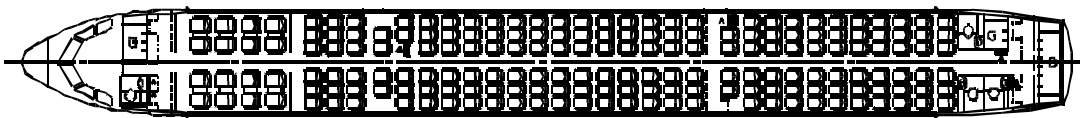
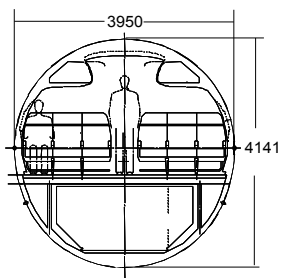
Pass	Passenger Weight (2 pass) kg	Distance from nose (m)	Moment kgm	Cumulative mass kg	Cumulative moment kgm	cg. (distance from nose) m	%mac	Cg %mac
1	181.4	5.5	997.7	51768	1290664	24.93	-0.00917	0.241
2	181.4	6.41	1163.572	51949	1291828	24.87	-0.00868	0.232
3	181.4	7.33	1329.444	52131	1293157	24.81	-0.00819	0.224
4	181.4	8.24	1495.316	52312	1294653	24.75	-0.00771	0.216
...	...	...	...	...	...	...	...	...

Table 3-57 – Weight and Balance Calculation

3.5 Results

Conceptual analysis of the medium range twin boom has yielded the following information indicating the mass, sizing and performance to be expected.

3-View diagram



General and Wing geometry data		
T/W		0.25
W/S	lb/ft ²	176
L/D		14.6
Overall length	ft	172
Span	ft	165
Wing Area	ft ²	3629
mac	ft	25
High Lift devices		Fowler Flaps Kreuger Flaps

Figure 3-14 - Twin-Boom General and Wing geometry data

Wing Properties		
Wing Area	ft ²	3629
Mac	ft	25
Span	ft	165
Aspect ratio		7.5
Taper ratio		0.25
Root chord	ft	35.2
Tip chord	ft	8.8
Sweep angle ¼ chord	deg	30
Thickness/chord ratio(average)		0.13

Figure 3-15 - Twin-Boom Wing properties

Tail Properties		Horizontal	Vertical
Area	ft ²	942.9	568.3
mac	ft	16.7	21.9
Span	ft	61.4	28.2
Aspect ratio		4.0	1.4
Taper ratio		0.3	0.3
Root chord	ft	23.1	30.3
Tip chord	ft	7.6	10.0
Sweep angle ¼ chord	deg	36.0	30.0
Thickness/chord ratio(average)		0.1	0.1

Figure 3-16 - Twin-Boom Tail properties

Fuselage Data		
Length	ft	172
Maximum width	ft	13.3
Seat abreast		2-2 First Class 3-3 Economy
Aisle Width	ft	1.64
Cross-aisles		1
Number of Toilets		4
Number of Galleys		3

Figure 3-17 - Twin-Boom Fuselage data

Landing Gear			
Unit Description		Main Unit: 2 x four wheel bogeys	
		Nose Unit: 2 wheels on one strut	
Main Gear	Tyre Diameter	in	38.0
	Tyre Width	in	12.7
Nose Gear	Tyre Diameter	in	30.4
	Tyre Width	in	10.1

Figure 3-18 - Twin-Boom Landing Gear data

	lbs
MTOW BASIC	243979
MZF	174535
OWE	134278
MPAY	40257
MFUEL	69444

Figure 3-19 - Twin-Boom Main Design Weights

		lbs
MFUSE	Fuselage	20293
MWING	Wing	16586
MTU	Tail unit	5880
MFUEL TANKS	Fuel tanks (x 2)	37355
MUC	Undercarriage	6300
MENG STRUCT	Engine associated structure	1873
MFLYCONTROL	Flying controls	1877
MENGINE	Engine (each)	4545
MCARGO	Cargo	3175
MHYD	Hydraulics	1767
MELEC	Electrical	2627
MAPU	APU	300
MAC	Air conditioning	1583
MDEICE	Deicing	808
MFURNISH	Furnishings	10060
MFIXED EQUIP	Fixed equipment	202
MCATERING	Catering	2758
MOTHER_OP	Other operational items	771

Figure 3-20 - Twin-Boom Detailed Weight Breakdown

Max operating altitude	ft	41,000
M _{TOW} BASIC	lbs	243,979
OWE	lbs	134278
M _{FUEL}	lbs	69444
Range @ full pax (98 kg/pax)	nm	4154
Take-off Field Length @ M _{TOW} s.l. ISA BASIC	ft	10839
Landing Distance	ft	7000
C _{LMax} (Clean)	C_L	1.0125
C _{LMax} (Landing)	C_L	1.85
Drag polar (cruise)	C_D	$0.0174 + 0.0641C_L^2$
No of engines		2
Thrust per engine	lbs	24442

Figure 3-21 - Twin-Boom Performance

Fuel Volume required	ft ²	3069
No. of fuel tanks		2
Mass of each fuel tank	lbs	18677
Tank diameter	ft	8
Tank length	ft	56
Tank pressure	bar	1.4

Figure 3-22 - Twin-Boom LH₂ Fuel Tank data

Length	in	121
Diameter	in	60
Weight	lbs	4545
c	kg/(sMN)	0.5447

Figure 3-23 - Twin-Boom Engine data

A. VORTEX DRAG	
Drag due to wing twist	0.0000375
Drag due to fuselage lift	2.25362E-05
Horizontal tailplane drag (trim)	0.000982145
SUBTOTAL	0.001042181
B. PROFILE DRAG	
Wing – minimum drag	0.0005623
- incremental drag	0.0082555
Fuselage- Basic drag	0.003173622
- Upsweep and incidence effects	0.002959868
Tailbooms	0.000563618
Nacelles	0.000778916
Horizontal tailplane	0.021752001
Vertical tailplane	0.021295954
SUBTOTAL	0.059341779
C. INTERFERENCE CORRECTIONS	
Wing/fuselage	
- vortex drag	0.001500362
- viscous interference drag	4.3929E-06
Lift effect on fuselage drag	0.002717926
Nacelle/airframe	0.0007
Tailboom/airframe – vortex drag	0.001908465
- Viscous interference drag	2.95636E-07
- lift effect on tailboom drag	0.012507736
SUBTOTAL	0.019339178
D. PROTRUBERANCES, SURFACE IMPERFECTIONS etc.	
Flight deck windows	7.39967E-05
Engine installation	
external drag – engine air intake/spillage	0.004641697
- engine air outlet/reversers	0.000183344
- oil cooler/radiator	0.000229179
Excrescences, surface imperfections, other extras	0.00057
- Surface imperfections	0.00041
- airframe systems installation	0.00056
- miscellaneous, unaccountable allowance	0.0002
SUBTOTAL	0.006868216

Table 3-58 – Twin-Boom Total Drag Summary

Weight & balance

Weight & Balance Chart LH₂ TWIN BOOM AIRCRAFT

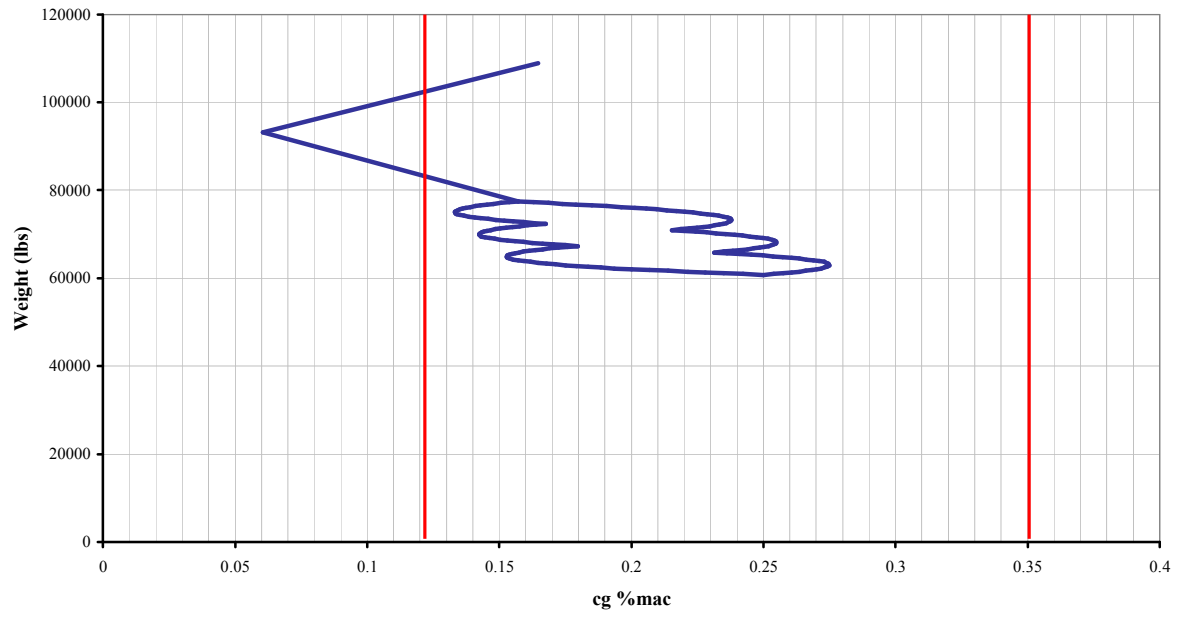


Figure 3-24 - Twin-Boom Weight and Balance Diagram

Payload-range

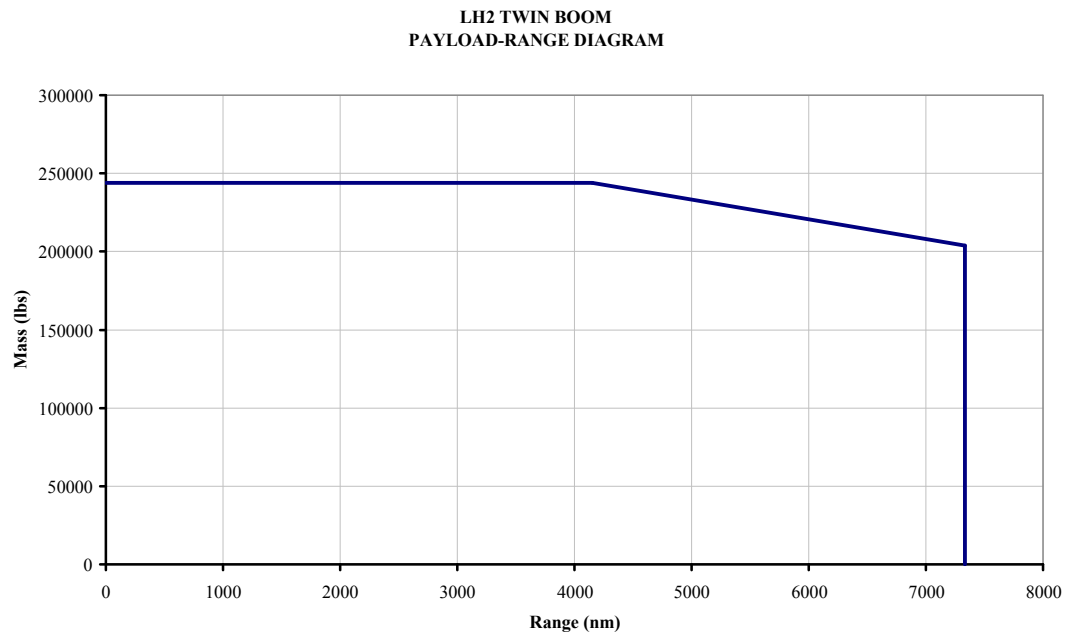


Figure 3-25 - Twin-Boom Payload Range diagram

3.6 *Configuration description*

The following section provides details of the performance, configuration and layout and operational issues having performed a concept design.

3.6.1 *Fuselage Layout*

Once the fundamental configuration was decided upon, it was possible to propose a layout for the fuselage with only secondary reference to other aspects of the design. This was particularly the case for the Twin-Boom with its conventional fuselage. In general, however, the fuselage design forms a convenient starting point for the overall layout process.

Overall consideration was given to the following aspects when designing the fuselage:

- ◆ passengers and freight
- ◆ fuel
- ◆ pressurization
- ◆ powerplant location

The Twin-Boom fuselage contains the passengers, provides overall structural integrity, provides protection against climatic factors and noise etc.

In establishing the outside shape of the fuselage, the aim was to achieve an aerodynamic streamlined form while minimising surface area thereby minimising both fuselage drag and mass. The main factor considered for the cabin was the cross-section shape which was kept cylindrical due to the requirements for high differential pressure and ease of manufacturing. A cylindrical cabin simplifies the structural design and manufacture enabling an efficient internal layout with little loss of space, whilst improving seating flexibility. Family concepts are also more easily developed i.e. by stretching the fuselage.

The passenger arrangement and cross-section in the Twin-Boom fuselage is conventional. Toilets and galleys in the Twin-Boom are arranged in line with the engines providing a 'passenger-free' space in case of blade loss.

Freight is carried in underfloor baggage for both the Twin-Boom in holds which use LD3 containers.

3.6.2 Wing and Tail layout

The Twin-Boom has a conventional tail. To avoid large regions of boundary layer separation and the associated drag, the tail length is 3x the diameter of the cylindrical fuselage section, with an upward sweep of 13° to ensure the tail clears the ground during rotation at takeoff and also during landing. There is also space provided at the rear to store the APU and air conditioning system.

The wing section shape and wing area are two of the five basic factors which affect wing lift and that can be altered by the designer. Although a thicker wing section provides more lift at a given speed, at high subsonic speeds, drag would also be increased to an unacceptably high level. Similarly, a compromise is achieved between a larger wing area and high aspect ratio and the subsequent increase in wing weight. Such a situation is well suited for optimization.

The wing area is optimized for cruise performance. Slats and leading edge flaps are utilized to increase stall angle and decrease stalling speed i.e. by increasing C_{Lmax} thereby providing acceptable low-speed performance. However, a limiting feature is the extent of the wing span which is available for the flap system (*Anderson, 1989*). The Twin-Boom fuel tank/boom attachments and engines limit the available span. The leading edge flaps are used in conjunction with the high speed wing sections to prevent

premature flow breakaway. Slats are used on the outer parts of the wings where a tip stall could cause a wing to drop prematurely.

The Twin-Boom requires a suitable wing-fuselage fairing to minimise interference drag. Dihedral is provided to enable engine clearance while also providing lateral stability particularly in gusty conditions.

The wing also has a high aspect ratio to minimise lift dependent drag. This is combined with moderate taper which simplifies manufacturing while closely approximating the ideal elliptical shape for minimum drag (*Stinton, 1983*). The structural limit to aspect ratio can be increased to an even higher level because of the structural support of the booms. However, if the wing is increased too much, it will be subject to a considerable degree of zero-lift drag and mass penalties, and so has been maintained at a reasonably high level, optimized to achieve a balance between fuel efficiency and empty mass.

A relatively thin wing with low t/c ratio was used together with a supercritical aerofoil section because of the high subsonic speeds. A large degree of sweepback is also used to delay the onset of compressibility effects. Both these methods increase the critical Mach number, M_{CR} . The taper ratio is kept to a reasonable value to avoid pitch up tendency while maintaining a low wing weight down without excessive C_L variation or unacceptable stalling characteristics.

Additional bending relief is provided by the fuel tank/boom structure as well as the wing-mounted engines.

The landing gear is attached to and retracted into the wings and is made easier because the Twin-Boom has no fuel stored in the wings. The undercarriage struts can also be kept short because the wings are low-mounted.

Empennage

A single centrally mounted fin is the most common arrangement and has been adopted for the Twin-Boom. The horizontal tailplane was located on the rear fuselage at a position higher than the wing thus preventing any possible problems due to tailwash. The empennage is located as far aft as possible to maximise the moment arm to the aircraft cg and therefore keep the control surface area and weight as low as possible.

3.6.3 Mass and balance

To establish the mass of the aircraft, the relationships were determined between the fuel requirements and the total mass which depends on the specified flight performance and requirements. The flight mission profile is broken into discrete phases where the take-off includes starting-up, taxiing to the end of the runway and acceleration to the climb-out speed. Climb is more difficult to analyse as both speed and altitude vary. However, the most important phase is the cruise which is simple to analyse and depends on aerodynamic efficiency (a measure of L/D ratio), the propulsive efficiency, and the airframe efficiency which is a measure of the M_{OWE}/M_{TOW} . The fuel used during descent and landing is minimal since the engine is operating at near idle conditions.

The weight and balance diagram is constructed by following a set loading as follows: passengers occupy the seats nearest to the window first. When these are filled, the rows next to the window seats are occupied followed by those closest to the aisle. The seats are occupied in two ways – starting from the front and starting from the rear, hence loops are formed. Finally, fuel is added by filling the first two fuel tanks (each tail boom having two tanks) and then the aft two tanks. Normally the fore and aft cg limits would be defined by stability and control analyses which is beyond the scope of the Conceptual design study. However, what is shown are typical average limits used as a basis for comparison. It can be seen the addition of fuel causes the cg to travel far forward. However, this can be avoided by ensuring the fuel flows in such a manner that the rear tanks are filled first.

Aircraft Mass

Wing

The wing lends itself to mass analysis because of its defined structural role. The most important parameters are the wing geometry and thickness, the design mass of the aircraft, normal acceleration factor and the Ultimate load factor.

The Twin-Boom wing weight includes the primary structure and continuity across the fuselage as well as fairings, high lift devices, and control surfaces but not control operating systems.

Although the fuel tank booms provide additional wing bending relief, no account is taken for this when calculating the wing weight because the fuel which is normally contained in the aircraft wing (and which would previously have provided bending relief) is no longer there so the situation is basically the same.

Fuselage

As mentioned, prediction of the fuselage mass is more difficult as it is influenced by many detailed layout consideration, however, an empirical method was used for the Twin-Boom as it has a conventional fuselage.

Tail unit

The tail units have a relatively low mass, but more significant than its' mass is its effect on the centre of gravity position and hence the aircraft stability characteristics due to its long moment arm. The most significant parameters are the areas of the tail surfaces. Formulae using empirical data were used and reference was also made to historical data.

In reality however, a full stability and control analysis would be required to accurately optimise the tail surfaces to account for the large roll inertia of the fuel tanks and provide sufficient control power and acceptable response during manoeuvres.

Landing gear

The landing gear mass was estimated to be a typical value, although in practice detail layout and design can give rise to variations on this figure. Apart from the loads, the length of the legs is the most important consideration. Two four wheel main bogey units and two wheel nose wheel steering is adopted.

Powerplant-and related structure

The hydrogen-fuelled engine data such as mass, sfc etc. has been taken to be that designed by Stefano Boggia and Anthony Jackson, (Engine A, *CRYOPLANE*, 2000).

The structural mass includes nacelle structure and engine pylon mass but because of variability, it is convenient to include these items within a total powerplant installation allowance. In addition, a percentage of each engine mass has been taken to account for all the related structure and includes accessories, internal pipework and ducts, and external removable panels.

Systems, equipment and operational items

These can contribute a large part of overall mass of the aircraft, and includes the fuel system, the flying controls, hydraulics and pneumatics, electrical systems, APU and accessory drives, instruments, avionics, air conditioning, pressurisation and oxygen, de-icing and furnishings. Data from the specification were used where given, otherwise formulae using empirical data was used.

Fuel tanks

For the Twin-Boom, although the structural booms are structurally efficient, the need to minimise their wetted area implied the use of small cross-section dimensions. Evidence suggests that total boom mass is not greatly different to that of a comparable conventional fuselage although structurally simplified (*Howe, 2000*). Furthermore, to simplify the analysis procedure, the fuel tanks are composed of cylindrical mid-sections with spherical ends. This enables the mass, wetted areas and profile drag to be readily calculated particularly since they are similar in shape to the fuselage. The wing/fuel tank junction needs careful streamlining to minimise any adverse interference drag effects.

The location of the Twin-Boom fuel tanks and the addition of fuel cause the cg to exceed limits. This situation is expected to get worse for a possible stretched longer range version or family concept, and a method of counteracting this problem will be required, probably by controlling fuel flow such that the cg limit is not exceeded (e.g. Concorde). Alternatively, although undesirable, balance may be provided by using a proportion of the fuel as ballast as required to maintain the cg within limits. A possibility is to use a portion of the underfloor space normally reserved for cargo as an auxiliary fuel tank however this detracts some of the safety advantages of the Twin-Boom (as well as reduces the space available for cargo). With the high location of the Twin-Boom fuel tanks, take-off rotation and landing does not pose any difficulty.

The hydraulics and pneumatics systems mass has also been factored by 25% to allow for the increased complexity of the fuel system and the requirement for insulated pipes and fuel feed lines.

3.6.4 *Lift and Drag*

The Twin-Boom has a relatively low L/D ratio which affects the cruising performance. This is due to the increased profile drag due to the large increase in wetted area of the fuel tanks.

The cruise C_L corresponds to an angle of attack range enabling the passenger cabin to remain virtually level. The maximum lift was estimated by assuming the same section was used along the wingspan. In practice, the wing sections will vary along the span to provide optimal aerodynamic characteristics often determined by CFD analysis and wind tunnel tests.

The drag was broken down into components of vortex-induced drag and profile drag. Provided all main aeroplane parts are considered as isolated bodies, most components of vortex-induced drag can be calculated fairly accurately, as can the profile drag. The wing, fuselage, and nacelle, and empennage are considered to be streamlined smooth bodies, and corrections were applied to allow for the interaction of the flow fields, protuberances and flow fields.

The interference drag is more difficult to accurately determine although empirical formulae provide useful estimates for conceptual design purposes. Because the Twin-Boom is similar in shape to the fuselage, the same interference effects are applicable to be both.

3.6.5 *Powerplant and Installation*

The Twin Boom has two wing-mounted podded engines and data is derived from unconventional hydrogen engines (*CRYOPLANE, 2000*). The wing-mounted engines provide easier access for maintenance and repair as well as additional wing bending relief.

The engine location of the Twin-Boom means that a sufficiently large rudder is required in an engine-out situation.

An additional consideration is that it is important to ensure the hot engine exhaust does not impinge on the fuel tanks leading to structural or fatigue damage or a significant increase in boil-off of the cold LH₂ fuel. An increase in insulation as well as careful local design is required.

3.6.6 Performance

The maximum range is usually obtained if a “cruise-climb” technique is employed, where the height is allowed to increase as the weight decreases and the L/D remains approximately constant. As this is not practical because of air traffic control requirements, a stepped climb is normally used.

The range was calculated using the Breguet range formula evaluated per unit mass of fuel for a given value of aircraft mass, speed, altitude and engine setting. The maximum ideal range occurs at $L/D_{\max}$. For maximum endurance, flight should be at V_{md} .

For take-off, the “high” tank layout of the Twin-Boom enables easier rotation at take-off but the penalty is a less aerodynamically clean situation.

3.6.7 Fuel Tank Structure

Since the Twin-Boom fuel tanks are exposed to the airflow, they were streamlined as far as possible using a fineness ratio similar to the fuselage to minimise the wetted area and ensure minimum interference. In case of disk burst, the following precautions should be observed:

- ◆ redundant wires, lines and connections
- ◆ fire-resistant materials, protective shields, and deflectors
- ◆ shut-off valves at each transition from one component to another.

Although tank insulation is beyond the scope of this study, there are various insulation systems and tank structural concepts offering various trade-offs of thickness and weight. Two types of hydrogen fuel tanks can be used:

- ◆ non-integral tanks which don't react the loads on the aircraft
- ◆ integral tanks which are load-bearing.

When calculating the required fuel and hence tank volume, a percentage allowance was made for any residual and unusable fuel, and boil-off.

The design of the fuel containment system is a very important as well as challenging aspect of liquid hydrogen fuelled aircraft. The material used for fuel tank containment must have specialist properties such that it is resistant to the extreme low temperatures of the cryogenic fuel and it must be impermeable (either with or without sealing). These requirements are addition to standard requirements of a structure, such as the ability to withstand certain load, have good strength and fatigue properties, and be accessible for inspection and amenable to repair. Thus the fundamental goal is to maintain structural integrity whilst achieving a lightweight structure. The fuel tanks are similar to fuselage structures in that they are similar in shape, fineness ratio and are subject to pressurisation loads. Therefore the same assumptions have been applied to calculate the tank weight. As mentioned although tank insulation design is beyond the scope of this thesis, it is instructive to consider its impact on tank volume and weight. The influence of differential thermal expansion of the tanks and the surrounding structure is heavily dependant on the thermal insulation system. The insulation may either be located inside the tank or on the exterior. If the insulation is applied to the inside of the tanks, then the exterior wall so the tanks will remain at a near-ambient temperature thereby minimising the differential thermal expansion between the fuel tanks and the surrounding structure. However, the overriding reason for not selecting such a scheme is that the insulation being constantly exposed to liquid hydrogen fuel must be impermeable to GH_2 . There is no known plastic insulation that is impermeable

to GH_2 . Furthermore, even if there was such a material, the inspection and repair of the insulation on the inside of the tank walls will be made very difficult. Applying the insulation to the fuel tank wall exterior brings about its own significant problems. Due to the significant differential thermal expansion, the tank itself will contract and expand as liquid hydrogen is introduced and used. Thus attachment of the fuel tank will be difficult, not only because of the dimensional changes but also because of the potential for leaks. Furthermore, external insulation is susceptible to damage.

In addition to the fundamental requirement that the insulation system control minimise hydrogen boil-off, it must also minimise the level of frost build-up on the aircraft to prevent parasitic weight whilst requiring the minimal amount of maintenance. Thus, optimisation of the insulation system will require minimisation of operating costs as well as the achievement of very levels of safety.

Because of the severe consequences of even a small leak, designs that are dependent on maintaining a high vacuum are not considered acceptable. A promising concept involved the use of borosilicate microspheres in a partially evacuated annulus surrounding the fuel tank. Also showing promise are rigid foam insulants. Thus, we would need to determine the optimum thickness of material that should be utilised to provide acceptable thermal protection for the least weight and cost. There is a trade-off to be made between the thickness of insulation and the resulting amount of hydrogen boil-off. Using the data provided in Table 3-59 which shows the density and thermal conductivities for three candidate insulation materials, we can approximate the effect on volume and weight on the fuel tanks by adding insulation.

Material	Density (lb/ft ³)	Thermal Conductivity (Btu/h ft °F)
Polymethacrylimide	2.2	0.018
Polyurethane	4.0	0.012
Polyvinylchloride	3.1	0.0087

Table 3-59 - Properties of Foam Insulation materials for LH₂ fuel tanks (*Brewer, 1991*)

Assuming a circular tank with unit length of 1 ft, and radius 1 ft, we can approximate the weight of the insulation for incremental thicknesses. This is shown in Table 3-60 and Figure 3-26. The data shows that although the increment to volume is not very significant, the weight increment is. There are obvious trade-offs to be made between the weight of the insulation system and the cost and thermal conductivity. So although Polyurethane is almost twice as dense as Polymethacrylimide it possesses 30% better insulating capability.

Insulation Thickness (in)	Volume (ft ³)	Weight (lbs)		
		Polymethacrylimide	Polyurethane	Polyvinylchloride
1	5.70	123	224	173
2	11.58	250	454	352
3	17.54	379	688	534
4	23.65	510	928	719
5	29.98	647	1176	912
6	80.02	785	1427	1106
7	94.46	927	1685	1306

Table 3-60 – LH₂ fuel tank weight increment due to insulation

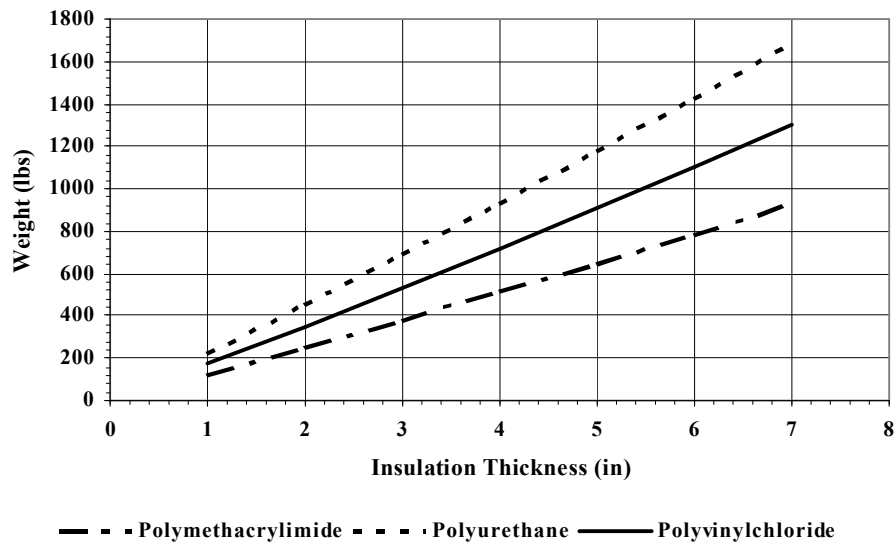


Figure 3-26 - LH₂ fuel tank weight increment due to insulation

Studies have suggested that an optimum insulation thickness is in the region of 3-5 inches (*Brewer, 1991*).

In reality, however, the amount of insulation needed will vary and depends on the insulation properties, the tank size (and shape), allowable boil-off rate. In order to estimate the insulation requirements, the heat flow into the tank should be analysed.

3.6.8 LH₂-fuel tank pylon structure (*twin boom*)

Although the LH₂-fuel tank pylon structure is a local design issue and is beyond the scope of the conceptual design phase presented here there is merit in discussing some of the considerations. The Twin-Boom pylon which connects the fuel tanks to the wings reacts loads imparted by the aircraft as well as aerodynamic loads associated with the airflow around the tank profile. Accessories and controls are provided to enable the fuel tanks to function safely and provide fuel supply to the engines and to allow for routing of the various pipes and connecting cables. Attachment to the wing is through fittings at the forward spar and upper skin panel.

The pylon design should be designed for minimum weight whilst ensuring structural integrity providing protection, at least to some degree, against catastrophic failure. The structure should provide easy access and removal of necessary components and material selection should be compatible with low temperatures.

3.6.9 Safety

The Twin-Boom has several potential safety advantages, particularly the physical separation between the passengers and fuel. Additionally, the high tank combined with the low wing configuration makes a suitable landing platform in an emergency landing or in the event of ditching and provides a convenient location for overwing emergency exits. The fuel tanks extend aft of the engines and so are out of the line of impact should a blade disk rupture or separate.

Emergency evacuation is defined by the airworthiness requirements (*JAR/FAR 25.803, CAA, 1995*) and states that all personnel must be evacuated within 90 seconds. The JAR also specifies the number and type of exits depending on the number of passengers. For the Twin-Boom, the high location of the fuel tanks eases emergency evacuation.

Conclusions

The Twin-Boom has a conventional wing and fuselage is therefore a relatively well refined design. Combine this with a structurally favourable configuration utilising the weight advantages of LH₂ fuel and the result is an unconventional configuration with much potential. The large fuel tanks provide wing bending relief that reduce wing weight, however conversely, the absence of fuel in the wing (as for a conventional configuration) means the advantage is cancelled out. The passenger distance from the fuel tanks provide a safer situation and can enable faster turnaround with refuelling occurring during passenger disembarkation.

Unsurprisingly, the main problem with the Twin-Boom lies in that large wetted area of the fuel tanks. This has many consequences demonstrated by the lower L/D ratio, the increased profile drag and the addition of aerodynamic interference drag at the wing/boom junctions. Under normal circumstances, it is difficult to accurately determine many of these aspects but in order to do so requires a combination of CFD analysis, wind tunnel testing and flight test.

Certain aspects will require careful local design. For example, at high angles of attack, separation at the wing-fuselage junction may result in a reduction of $C_{L_{max}}$, although this can be minimised by suitable fairing/filleting, providing optimised twist and aerofoil section etc. Although the tanks themselves will in reality provide some lift this has not been accounted for. There are some operational issues such as the ability to meet the emergency evacuation requirements and the obstructed view outside the windows at the rear of the Twin-Boom cabin.

As this stage in the design there are still uncertainties. Nonetheless, there are no show stoppers but instead there is much scope for optimisation and the adoption of careful local design can minimise the drag and reduce weight further.

4.0 HYDROGEN SAFETY

The conceptual design process presented in Chapter 3.0 has resulted in a LH₂ aircraft configuration that offers potential advantages - the **Twin-Boom** (TB). However, one of the critical issues regarding the successful and accepted use of hydrogen fuel is that of **safety**. This chapter is therefore dedicated to addressing the subject of safety and in particular highlighting the main hazards present in the production, distribution storage and use of liquid hydrogen. Throughout this chapter, safety is addressed and the necessary elements of safety are reviewed in order to demonstrate its viability and the safety issues associated with the liquid hydrogen. Where applicable, the Twin-Boom is used as an example since it was the configuration that the author (and others involved in the brainstorming) had conceived and further developed from scratch.

For the successful introduction of liquid hydrogen into operational use, it must either be demonstrated that hydrogen fuel is *at least as safe* as kerosene fuel or that suitable safety measures may be implemented without providing a major hazard. This is vital to hydrogen gaining worldwide acceptance. Of course, by their very nature and purpose, any fuel requires that certain procedures be followed to provide safety for the operator and users since they are, after all, required to combust and provide energy when mixed and ignited!

Safety aspects associated with properties of the hydrogen fuel as well as hazards of operation are studied. The level of risk is presented and methods of mitigating the risks are offered. Safety is associated with characteristics of the fuel, operation of the aircraft, the infrastructure and operation and interface between them. This is illustrated below in Figure 4-1.

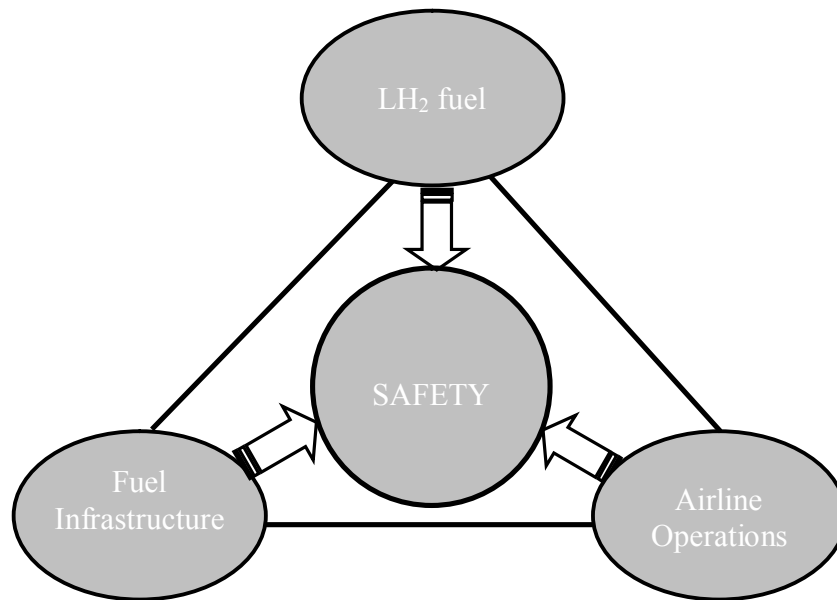


Figure 4-1 - Interdependence of LH₂ fuel, airline operations and airport infrastructure affecting overall Safety.

4.1 Characteristics of Liquid Hydrogen

Studying the hydrogen properties (as shown in Table 2-2) reveals that the energy required for ignition of hydrogen is low, has a wide limit of flammability, high volatility, and high flame velocity. Although these are undesirable, they could also contribute to preventing accumulation of gaseous hydrogen, which could ignite, causing conflagration, or even detonation. Similarly so for its combustibility and detonability ranges, where it is the lower limit of these properties which is most significant (since the combustible mixture ignites as soon as the lower limit is reached).

Hydrogen has a higher ignition temperature and a lighted cigarette will not ignite hydrogen in air, unlike kerosene. The minimum ignition energy of hydrogen means it will ignite with a spark one tenth the energy of other fuels. In reality, however, a small spark is sufficient to ignite even hydrocarbon fuels in air.

The high diffusion velocity of hydrogen in air causes it to mix rapidly in confined spaces. However, this combined with its very low density means that hydrogen will also dissipate very rapidly.

When hydrogen burns, the thermal energy radiated to the surroundings is lower than that of kerosene and because of its low emissivity, the surrounding area subject to damage will be smaller. The problem is that hydrogen flames are invisible to the naked eye, making it possible for personnel to be inadvertently burned.

Hydrogen is the smallest molecular structure in existence, which lies at the origin of a number of its characteristics including:

- ◆ low density, both in liquid and gas phases
- ◆ high aptitude to diffuse through fluids, condensed matter and mechanical gaps (interfaces) or crystallographic gaps (grain boundaries, macro- or micro-structural defects).

4.2 Risks related to low temperatures

Any traces of air or moisture in liquid hydrogen circuits can freeze and can clog circuits. Any air input into a cryogenic circuit, e.g. due to defective sealing, or a faulty valve, ultimately results in a risk of defect. It is this kind of contamination that is the probable cause of failure of the ARIANE mission (flight 70) in 1994. Low temperatures cause ice accretion and can freeze equipment as well as degrade operation of valves and systems.

The extremely low temperatures can significantly modify material characteristics that are exposed to them, usually leading to reduced plasticity and embrittlement. All materials which may come into contact with the LH₂ must be compatible with these temperatures such as certain Aluminium alloys, austenitic steels, copper-titanium

alloys, Teflon™. The low temperatures are also likely to cause high thermomechanical stresses, with the potential risk of loss of sealing. Finally, low temperatures represent a potential hazard to personnel by frostbite. Asphyxiation may also result from this large volume of gaseous N₂ and H₂ displacing the oxygen present in the atmosphere of any unventilated room.

4.3 Phenomena associated with combustion

By way of example, consider the following case:

A potentially explosive volume of 1m³ of air + hydrogen mixture in 90%-10% proportions represents a hydrogen mass of 8kg. The explosion of this relatively small quantity of hydrogen leads to an overpressure of approximately 130 mbar at a distance of 5 m and 50 mbar at 10 m.

This clearly illustrates the fact that ignition of a hydrogen leak, however small, in the ambient environment inside the Twin-Boom structure, is liable to cause major damage potentially resulting in the loss of the aircraft.

4.3.1 Danger zones of spilled liquid gases

There is a useful method (*Marc Pellet and Jean-Pascal Pitton, CRYOPLANE, 2000*) that provides a useful insight into the necessary safety distances which should be adopted. Consider that the Twin-Boom contains 15 tonnes of hydrogen which combusted. This quantity of hydrogen would consume 120 tonnes of oxygen, corresponding to 515 tonnes of air. The reaction would therefore produce 135 tonnes of steam mixed with 380 tonnes of nitrogen. Allowing for the different thermal and thermochemical properties involved, the uniform temperature of this gas mixture would be approximately 2,300°C. The volume occupied by this mass of gas at a pressure of 1 bar corresponds to a spherical fireball with an approximate radius 100m.

Figure 4-2 shows the range of the danger zones, in terms of distance, for Hydrogen, Methane and Propane fuel when 3.3 m³ is spilled in a 4m/sec wind. This shows that the distance that the hydrogen spills is far less than that for Methane and Propane. The main reason for this is that hydrogen diffuses and becomes buoyant very quickly.

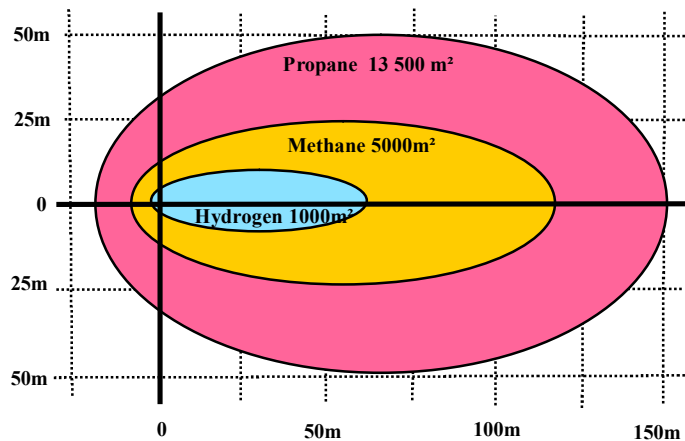


Figure 4-2 – Range of danger zones for various fuels when 3.3m³ is spilled in a 4m/sec Wind (*CRYOPLANE, 2000*)

As an initial approximation therefore, a 100-metre radius is accepted to represent a satisfactory estimate of the hazard distance of a Twin-Boom aircraft with full tanks.

4.4 *Specific hydrogen hazards*

Table 4-1 provides an extensive insight into the specific hazards that may be present either during use or any operational procedure. Means of prevention of an incident occurring has been suggested, or in the case of the incident having occurred, a means of protection. This list, although extensive, is not exhaustive.

Related risks	Means of prevention/protection
Volume expansion of LH₂ <i>Trapped liquid</i>	<ul style="list-style-type: none"> • Try and ensure enclosures and cavities within the Twin-Boom tanks are unlikely to trap liquid • Use of venting systems (GH₂ or GHe) for flushing. • Insulating fuel systems and equipment • Protection of all system sections by safety devices e.g. burst disks and safety valves • Monitor internal system pressure with related emergency procedures e.g. system depressurisation.
Buoyancy <i>Gas accumulation</i>	<ul style="list-style-type: none"> • Provide ventilation • Monitoring of hydrogen concentration, pressure, leak detection and evacuation systems
Flammability <i>Ignition, spontaneous combustion</i> <i>Person being caught in a hydrogen flame</i>	<ul style="list-style-type: none"> • Venting/disposal of unwanted GH₂, perhaps through the rear of the Twin-Boom tanks. • UV or IR flame detection • Inerting of lines before and after system venting • Activation of fire extinguishing spray systems in case of flame detection or emergency activation • Operator training concerning risks specific to hydrogen and emergency procedures • Provision of flameproof clothes and personal protective equipment
Low temperature <i>Ice accretion</i> <i>Embrittlement</i>	<ul style="list-style-type: none"> • Thermal insulation of equipment, pipelines etc. • Anti-/De-icing • Use of compatible materials • Temperature monitoring, periodic inspection and regular de-/anti-icing of equipment • Emergency procedures in case of operating loss of equipment e.g. blocked valve
Small dimensions of molecule <i>Leak at interface level</i>	<ul style="list-style-type: none"> • Minimise interfaces and mechanical joints • Use advanced seals • Perform regular helium tightness tests • Hydrogen detection near interfaces that may leak • System redundancy enabling isolation of a leaking system

Table 4-1 - Specific hazards due to fuel properties or as a result of operational procedures (*CRYOPLANE, 2000*).

4.5 Infrastructure-specific safety aspects

4.5.1 Hydrogen production methods

Although there are many possible production processes for hydrogen, two main methods form the current state of the art. **Natural gas (NG) steam reforming** is used for 97% of the present worldwide hydrogen production mainly for economic reasons, and is not expected to change significantly in the near future. The other main possibility is **alkaline water electrolysis**. This is useful because of its potential of coupling to almost all sources of primary energy.

For on-site hydrogen production, the main hazardous components and the undesirable events that may be a safety concern are GH₂ leakage and the presence of sparks.

4.5.2 Hydrogen liquefaction

Table 4-2 shows that the most susceptible components in the liquefaction system with regards to safety are the accessories and component connections.

Functional Unit	Hazardous components	Undesirable events
<i>Liquefaction</i>	GH ₂ /LH ₂ piping system	Rupture by external forces or internal pressure, or leakage Embrittlement
	LH ₂ piping system insulation	Condensation of atmospheric air or failure Impact damage
	Shut-off valves, gaskets and sealing	H ₂ leakage, or blockage (valves) due to ice accretion
	Connections, accessories	LH ₂ leakage, spilling
	Electrical power supply	Spark-source for hydrogen ignition
	Heat exchangers	Cooling water freezes ⇒ possibility of mechanical burst

Table 4-2 - Most hazardous liquefaction components and associated undesirable events.

Safety distances of the liquefaction plant must be maintained w.r.t. other installations and airport traffic to avoid knock-on effects and isolate accidents. Earth mound/barriers may provide additional protection although it is believed that with good safety systems in place, these may be unnecessary.

4.5.3 Storage

Table 4-3 shows the hazardous component and undesirable events relevant to the storage of LH₂. Underground storage tanks provide protection in case of rupture, however, soil around the tank is likely to freeze and corrosion issues also need consideration. Access to the tank should be restricted. Above ground storage tanks may be located in open trenches with concrete walls providing protection while enabling accessibility for maintenance.

Locating the storage tanks at the airport is a compromise between maximising distances as required by safety while minimising transfer losses by having shorter pipes.

Functional Unit	Hazardous components	Undesirable events
Liquid hydrogen storage tank	Tank vessel	Rupture - large LH ₂ spilling
	Insulation system	Loss of insulation effectiveness ⇒ heat + pressure rise ⇒ venting
	Gaskets and sealing	LH ₂ leakage Embrittlement
	Equipment (connections tank⇔H ₂ distribution)	LH ₂ leakage, spilling

Table 4-3 - Hazardous components and undesirable events caused in the hydrogen fuel storage facility.

4.5.4 Distribution

LH₂ can be distributed via pipeline to various filling stations utilising open trenches covered with grids. Table 4-4 shows the hazardous components and undesirable events relevant to the distribution of LH₂. Distributing the hydrogen via trenches that are open will allow venting of hydrogen, and enable regular inspection and cleaning. Hydrogen safety sensors can be installed to detect the formation of explosive mixtures with oxygen or detect any leakage from pipelines or failure of insulation. During the interim transition from kerosene to hydrogen, it is possible to utilise tanker trucks as an intermediate solution and means of distribution.

Functional Unit	Hazardous components	Undesirable events
Liquid hydrogen distribution	Pipeline	Rupture, explosion
	Shut-off valves	Pressure rise: LH ₂ leakage, spilling
	Accessories	LH ₂ leakage, spilling
	Insulation system	Loss of insulation $\Rightarrow$ heat + pressure rise

Table 4-4 - Hazardous components and undesirable events caused in the hydrogen fuel distribution facility.

4.5.5 Filling Stations

The main hazards at the hydrogen filling stations are shown in Table 4-5. LH₂ tank couplings for the Twin-Boom are generally state of the art, and are already in use in the space industry, as well as under current development in the automotive industry. However, redesign is necessary for aircraft operation to enable the couplings to cope with the high flow rates required for filling the large volume tanks. One of the main components is the filling pump, which could be realised using a hook-up of a special truck according to the hydrant concept. Moving parts of the pump in particular, might encounter friction problems and need careful design to prevent sources of ignition.

Material selection also needs careful consideration. The main hazards concern leakage and rupture of couplings or pipelines.

Functional Unit	Hazardous components	Undesirable events
Liquid hydrogen distribution	Twin-Boom coupling	Failure, LH ₂ spilled until shut-off valve reacts, also spark emission, rupture
	Valves	Overpressure-LH ₂ leakage, blockage
	Piping	LH ₂ leakage, spilling, rupture
	Gaskets and sealing	LH ₂ leakage

Table 4-5 - Hazardous components and undesirable events caused by fuel distribution at the filling stations.

4.5.6 Summary

The main hazards overall are related to component failure of pipes, tanks and connections resulting in hydrogen release posing an additional hazard if a flammable mixture is formed. Venting and installation of gas alarms therefore are crucial safety measures. So too is careful local design, material selection, leak detection and adequate safety and emergency procedures. On the other hand, hydrogen release alone does not cause accidents, since it always requires an ignition source. Electrical installations must be explosion-proof and all installations must be grounded which is compulsory at the aircraft filling station. “Non-compliant” vehicles must not be operated around hydrogen facilities.

No explosive mixture must be formed when tanks are emptied. The entire LH₂ storage and flow system should be equipped with venting systems to dispose of hydrogen safely and prevent ingestion and accumulation of oxygen. Whether GH₂ is to be recycled needs consideration, and will ultimately depend on its cost effectiveness.

Safety distances should also be observed, and extensive operator training should be conducted.

4.6 Hazards & accident scenarios

The physical and chemical properties of hydrogen fuel indicated the type of hazards inherently present in the fuel which could potentially cause problems at component level and has been described. A summary of the effects of such incidents are shown below in Table 4-6.

4.6.1 Hazards

Major	Minor
Explosion	Cold injuries
Fire	Asphyxiation
Material embrittlement	Air condensation and oxygen enrichment
Thermal stresses	

Table 4-6 - Major and minor hazardous properties of LH₂ fuel.

In any incident involving hydrogen fuel, it is crucial whether the hydrogen release occurs in open or confined areas. In confined and partially confined areas, ignition and propagation of the flame, characterised by high-pressure and temperatures, is very likely to occur. In open areas, however, detonation is unlikely.

4.7 Conclusions

In conclusion, the potentially hazardous characteristics of LH₂ can be summarised to include the following:

- draws heat quickly from surroundings and vaporises rapidly
- volume increases by factor 50 (asphyxiation in enclosed areas)

- water vapour freezes (cold GH_2 continues absorbing heat) forming dense cloud during vaporisation
- noises from contracting objects (heat withdrawal)
- oxygen and nitrogen of ambient air can condense or freeze
- deflagration effects are 'small' if ignition occurs immediately upon liquid release - initial fireball size increases with delayed ignition

The general sequence of events that usually occur in the lead up to an accident is shown in Figure 4-3. This shows that unless hydrogen is released and ignited it may not cause an accident. Thus the main aim is to prevent the release of hydrogen but also to ensure that in such an event, there are no ignition sources present that could lead to ignition. Nonetheless, since absolute safety can not be achieved protection should be provided to personnel and property.

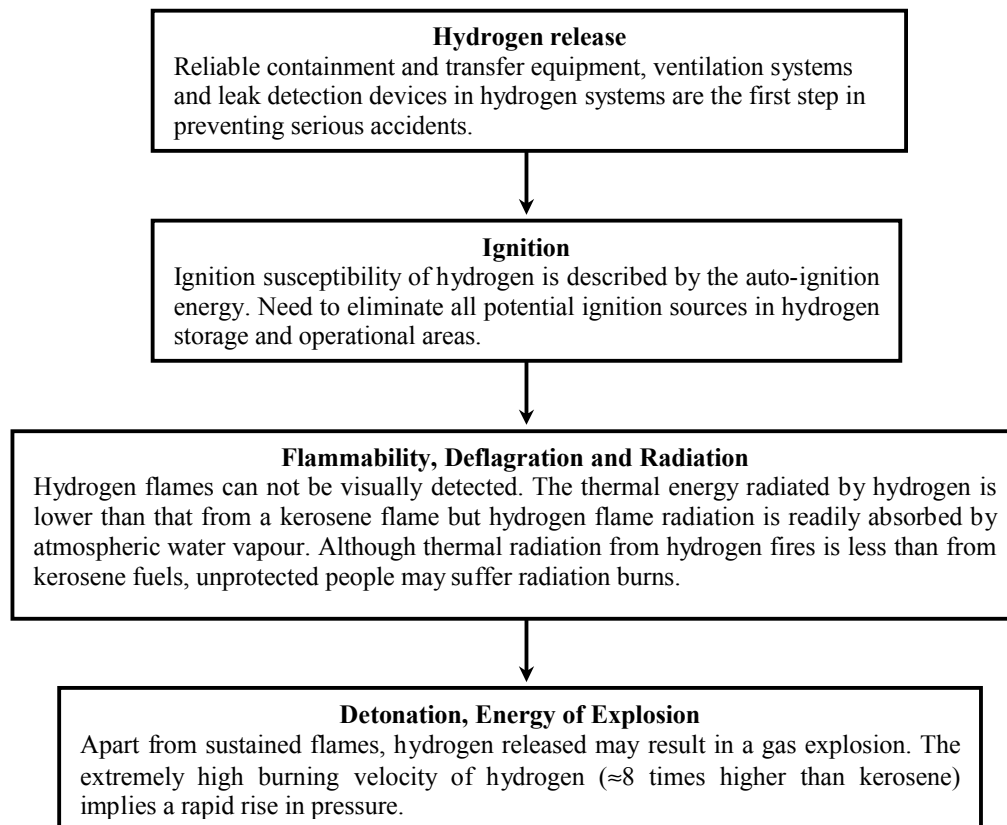


Figure 4-3 - General sequence of events that usually occur in the lead up to an accident
(Boeing Commercial Airplane Company, 1976).

5.0 HYDROGEN AIRCRAFT CERTIFICATION

In Chapter 3.0, it has been shown that design of the hydrogen-fuelled Twin-Boom aircraft concept is technically feasible. Subsequently, the relevant safety issues were analysed in Chapter 4.0 using the Twin-Boom as a case study where applicable and it was demonstrated that, for all intents and purposes, hydrogen fuel *is at least as safe* as kerosene. However, the story does not end there. Any new aircraft that is to be introduced into service must attain an airworthiness certificate before the aircraft type is allowed to perform routine flights. Attaining this airworthiness certificate is a very lengthy and costly process and involves demonstration by the aircraft manufacturer that the airworthiness regulations appropriate to that class of aircraft have been met. To this end, aircraft certification is addressed in this chapter; with direct applicability to the Twin-Boom where relevant. In particular, those existing regulations that require modification and those that simply do not exist yet are required for safe operation of liquid hydrogen fuelled aircraft have been identified.

Previously, the Joint Aviation Authorities (JAA) used to govern European aircraft manufacturers which had to follow Joint Aviation Regulations (JAR). However, because European countries have long sought to harmonise procedures and standards in the field of aviation safety, through the JAA, the European Community has now taken over responsibility from the national authorities of its 25 European Union (EU) Member States to produce common rules in the field of airworthiness and environmental protection. This led to the creation of the European Aviation Safety Agency (EASA).

In 2003, EASA took over responsibility for the airworthiness and environmental certification of all aeronautical products, parts, and appliances designed, manufactured, maintained or used by persons under the regulatory oversight of EU Member States. This uniform system is intended to bring about advantages including ensuring that all aircraft are designed, built, and maintained to the same high standards,

no matter where they are based. It is also hoped, that by ensuring the highest environmental standards are agreed and implemented throughout Europe, environmental pollution will be reduced and quality of life will be improved, particularly through noise reduction.

As mentioned, the airworthiness certification process forms an extremely substantial part of the aircraft design process and accounts for a large proportion of the initial costs. Thus, any aircraft, unconventional or otherwise, must meet the necessary regulations and airworthiness standards which will enable the airline to operate it. Herein lies the dilemma - such regulations **do not** exist for aircraft operating on hydrogen fuel. Existing regulations and requirements are extensive, and although many will remain the same after transition to hydrogen fuel, inevitably many will need modification, or entirely new requirements devised. This difficulty is compounded by the fact that the Twin-Boom is unconventional.

In line with analysing the safety and regulatory issues with direct reference to the Twin-Boom concept, what is presented here is a continuation in the analysis formed of a comparative study into JAR rules (*CAA JAR, 1955*) which was in existence at the time of writing. This is in concurrence with a study performed by Giuseppe Mingione (*CRYOPLANE, 2000*). These JAR rules have been addressed specifically with regard to introducing the LH₂-fuelled Twin-Boom configuration. As well as identifying the relevant rules, the need to change/complement the rules have been described to enable the Twin-Boom aeroplane to be designed and operated. Thus although JAA have now been superseded by EASA and the corresponding references to the JAR detailed in this Chapter have now changed (since the transition of Authority from JAA to EASA), the actual words and descriptions remain the same.

5.1 Engines

JAR 25.1041 General

The regulations state that the powerplant cooling provisions must be able to maintain the temperatures of powerplant components, and engine fluids, within the temperature limits established for these components and fluids during flight operating conditions and after normal engine shutdown. This should be facilitated to a greater extent with LH₂-fuelled aircraft due to the very low temperature of the fuel and hence its greater cooling capacity.

Unconfined engine failure (JAR-ACJ 25.903 rotor)

The JAR prescribe an engine failure model to account for the possibility of engine or rotor debris impacting the aircraft in an area confined by two planes forming an angle of $\pm 3^\circ$ ($\pm 5^\circ$ for small debris) with the engine rotating component plane.

Of course this is important for all aircraft which must take measures to avoid debris damage/rupture to fuel tanks. However, the Twin-Boom hydrogen fuel tanks are particularly susceptible due to their large surface area. Although, present engine failure models could be applied, the high potential risk of catastrophic accident in case of tank failure may mean that modifications to the regulations are required, perhaps making them more stringent. The Twin-Boom has both engines placed well forward of rearward-extending tanks providing a 'safe' configuration in terms of engine disk burst. In addition, galleys and toilets, rather than passengers seats, occupy space in the fuselage directly in line with the engines which provides an added safety measure.

JAR 25.1197 Fire-extinguishing agents (powerplant), JAR 25.1203 Fire-detector system (powerplant)

In case of a hydrogen-fuelled engine fire, it is vital that correct fire extinguishing agents are used. These will inevitably be different from those used on kerosene fires and their effectiveness must be demonstrated by tests. Hydrogen fires are especially difficult to counter and it has been proposed that the best solution is to cut-off the fuel source rather than attempting to extinguish a hydrogen flame. Nonetheless, fire extinguishing agents are still necessary and must be provided.

5.2 Fuel System

JAR 25.951 General, JAR 25.952 Fuel system analysis and test, JAR 25.961 Fuel system hot weather operation

Each fuel system must be capable of sustained operation throughout its flow and pressure range, however the requirements state that sustained operation must be with the “*fuel initially saturated with water at 80°F and having 0.75cc of free water per gallon added and cooled to the most critical condition for icing likely to be encountered in operation*”.

The requirements prescribe that the fuel temperature must be at least 110°F. It is clear that the Twin-Boom fuel system has differing requirements since the system characteristics need definition with respect to specific hydrogen properties. Because of the susceptibility of water and other elements freezing upon contact with LH₂, these requirements must be modified, with the acceptable fuel temperatures reviewed. It is expected that a certain ‘tolerance’ is required for the hydrogen fuel system, in that the LH₂ must operate satisfactorily and without hazard even if contaminated to a certain degree.

Due to the very low fuel temperature, the fuel system will be in effect operating continuously in ‘hot weather’ and so efficient insulation and system level design is essential to prevent excessive vapour formation due to boiloff. Proper fuel system functioning under all probable operating conditions must be shown by analysis and those tests found necessary by the Airworthiness Authority.

JAR 25.953 Fuel system independence; JAR 25.903 Cross-feed of fuel

Each fuel system must supply fuel to each engine through a system independent of each part of the system supplying fuel to any other engine. It is necessary to ensure that should one fuel source be unavailable then there is always another. Thus the Twin-

Boom concept has two main fuel tanks (per engine), each divided into separate secondary tanks (also providing a secondary benefit with a certain level of cg control). Each tank has a separate booster pump enabling independent supply of fuel.

JAR 25.954 Fuel system lightning protection, JAR-ACJ 25.581 Lightning, JAR-ACJ 25.899 Static electricity

The fuel system must be designed and arranged to prevent the ignition of fuel vapour within the system by direct lightning strikes. Any encounter with lightning must not adversely affect the aeroplane flight capability and so lightning protection is required.

The high electrical conductivity of aluminium alloys normally used in aircraft construction helps suppress sparks due to lightning strikes. However, composite materials such as carbon fibre reinforced plastics prove difficult in providing equivalent protection because of their lower electrical conductivity. JAR provides a lightning characteristic model which may need modification according to specific hydrogen properties, particularly if future aircraft are predicted to be constructed to a greater degree using composite materials.

JAR 25.993 Fuel lines through a pressurised cabin

Fuel lines must react support loads and vibrations without leakage. Fuel lines must be designed and installed to allow deformation and stretching without leakage.

Due to the catastrophic effect of hydrogen leakage, these requirements could be reviewed to prohibit fuel lines through the passenger cabin. Also, the very low temperature of the liquid hydrogen fuel means that due to material embrittlement fuel line flexibility will be difficult to achieve.

5.3 Fuel Tanks

JAR 25.963 Fuel tanks: general, JAR 25.965 Fuel tanks tests

These requirements state that each fuel tank must be able to withstand, without failure, vibration, fluid and structural loads that it may be subjected to in operation, which must be demonstrated by tests. Any fuel tanks within the fuselage must be able to resist rupture in an emergency landing. The tanks must be protected from exposure to scraping action with the ground, one reason why the Twin-Boom utilises over-wing attachments.

There must also be a means to prevent the buildup of an excessive pressure difference between the inside and outside of the fuel tank. The special properties of LH₂, means these requirements could be made more severe, and tests on insulation will be required. Critical components such as insulation should be designed following the fail-safe philosophy. An insulation failure resulting in an increase in the temperature of stored hydrogen can lead to a large rapid pressure increase so a pressure relief system must be provided in each isolated volume. Additionally, maintaining tank pressure above atmospheric prevents air entering the tank.

JAR 25.971 Fuel tank sump, JAR 25.975 Fuel tank vents, JAR 25.969 Fuel tank expansion space, JAR 25.975 Venting

It is a requirement that each fuel tank have a sump with a capacity of not less than 0.1% of the tank capacity or a quarter of a litre unless operating limitations are established to ensure that the accumulation of water in service will not exceed the sump capacity. For the LH₂-fuelled Twin-Boom fuel tanks, **no** water at all must enter the fuel tank. In addition, each fuel tank must be capable of being vented effectively under normal flight conditions, during ascent and descent, and refuelling and defuelling.

JAR 25.969 states that each fuel tank must have an expansion space of not less than 2% of the tank capacity. If kerosene fuel, which is generally cold warms up, it expands. If the expansion becomes greater than the space available, the fuel spills through the vent pipes onto the apron, normally through the wing tips, which presents a hazard.

However, with hydrogen fuel, venting, as previously described, is not so straightforward. Venting will be required for gaseous hydrogen and so while there will still be a need for an expansion space above the liquid, according to specific tank design, this percentage will need to be re-thought based on the use of LH₂.

Because of the very low temperature of LH₂, any slight increase in temperature will lead to boil-off even when insulated since the insulation will not be 100% effective. To avoid excessive increases in tank pressure, hydrogen gas must be vented from the Twin-Boom aircraft. The vent system should contain a liquid trap so that only gaseous hydrogen is vented outboard. A pressure valve is required on the vent to prevent ingress of air to the ventilation system which should also be protected from lightning. Although, vents are mentioned in present regulations, they must be upgraded for specific hydrogen problems.

JAR 25.981 Fuel tank temperature

These requirements state that the highest temperature allowing a safe margin below the lowest expected auto-ignition temperature of the fuel in the fuel tanks must be determined. It is also a prerequisite that no temperature at any place inside any Twin-Boom fuel tank may exceed this temperature. This must be demonstrated under all probable operating, failure, and malfunction conditions of any component whose operation, failure, or malfunction could increase the temperature inside the tank. However, LH₂ fuel dictates that the temperature inside the Twin-Boom fuel tank must not only be low enough to avoid autoignition, but must also minimise **boil-off**. This item must therefore be revised since auto-ignition temperature is not the only critical temperature for the Twin-Boom tanks.

JAR 25.1001 Fuel jettisoning system

A fuel jettisoning system must be installed on the Twin-Boom unless it is shown that it

meets the climb requirements of *JAR 25.119* and *25.121(d)* at M_{TOW} minus the weight of fuel necessary for a 15-minute flight comprised of a take-off, go-around, and landing at the airport of departure with the aeroplane configuration, speed, power, and thrust the same as that used in meeting the applicable take-off, approach, and landing climb performance requirements.

Not all aircraft have a fuel jettison system because the landing weight needs to be close to the take-off weight. This is particularly the case for short range aircraft. Providing a jettison system increases the complexity of the system and increases the weight which outweighs any weight saving in providing extra capability in the landing gear. This will therefore have a resultant increase in cost. Typically, if $M_{LW} > 95\% M_{TOW}$, there will be no jettison system.

Since the mass of fuel on the Twin-Boom (or any LH_2 aircraft) is less than that on a kerosene aircraft over the same range, the empty weight will be higher due to the heavier tanks, and so aircraft even in the medium-range category may be designed without the need for a fuel jettison system by ensuring that M_{LW} is close enough to M_{TOW} .

If the Twin-Boom does require a fuel jettisoning system, it must be capable of jettisoning enough fuel within 15 minutes, starting with the weight (described above) to enable the aeroplane to meet the climb requirements.

During any flight tests of the Twin-Boom, it must be shown that the:–

- ◆ fuel jettisoning system and its operation are free from fire hazard;
- ◆ fuel discharges clear of any part of the Twin-Boom and
- ◆ fuel or fumes do not enter any parts of the aeroplane

If it isn't possible to install jettisoning capabilities for the LH₂ aircraft then design requirements will be impacted. The engine will need to be more powerful to increase normal climb capability and engine climb-out, leading to a heavier structure to support the increased M_{LW}. The problem lies in the fact that the hydrogen fuel volume is four times greater and additionally weighs $\approx 2/3$ times less, so is likely to take a longer time to discharge to a low enough weight than the stipulated 15 mins. This is complicated by the fact that hydrogen will freeze once exposed to the air, and so a specially designed jettisoning system will be required.

5.4 Structure

Damage by ground vehicle

Although not included in JAR-25, damage by a ground vehicle could prove to be a great enough risk to the Twin-Boom that special regulations are warranted. Although this is an operational item, it needs consideration in the design phase and indeed is one reason why the fuel tanks are located *above* the wing.

JAR-ACJ 25.631, JAR-E-800

The aeroplane must be designed to assure capability of continued safe flight and landing after impact with a 4lb bird. This aspect must be taken into account in the design of the hydrogen tanks as well as the engine which must also be able to ingest birds of a prescribed weight.

Crashworthiness requirements – fuselage structure/tank/tank support

JAR prescribes accelerations that the fuel tank and its associated support must absorb in case of a crash. In addition JAR also prescribes vibration tests to assure absence of leakage in fuel tanks.

Very little information, if any, is available with regard to the crashworthiness ability of tanks containing hydrogen fuel and so it is unclear of the consequences of rupture or

damage. Extensive testing is vital to ensure a safe design and in order to meet the crashworthiness requirements. Such tests should include the effects of varying degrees of damage to the overall safety of the Twin-Boom aircraft.

5.5 Safety

JAR 25.1419 ice protection

If certification for flight in icing conditions is desired, the aeroplane must be able to safely operate in continuous maximum and intermittent maximum icing conditions. This is particularly important for the Twin-Boom because it is expected that ice formation could potentially be a problem if not addressed satisfactorily. It is conceivable that although certification in icing conditions is subject to whether or not the aircraft will operate in such conditions, the Twin-Boom aircraft **must** be certified to meet this regulation since the very low fuel temperature means that the surrounding structure and systems will in effect be operating in icing conditions and protection should be provided accordingly.

Evacuation (JAR 25.803)

Each crew and passenger area must have emergency escape means to allow rapid evacuation in the event of a crash landing and with the possibility of fire at the same time.

For aeroplanes having a seating capacity of > 44 passengers, it must be shown that the maximum number of passengers and crew, can be evacuated from the aeroplane on the ground under simulated emergency conditions within 90 seconds following specified procedures whereby no more than 50% of the emergency exits in the fuselage sides may be used for demonstration.

It is possible that evacuation requirements will be more stringent. This requirement will not be easy to meet particularly as the tanks potentially pose a certain degree of

obstruction. However, the Twin-Boom fuel tanks are far enough from the passenger cabin to allow normal slides and exit chutes to be utilised.

JAR 25.1091 Hydrogen leak protection of engine and APU intake

At ambient temperature, hydrogen is invisible, odourless, tasteless and undetectable by human sense. In addition, all substances (except helium) freeze in liquid hydrogen and therefore additives or dyes which normally can provide a visual form of detection, as used with kerosene, can not be used. Hydrogen detection means must therefore be developed specifically for airline and airport operations, since hydrogen detectors developed for space applications, may be prohibitively expensive for production aircraft.

This regulation states that means must be provided to prevent hazardous quantities of fuel leakage or overflow from drains vents, or other components of flammable fluid systems from entering the engine air intake and APU systems.

Aircraft weight increase through accumulation of ice (insulation failure, cryo-pump-effect)

Regulations prescribe certain requirements for flight in icy conditions and also describe an atmospheric model regarding atmospheric liquid water content and temperature. An amendment could be required for LH₂-aircraft since if the insulation fails, a cryo-pump-effect leads to the easy formation of ice at very low temperatures even at temperatures where ice would normally not form for a conventional aircraft.

In the case of current aircraft, the fuel stored in the wing is in direct contact with the wing skin and is very cold post-flight. In this condition, ice can easily form on the wing upper surface even at relatively high external temperatures.

Greater ice formation is expected for the LH₂-fuelled Twin-Boom aircraft. If enough ice forms on non-critical surfaces e.g. fuselage, it could detach and impact other aircraft components e.g. engine ingestion and cause damage. Additionally, because more ice will be formed current de-icing systems will need testing.

Effect of hydrogen on aircraft fatigue life (JAR 25.571): Damage tolerance and fatigue evaluation of structure

Some components of the Twin-Boom e.g. pumps and valves, must operate at very low temperatures for years. Liquid hydrogen causes embrittlement for most metals and hydrogen atoms can penetrate some metals then react to create cracks and cavities. These phenomena will adversely affect aircraft component life and must be taken in account during aircraft design and material selection. Following the fail-safe philosophy, in case of failure of an aircraft component, the remaining structure must withstand loads without failure or excessive structural deformation until the damage is detected. By using the safe-life approach aircraft components must be designed to fail only after a prescribed life duration.

Fuel contamination (JAR-E-670) Contaminated fuel testing

Present regulations describe tests on contaminated fuel and prescribe the amount, type and temperature of contaminants. These quantities require updating to account for specific LH₂ fuel properties, particularly since LH₂ causes most common substances to solidify, including oil and grease. Therefore, solid contaminants need to be avoided altogether to prevent blocked valves.

Purge system

Careful purging of the fuel manifold and tanks with nitrogen after engine shutdown may be required to prevent the formation of explosive fuel-air mixtures. Adequate ventilation of any engine cavities to eliminate the possibility of flammable mixtures may also be required. This issue is not addressed in the JAR yet is vital to safe

hydrogen operation. It may be necessary to maintain a certain degree of fuel flow through the system rather than allow the tanks to remain stagnant which would lead to an increase in boiloff.

Instrumentation

Warning indicators and pressure sensors must be instrumented and provided at the pilot/co-pilot station to indicate pressure, temperature and other critical parameters. Leak detection and insulation integrity also need monitoring. Extensive instrumentation will also be required by ground crew for operational use during turnaround and maintenance procedures.

Pressurisation

JAR 25.841 Pressurised Cabins, JAR 25.843 Tests for pressurised cabins

Although these requirements are for cabins, they are (to a certain degree) applicable to the Twin-Boom fuel tanks which are also pressure vessels. Pressure relief valves must be provided to limit the positive differential pressure to a predetermined value at the maximum rate of flow delivered by the pressure source. A means must also be provided by which the pressure differential can be equalised and/or the intake or exhaust airflow must be regulated for maintaining the required internal pressure and airflow rates.

The fuel tanks must undergo strength tests where the complete pressurised vessel must be tested for the pressure differential specified. Tests of the functioning and capacity of the pressure differential valves, and emergency release valve should also be demonstrated. Tests should be conducted over a range or combination of pressure, temperature and moisture up to the maximum altitude at which certification is required.

5.6 Fire Protection

Fire and explosions (JAR-E-530) *Fire precautions*

Hydrogen can explode in contact with air or oxygen if it is partially enclosed (at least three sides), otherwise it will simply ignite rapidly without explosion. Air cannot be permitted to come in contact with liquid hydrogen at any stage prior to combustion in the engine. As well as creating an explosive mixture that can be ignited in the valves, the air will freeze.

Fire and explosion problems were previously addressed in the Tupolev Tu155 project (a three-engined version of the Tu154 but with the engines modified to use LH₂). In this case, the fuel tanks were installed inside the fuselage tail section. To minimise fire and explosion hazards, the fuel tank and pipelines were of double vacuum construction. A pressurised bulkhead was installed in front of the tank in order to use a higher pressure in the cabin and avoid hydrogen entering the cabin in the event of a leak from the fuel system. Sensors to monitor gas concentration and additional fire extinguish systems were also installed. The systems operated successfully and without incident.

JAR 25.851 Fire extinguishers

Onboard fire extinguishers must be provided for the Twin-Boom. The types and quantities of each extinguishing agent must be used appropriate to the kinds of fires likely to occur, in this case Hydrogen fuel. However, there may be instances where the fuel mixes with other substances in the case of a leak whereby the combined properties are altered. Such possibilities should be accounted for.

5.7 APU

JAR 25A939 APU operating characteristics

The Twin-Boom is expected to have an APU which also runs on liquid hydrogen, and will therefore be subject to the same safety issues and hazards as the fuel system. The APU operating characteristics must be investigated in flight to determine that no adverse characteristics (such as stall, surge, or flame-out) are present, to a hazardous degree, during normal and emergency operation within the range of operation

limitations of the aeroplane and of the APU. These requirements must be satisfied in the event that a LH₂-APU is installed on the Twin-Boom.

JAR 25A952 Fuel system analysis and test, JAR 25A953 Fuel system independence, JAR 25B961 Fuel system hot weather operation

Proper fuel system functioning under all probable operating conditions must be demonstrated by analysis and tests. Each fuel system must allow the supply of fuel to the APU through a system independent of each part of the system supplying fuel to the main engines. As for the main fuel system supplying the engines, the APU fuel supply must also perform satisfactorily in hot weather operation and it must be shown that the fuel system from the tank outlet to the APU is pressurised under all intended operations so as to prevent vapour formation. The requirements state that the fuel temperature must be at least 110°F at the start of the climb which will need to be modified for the Twin-Boom.

Overall, there is interest in using APUs to replace existing gas turbines (even without converting them to operate on liquid hydrogen). With LH₂ as a fuel, the case for a fuel cell APU becomes much stronger and would require complete reconsideration of the requirements described above.

6.0 LH₂ AIRCRAFT GROUND OPERATIONS

6.1 Introduction

Despite having studied the properties of hydrogen fuel, designed potential LH₂-fuelled aircraft configurations and estimated their mass, size and performance, delved into the operational and physical safety issues, and analysed the airworthiness regulations and certification issues necessary to actually certify it, there are still pieces missing from the jigsaw – *what happens to any aeroplane once it lands and isn't flying (which is most of the time)?*

At the airport, there must be means of supporting Twin-Boom aircraft to be ready for their next flight as well as ensuring they are satisfactorily maintained to maintain flightworthiness. Time on the ground includes turnaround operations, i.e. between the Twin-Boom landing and departing, and aircraft maintenance, both scheduled and unscheduled. This forms the subject area of this chapter and the aim is to present a well defined review of proposed aircraft turnaround and maintenance procedures (again specifically for the Twin-Boom aircraft) set against conventional methods, highlighting pertinent areas of equipment or operational procedures that may require modification. The means and methods by which a Twin-Boom aircraft will operate on the ground are examined. Any foreseeable part or process of supporting it on the ground which will require change has been highlighted and any new operational procedure and equipment for aircraft support during turnaround and scheduled/unscheduled maintenance have been determined.

The objective is to minimise the need for new or modified requirements such that the ground support equipment and operational procedures used to perform these tasks are not vastly different or new, or that modified vehicles or equipment are not required. Achieving this goal means that existing equipment are utilised as much as possible, costs kept as low as possible and transition to hydrogen fuel may be more amenable. It

is worth remembering that at some point in the future during the interim transition from kerosene to hydrogen, there will be both Kerosene-fuelled conventional aircraft *and* LH₂-fuelled aircraft in the same fleet.

6.2 Airport compatibility

In the past years, much investment has been made by airport operating authorities in runways, taxiways, boarding gates, passenger and cargo loading equipment etc. (Sorrallump, 1997). This investment is a major consideration for the design and introduction of new large aircraft types; hence designers must try to design aircraft to operate within existing bounds of the current largest in-service aircraft, e.g. the 747, and soon A380.

Airframe aspect ratio, for example, is being kept to a minimum against aerodynamic efficiency to limit wingspan to 80m, corresponding to ICAO Standard F for airport design (Knight, 1976). An 80m wing span will be tolerable for most world airports in current use for long range operations. No major problems with runway and taxiway geometry are likely, except the possible extension of taxiway curves to accommodate an enlarged landing gear track or aircraft turning radius. However, runway strengthening may be required as a result of the weight increase. Aircraft length should not be a problem unless the tail when parked protrudes into a taxiway. Fuselage/cabin layout design is important in operating the aircraft in current facilities and cargo loading, fuelling, and all servicing should be feasible with current equipment.

6.3 Environmental Impact

Pressure from environmental bodies to reduce noise limits further is proving a challenge for designers, especially as heavy aircraft airframe noise becomes dominant on approach. Emissions from such aircraft may be higher than those of a smaller type of aircraft using the same technology. The reduced fuel burn, however, should lower

emissions per passenger and in this respect larger aircraft are more environmentally-friendly than smaller ones.

There is no current legislation regarding internal noise or vibration levels on airliners, but to meet the pressure of increasing passenger demands for comfort it is important that environmental aspects are considered in their entirety. Effort should be made to reduce internal and external noise and vibration (as well as pollution).

6.4 Flight servicing - Turnaround and Maintenance

In order to evaluate the necessary changes to airport terminal facilities and operations, it is necessary that the following are identified:

- a. support equipment and maintenance facilities required for the Twin-Boom aircraft including safety considerations
- b. different LH₂-fuelling system concepts including the technical and economic impact of those systems on airport and airline operations
- c. R&D required to ensure the LH₂ fuel air transport system at the airport could be made available.

This is more fully described in Figure 6-1.

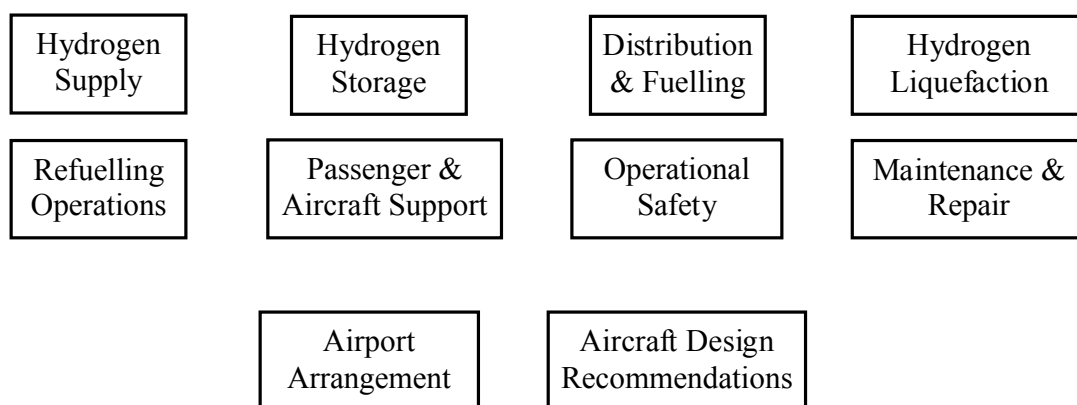


Figure 6-1 - Factors contributing to the formulation of aircraft ground operation concept (*Boeing Commercial Airplane Company, Sept 1976*).

In order to define the ground support and maintenance requirements for a LH₂ aircraft, and particularly the Twin-Boom, the terminal facility, the LH₂ fuelling system, and the airline operational requirements will have to be established (Figure 6-2).

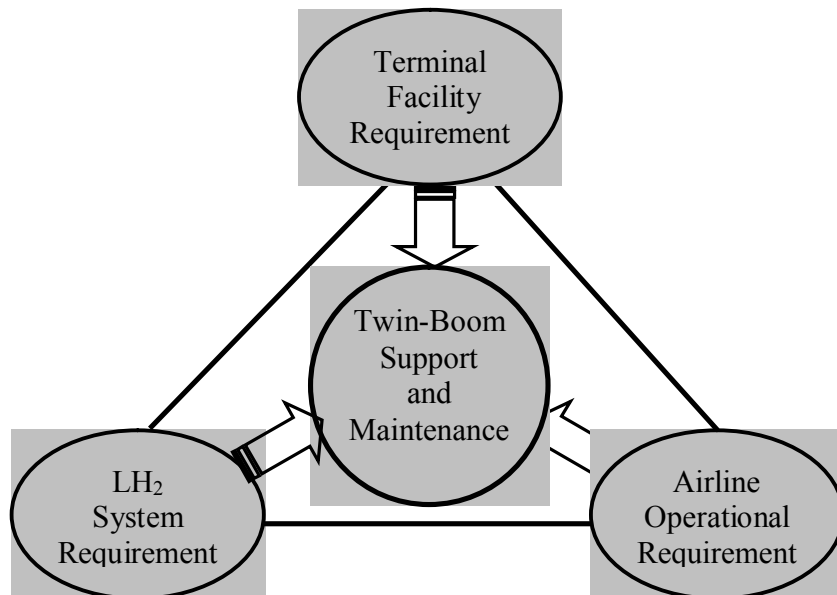


Figure 6-2 - Interdependence of tasks that define the overall aircraft support required
(Brewer, 1991).

Clearly, it is desirable to have facilities and equipment as interchangeable as possible within a particular airline operation, particularly as the cost of Ground Support Equipment (GSE) is significant. It can be seen in Table 6-1 that many GSE are interchangeable between different types of aircraft. Normally, gate positions are permanently assigned or leased by the carrier. The versatility of these gates and GSE to handle all types of aircraft within the fleet interchangeably enhances the operation's economy by minimising the number of equipment, operators, maintenance required, and the physical area to park equipment.

Recommended Ground Service Equipment	Maintenance level	DC8	DC10	B707	B727	B737	B747
Towing tractor	F	•	•	•	•	•	•
Potable water truck	F/S	•	•	•	•	•	•
Lavatory truck	F/S	•	•	•	•	•	•
Air starting truck	F/S/O	•	•	•	•	•	•
Preconditioned truck	F/S/O	•	•	•	•	•	•
Electrical power truck	F/S/O	•	•	•	•	•	•
Hydraulic power unit	F/S	•	•	•	•	•	•
Baggage container	F/S		•	•	•	•	•
Fuel hydrant truck	F/S/O			•	•	•	•
Hydraulic flush unit	O	•	•	•	•	•	•
Aerial Maintenance stand	S/O	•	•	•	•	•	•
Wing jack	F/S/O		•	•	•	•	•
Fuselage jack	F/S/O		•	•	•	•	•
Axle jack	F/S/O		•	•	•	•	•
Hydraulic test bench	O	•	•	•	•	•	•
Generator test stand	O	•	•	•	•	•	•
Fuel test stand	O	•	•	•	•	•	•

S = Shop, F = Flightline, O = Overhaul

Table 6-1 - Commonality of ground support equipment used by wide-body aircraft
(Chudoba, 1995).

The airfield can be defined as comprising runways, taxiways, safety strips and apron areas used for parking, manoeuvring and aircraft servicing. The terminal has facilities for departure and arrival e.g. catering, baggage, parking, roadways etc. There are airline support facilities for aircraft maintenance in hangars as well as for GSE. Airport regulations have a significant influence since they control maximum vehicle width, restrict engine running (particularly at night) and limit aircraft movement at night etc.

Overall, there are three main types of flight servicing:

1. pre flight servicing
2. turnaround servicing
3. post flight servicing

For commercial aircraft, the *turnaround* sequence is the most critical and can be described as “*the events and actions necessary to prepare an aircraft, which has landed, for its next scheduled flight*”. It is the turnaround phase that is studied in detail. Minimum ground times are provided for aircraft turnaround in which the operation must be completed. However, aircraft efficiency and productivity greatly depends on ground handling operations influencing time on the ground and severely impacting the aircraft economics. Personnel must be sufficient in number and suitably trained to enable faster turnaround times, particularly at peak periods with maximum load factors. Training will prove even more important when dealing with hydrogen fuel due to its special properties.

An example of the turnaround sequence is shown in Figure 6-3. This shows a “conventional” LH₂-fuelled aircraft with internal LH₂ fuel tanks at forward and aft positions of the fuselage. Various turnaround services that take place are shown as are aircraft connection points enabling various services to be performed simultaneously.

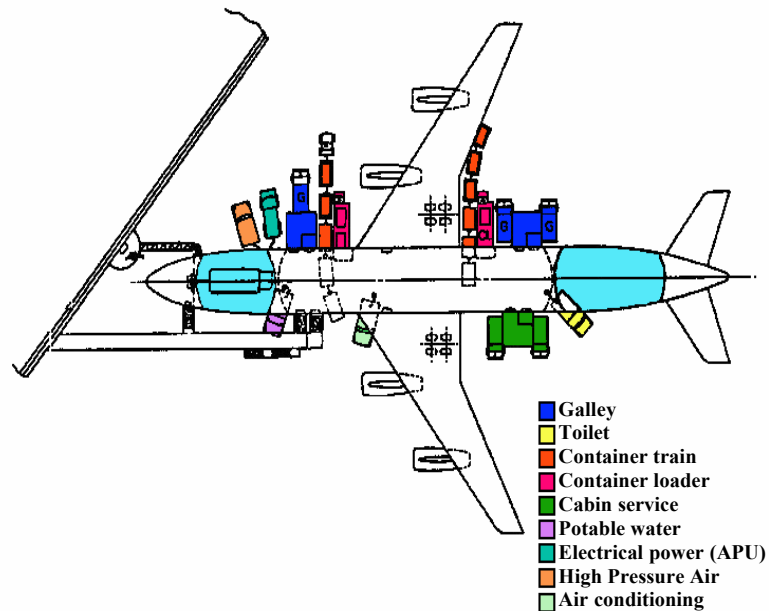


Figure 6-3 - Typical aircraft servicing diagram (*Brewer, 1976*).

To analyse ground handling operations in greater detail, it is important to have an overall understanding of the purposes and logical sequence of the main activities. It is also sometimes necessary to address the specific Twin-Boom configurational characteristics.

6.4.1 Example turnaround sequence - Tristar

To further help illustrate the procedure involved and the order in which they are performed, let us take the following example:

Tristar departure – a wide-body aircraft with expensive GSE.

Turnaround completed at Terminal 1 at LHR.

- arrived with 285 passengers at 1552 and departed at 1709 with 181 passengers destined for Paris.

- A total of 4,400 imperial gallons of fuel (kerosene) was uplifted during turnaround.
- The aircraft APU was used for air conditioning and main engine starting.

The sequence and timing of events is shown below (Table 6-2).

Time (mins)	Operation
0	Aircraft arrived at pier and jetty positioned
+1	Elevator positioned at front and rear holds
+1	Fixed electrics connected
+1	Water servicing unit arrived
+1	Baggage conveyor to rear bulk cargo compartment
+2	Catering vehicle arrived
+2	Baggage dollies in position at rear elevator
+6	Fueller arrived at port side of aircraft
+7	Fuelling platform positioned under fuelling point
+7	Toilet servicing unit at rear servicing point
+8	Baggage dollies depart
+8	Water servicing unit departs
+12	Cleaning crews board aircraft
+13	Toilet servicing moves from rear to forward servicing point
+17	Low loader with outgoing pallet arrived
+18	Toilet servicing unit departs
+20	Low loader for incoming freight positioned at front elevator
+22	Freight van positioned to unload rear bulk cargo compartment
+26	Low loader with incoming freight departs
+26	Low loader with outgoing pallet positioned at front elevator
+27	Cleaning crew leave aircraft
+30	Departing baggage arrives on four dollies
+35	Departing baggage dollies leave
+36	Low loader departs from front elevator
+38	Elevator departs from front hold
+38	Freight van departs from rear conveyor
+40	Catering vehicle departs
+52	Towing tractor and tow bar arrive and hook up
+55	Departing baggage dollies arriving (four off)
+58	Departing baggage dollies leave (four off)
+59	Elevator departs from rear hold
+60	Jetty removed
+63	Engine started using APU
+67	Aircraft pushed back
+70	Tow bar removed – aircraft taxied out

Table 6-2 - Turnaround operations performed on a Tristar aircraft (*Chudoba, 1995*).

6.4.2 Critical path

In every operation which involves several activities performed in a logical order or in parallel, there exists a series of tasks which determine the overall time elapsed to perform the entire procedure. The path of activities or procedures which are interdependent define the critical path. For conventional aircraft turnaround, cleaning is usually the determining factor and has the most influence on ground time, and is generally linked to manpower. Refuelling is usually not on the critical path if two refuelling ports are used and/or a sufficient fuel flow rate is achieved.

6.5 Turnaround

Each sequence of the turnaround phase has been evaluated using *Jane's airport equipment, 1990* as an aid. A summary of conventional procedures and equipment is provided in Appendix B. What is presented here is a summary of the main changes to the processes employed or equipment required. Refuelling, manoeuvrability, parking, maintenance etc. have all been systematically checked for changes becoming necessary in consequence to the use of hydrogen fuel. Such changes concern procedures, timing of activities, equipment, tools, facilities, etc. A similar approach has been adopted for the maintenance phase although the difference is that maintenance does not follow a set standard sequence of events. Recommendations with regard to aircraft design and provision of facilities and infrastructure have been formulated and are presented.

6.5.1 Aircraft Parking and Docking, Disembarking, and General Aircraft Servicing

As for conventional aircraft, upon landing, the Twin-Boom will dock under its own power and be moved into position by an existing tug or towing tractor vehicle. As the Twin-Boom is similar in weight to conventional aircraft (as increased fuel tank weight offsets much lighter fuel weight), existing tow tractors will provide sufficient pulling power. Undercarriage design should not differ.

Since tow tractors are low profile and able to accept different aircraft undercarriages, they will not need alteration to their configuration particularly as the fuel tanks for the Twin-Boom aircraft are located *above* the wing. One foreseeable change which may occur is as a result of safety since tow tractors use spark ignition engines. This is also true of all servicing vehicles e.g. those used for **disembarking, cleaning, catering and galley servicing, baggage and freight handling, toilet servicing, and water servicing.**

To ensure that safety is maintained, vehicles should either:

- a) be kept a certain distance away from tank and refuelling processes
- b) be removed from area before allowing refuelling to commence
- c) have their engines modified, use spark arrestors, or use diesel engines

Preferably a combination of these will be employed which will enhance safety. Needless to say, extra care should always be taken to ensure that any collisions do not take place particularly given the large and exposed fuel tank structure.

As a general rule and in order to prevent the build-up of static electrical charges, onboard electric equipment should be grounded during all turnaround operations.

Docking guidance systems, although rare, are in operation and automatically move the aircraft nosewheel using electrohydraulic power. Again it must be ensured that no risks of sparks are present during a potentially hazardous situation such as refuelling. Furthermore, however, care must also be taken that hydrogen fuel does not leak onto the electrohydraulic line nor does it cause its failure, e.g. by embrittlement. Docking guidance systems are able to provide extra useful information regarding LH₂ fuelling operations, potential hazards etc. to the ramp personnel and various operators, and so will help provide a safer environment.

In order to keep systems compatible and turnaround times low, it is recommended that the same procedures are adopted when performing the following servicing activities: docking and servicing, cleaning, catering and galley services, baggage and freight handling, toilet servicing, and water servicing.

These tasks should not be physically affected by the transition to hydrogen. It is clear however, due to the greater involvement of personnel, that emergency and safety procedures and training will be essential for preventing accidents. This applies to all ramp personnel and is a general requirement rather than specific to this phase of the turnaround.

In addition, properties of the LH₂ fuel may be utilised in various servicing procedures. For example, water which is drawn from the main pressurised water tanks and which normally passes through filters cooled by dry ice, may instead be cooled by the LH₂. Also, in the event of a hydrogen fuel cell being used instead of the normal APU, the water by-product may be used for onboard water services, even drinking water (e.g. as used in Apollo space mission).

There is also more potential for utilizing the cooling ability of the hydrogen in some instances during general servicing, e.g. brake cooling carts, preconditioned air systems etc. Another possibility, perhaps likelihood, is the use of hydrogen to fuel general purpose vehicles e.g. those vehicles used to transport ramp personnel and equipment in and around the airport and apron.

6.5.2 Aircraft refuelling

Refuelling is not usually started before all passengers have disembarked. An extra precaution that may be taken is to place the passenger exit far enough away from the refuelling point so that both may be done simultaneously. Preferably, all aircraft should

be parked and fuelled in gate positions physically close to the terminal as is current practice. This promotes quicker turnaround times.

Fuel Subsystems

Aircraft fuel subsystems consist of all fuel-oriented systems up to the interface at the engine fuel control system and covers the functions of storing fuel, supplying fuel to the engine and APU, transferring fuel, pressurising/venting, jettisoning, and purging.

Fuel containment system

Fuel is stored in thermally insulated tanks. Separate redundant tank compartments with their own separate pressurisation and vent systems correspond to the number of engines according to convention whereby each engine is fed from an independent source during takeoff and landing as prescribed by the regulations.

Integral tanks carry fuselage structural loads as well as provide fuel containment, whereas non-integral tanks serve only as a fuel containment vessel. The LH₂ fuel containment system must be cylindrical to minimise boil-off and can be external to the main fuselage as for the Twin-Boom, or internal.

The fuel containment system refers to both the fuel tank structure and its associated supporting structural components, and the tank cryogenic insulation system. There are many tank insulation concepts and these include both active and passive configurations.

Fuel jettison

Inasmuch as the LH₂ aircraft meets the climb requirements (*FAR 25.1001* (b) and (c)) with full fuel load, a fuel jettison system is not legally required. However, there are some situations whereby a jettison system would be desirable. For example, in an emergency landing, fuel is jettisoned to reduce weight and hence landing speed. Assuming a full fuel load and climb to 3 048m (10 000ft), the time to jettison fuel

down to reserve level would be approximately 1.4 hours for a kerosene aircraft. This time will be increased for LH₂ aircraft since the fuel volume is far greater, and the fuel weight makes up a smaller fraction of the total weight than in the case of a kerosene aircraft. For transport aircraft, if the certified M_{TOW} is $> 105\% M_{LAND}$, provision must be made to jettison enough fuel to bring the weight of the aircraft down to the certified landing weight. The fuel jettisoning system and its operation must be free of fire hazards, and the fuel must discharge clear of any part of the aeroplane, which is particularly important for hydrogen fuel, and most important of all, aircraft control must not be compromised.

Fuel Systems

The aircraft fuel system is used to deliver fuel to the engines safely under a wide range of operational conditions. The system must safely contain the fuel, allow filling and draining of the tanks, prevent unwanted pressure build-ups in the system, protect the system from contamination and assume a steady supply of fuel to the engine. The system must provide a means of monitoring the quantity of fuel on the aircraft during flight and a means of checking fuel pressure, temperature and flow rate.

Transport aircraft use pressure-fed fuel systems which use a pump to transfer fuel at high pressure when delivered to the fuel control component at the engines. The system may also use pressure from the fuelling station or fuelling truck to force fuel into the aircraft tanks, achieved through a fitting, usually on the side of the aircraft or under the wing. A fuelling control panel allows the operator to monitor the fuel quantity and control the fuel valve. When a fuelling connection is made at the fuelling panel and the valve on the fuel hose is opened, the fuelling manifold is pressurised with fuel. The operator can then select the tanks to be filled by opening electrically operated fill-valves.

Vent systems

Vent systems are designed to prevent the build-up of pressure in the fuel tanks and allow proper flow of fuel from the tanks. The expansion of fuel in the tanks when they are full could pressurise the tanks sufficiently to cause structural damage if the tank is not vented. Also, without a vent, as fuel is used, a vacuum would build-up in the tank and fuel would not be able to leave the tank.

For a light aircraft, the vent system might be as simple as a hole in the fuel cap or tube connected to the atmosphere. Large aircraft are not so straightforward, requiring a vent system which allows each tank to vent to a high point in the system once tank pressure exceeds a threshold.

Defuelling

There is more to the refuelling operation than seems at first glance. If the aeroplane is flying at high altitude, the remaining fuel in the tank will be cold, and at the warmer ground temperatures, condensation from moisture in the air will form on the inner tank walls. Airline operators (particularly in countries with a high humidity climate) must perform regular drainage.

Conventional practice

Refuelling (*Goodger, Vere, 1985*)

1. Person responsible should first ensure aeroplane is in a safe place, the wheels are chocked/ brakes set, and all safety precautions observed.
2. Fire extinguishers and safety equipment should be placed within easy reach.
3. Every piece of equipment used in doing the work should be absolutely clean. The hose nozzle should not be dragged over any parts of the aeroplane.
4. The flow of gasoline through a hose may build up a static charge of electricity so that when the refuelling nozzle is removed, the static charge will ignite the fuel. Therefore, before refuelling, the nozzle of the hose must be grounded.

The procedures for refuelling are dependent on the airport infrastructure, whether hydrant or bowser. On short and medium haul flights, the amount of fuel required and the resulting time is usually not a problem. The refuelling does not constrain the turnaround time but is dependent on the amount of fuel required and the fuel flow rate.

Defuelling (*Goodger, Vere, 1985*)

1. The aircraft to be defuelled is moved to an open area at a distance from any other aircraft, structure, and vehicle.
2. Suitable fire extinguishers are provided.
3. Inert gas is supplied for purging tanks.
4. The aircraft is grounded to earth.
5. Personnel in the area wear shoes with rubber or plastic soles which can not cause sparks. All ignition sources should be removed from the area.
6. Use no electrical equipment in the area except that which has been certified flameproof.
7. Provide for fuel disposal. Metal fuel containers which could cause sparks in handling should be avoided.
8. If tools are required to open fuel drain valves, use tools which can not cause sparks.

Sometimes it is necessary to remove fuel from the aircraft for maintenance, repair or adjustment for flight plans. If the fuel is free from contaminants, it is stored, but otherwise should be segregated. Defuelling is carried out far from the apron, and the safety precautions for fuelling must be observed.

The fuelling takes place using hydrant refuelling points fixed around the aircraft stands, or a fuelling tanker/hydrant service vehicle. These have a lifting platform and provide refuelling rates of up to 5000 litres/min (*Janes Airport Equipment, 1990*). Some refuellers are portable with a manual DC/AC petrol or diesel driven pump. Alternatively, a fuelling tanker may be used (Figure 6-4).

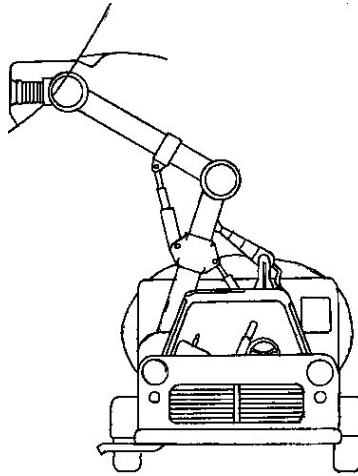


Figure 6-4 - Example LH₂-refuelling unit (*Boeing Commercial Airplane Company, Sept 1976*)

There are also fuel facility maintenance trucks used for cleaning hydrant pits and general maintenance.

Fuel hydrant cleaning vehicles have explosion-proof equipment and include a fresh air blower for aeration and ventilation, a suction facility for extracting fuel and water mixtures, and compressed air for cleaning the pit where the hydrant is stored.

Fuel storage systems are also used and comprise self-contained self-supporting transportable jet-fuel storage and dispensing providing facilities for refuellers.

Other equipment include tanker loading equipment, refuellers with spark arresting silencers that direct the exhaust away from the fuelling operation, and defuellers for draining fuel and condensation.

There are four alternative procedures for performing the fuelling operations at the terminal including:

- ◆ parking and fuelling aircraft at gate positions physically close to the terminals (current practice)
- ◆ parked aircraft to be fuelled at gates physically removed and possibly structurally protected from the terminal with an extended connector for passenger loading.
- ◆ fuelling aircraft in an isolated area from the terminal with conventional docking before and after fuelling.
- ◆ Fuelling aircraft in an isolated area with transporter connection to the terminal.

Proposed LH₂ aircraft procedure

A significant challenge to the successful introduction of LH₂-aircraft is the availability of the necessary infrastructure, particularly the availability of a system to produce, store and distribute the liquid hydrogen in an efficient, reliable, and above all safe way. Analysis of the fuelling procedure assumes that such a system is in place.

Fuel transfer

LH₂ fuel may be distributed through pipelines which may either be transferred under pressure or using pumps. The pressurised storage transfer method is simpler and more flexible (flow rate vs demand); however losses may occur between the pressurant gas and the LH₂ fuel. Conversely, pump fed systems may be unreliable and require maintenance. The pipelines must be insulated and may either be located above ground or underground, but either way must be protected from mechanical damage.

Alternatively, LH₂ fuel may be transferred via fuel tanker trucks. These will need to be insulated and specially adapted to contain the cold fuel while minimising boil-off. This method requires less capital cost and offers more flexibility than a fixed distribution pipeline; however more ground traffic congestion occurs on the apron and the operating costs are higher.

Tanker trucks may be used to fuel or defuel LH₂ aircraft parked at remote places such as maintenance and cargo areas. The tanker truck may also be used to offload LH₂ fuel from a disabled aeroplane prior to recovery.

For both methods, means of GH₂ boil-off recovery may also be provided, and equipment for measuring and controlling LH₂ fuel flow parameters will be required. Leak detection systems as well as fire extinguishing agents will also be required.

Refuelling

Due to the different characteristics of LH₂ fuel, the fuelling procedure will vary. Since any fuel system should be used to deliver fuel to the engines safely under a wide range of operational conditions, the same requirements apply to the Twin-Boom. The fuelling system will require the most change since it involves direct handling of the cryogenic fuel. The current interface between the kerosene fuel supply and the Twin-Boom fuel tanks will change as will most if not all of the fuel system components. Additional complications arise from the need to consider what to do with the boil-off, provide insulation, and provide venting without allowing direct contact of the fuel with oxygen.

The long external fuel tanks of the Twin-Boom provide ample space for possible refuelling points, enabling the process to be carried out a larger distance away from other turnaround operations which are going on simultaneously. This means that other turnaround procedures, e.g. passengers disembarking, cleaning etc. may be performed simultaneously.

The cryogenic properties of the LH₂ dictate that special procedures be followed in filling and draining a fuel tank. There are just a few gases that aren't liquefied upon exposure to LH₂ e.g. when purging the air from the tanks. Another problem involves finding a means of tank pressurisation. The fuel can not be vented as for a conventional

aircraft because any air entering the LH₂ tank would freeze. Also, fluctuating tank pressure would cause large losses through boil-off.

Prior to the introduction of hydrogen into the tanks, all traces of air, oxygen, nitrogen, CO₂ and water vapour must be removed. Tanks and piping systems must be purged with an inert gas, e.g. Helium. The inert gas concentration also has to be decreased down to an acceptable level, followed by a cold hydrogen gas cycle to chill down the system, and prepare it for refuelling (*Pohl, H.W. Schmidtchen, U. Behrend, E and Rostek 1997*).

The fuelling system interfaces with the airport ground supply through two adapters located on the Twin-Boom aircraft as shown in Figure 6-5.

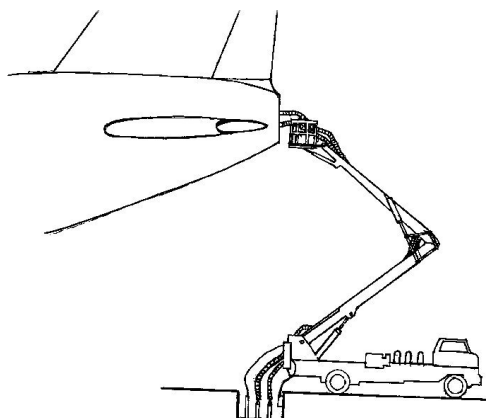


Figure 6-5 – Connection between LH₂ fuel hydrant and fuelling manifold adapter on aircraft tail (*Boeing Commercial Airplane Company, Sept 1976*).

LH₂ is supplied to the fuelling adapter and displaced hydrogen gas from the Twin-Boom fuel tanks is returned to the liquefaction facility at the airport for recycling by means of a vapour recovery adapter. Fuel is discharged into each tank by a fuelling

manifold. The fuel level control system consists of a shutoff-valve actuated by a signal from a level sensor which terminates flow to each tank when it is full.

Vapour released during the fuelling operation flows through tank pressure regulators into common vent lines. The fuel tanks are protected from overpressurisation in the event that a shutoff-valve fails to close when the tank is full by limiting the ground system delivery pressure and by sizing the vent lines to allow the LH₂ to overflow through the vent system to the vapour recovery adapter.

Consideration of the refuelling process assumes that the fuel tanks are cold and able to directly couple to the fuelling receptacle whether a pipeline or fuel tanker. However, there will be times at which the aircraft fuel tanks are warm. For such occasions there will be a differing procedure. Prior to the introduction of LH₂ into the tanks, all traces of air, oxygen, nitrogen, CO₂ and water must be removed. To accomplish this, both the fuel tanks themselves and also the pipes must be purged with an inert gas, such as helium to remove any foreign gases. The concentration of foreign gases should be at an acceptable level. Once the tanks are inert, the Helium should be removed. Subsequently, the tanks and pipes may be precooled, perhaps using GH₂, followed by a cold hydrogen gas cycle to chill down the system to be made ready for refuelling.

Vent gas disposition

In LH₂ aircraft, to avoid excessive tank pressure due to GH₂ due to boil-off, a means must be provided to vent the fuel tanks. The vented GH₂ may either be burned off to the atmosphere or may be recycled. It is preferable that the GH₂ be reused, however the deciding factor will be an economic and safety one. LH₂ venting is a more complex process since the fuel should not come into contact with the atmosphere.

Vent gas disposition will occur not only during refuelling but also during ground overnight parking, during overhaul, maintenance and repair. Thus, coupling to GH_2 recovery lines must be available in remote areas where such activities may occur.

Refuelling time

An important challenge for the Twin-Boom aircraft is maintaining turnaround times as close as possible to current schedules. The time required for transferring hydrogen must be studied to ensure that no delay will take place.

Example: Let us take a LH_2 aircraft with a fuel weight of 13 650 kg (36 500 kg for kerosene) and associated fuel volume of 199,250 ltrs (45,000 ltrs). Assuming a actual fuelling rate of $\approx 5000 \text{ ltrs/min}$ (*Jane's airport equipment, 1990*), refuelling time is 40 mins for the LH_2 aircraft compared with 15 mins for a current kerosene aircraft. This assumes the time for connecting/disconnecting the fuel hoses is the same for both aircraft.

Refuelling is a complex process of coupling, refuelling, and decoupling and should be as safe, simple, and fast as possible. There is obvious need to minimise the time required for connection, purification, refuelling and disconnection, but this should not be done at the cost of safety. The filling level of the tanks should provide some ullage space for expansion.

Connecting and disconnecting the fuel line to the aircraft should be easy, but only suitably trained personnel should be allowed to perform this task (as is current practice) for obvious reasons. The filler connection should be specifically designed to be only compatible with LH_2 to prevent misuse. Currently, coupling units for hydrogen-fuelled automotive vehicles already exist and although this system might also be suited for small aircrafts, the throughput is not yet sufficient for large ones.

Defuelling

Defuelling of LH₂ aircraft will be necessary for extended for out of service periods e.g. maintenance or during fuel tank repair. The fuel obtained from the aircraft fuel tanks must be stored. Defuelling may occur either:

- At the gate (where refuelling takes place)
- At a designated area remote from the gate
- By means of tanker trucks or dedicated mobile storage units

Since it is envisioned that defuelling will be infrequent, it is proposed that defuelling is performed at a place remote from the gate. However, it is envisaged that there are circumstances in which mobile storage/defuelling units will be required. This place may also be close to the maintenance facilities. With the LH₂ aircraft in position, a recovery hose is connected from the mobile storage unit to the LH₂ fuel tanks and defuelling tanks place as normal. Alternatively, the tanks may be warmed up using GH₂ until the tank temperature reaches the Nitrogen condensation point at which point the tanks may be warmed directly using Nitrogen. Used Nitrogen is vented through the GH₂ recovery line and conducted back to a liquefaction facility, where it will undergo processing to separate the Nitrogen from the Hydrogen. A Nitrogen cycle is performed until the tank temperature reaches dew point for ambient atmospheric temperature. At this point the tank is warmed and inerted.

Re/defuelling Safety

The primary hazard associated with the LH₂ fuelling/defuelling is leakage and subsequent fire. The hazard is minimized by automatic shutdown of the fuelling operation but closing the valves. The fuel system should be grounded during the fuelling/defuelling operation. Radar and HF equipment must be turned-off, connection and/or disconnection of electrical equipment is not permitted. The APU, unless an emergency, must not be started or shutdown, Fuel zones should be established around fuel vents, fuelling hoses and the fuelling equipment. Open flames from cigarettes,

lighters, welding etc. must be kept out of this zone as should metal-wheeled equipment. There should be a clear path and emergency route in the event of an incident. In the event of a fire, established fire fighting procedures should be in place. Vehicles used during this operation must be electrically or diesel powered to avoid any sparks.

6.5.3 *Ground power, Engine Starting*

Conventional practice

During the aircraft turnaround, electrical power is required for many functions including supplying air for engine starting and cabin air conditioning, refuelling, operation of lights, galley equipment, instruments, radio communication, etc. There are two options. Power may be supplied by a separate ground power unit/fixed electrics installation or by using an APU fixed to the aircraft. The power requirement may vary considerably, from 28V to 200V using an alternator driven by a diesel engine.

More common than the ground power unit is the APU normally included as standard equipment onboard aircraft. The APU lends versatility to the aircraft and minimises the ground support crew required. Normally the APU provides 400Hz power and pneumatics for cabin air conditioning and engine starting. Although the APU inflicts a not insignificant weight penalty ($\approx 300\text{kg}$) on the aircraft, it can render the aircraft independent of ground power sources and can provide electrical power, hydraulic power, and cabin air supply in flight. APUs however, contribute somewhat to ground noise.

Frequency converter units can also be used for ground power applications and are mounted on trailers to aid operation and maintenance, permitting monitoring and testing of critical circuits.

In regards to engine starting, a variety of systems may be used although the principal adopted in each of these is the same. To reduce the size and weight of the engine,

today's bypass and large fan engines all use air starters which obtain a supply of compressed air from an air-start unit on the ground or from the APU or another main engine which has already been started. Electrical power for starting depends on engine type and can vary from 28–112V. The air is provided by a compressor which is driven by an engine. There are three modes of operation: idle, jet start, and air conditioning. The starter can also have a two-engine start capability with excess stowed air to motor each engine in order to clear residual fuel in case high exhaust gas temperature is encountered during the start attempt. The air starters can be used in apron or ramp areas, alert pads, maintenance hangars and engine test facilities.

The time required for engine starting varies considerably depending on company policy and airport regulations. Due to restrictions at some airports, the authority only permits one or two engines to be started prior to push-out to reduce jet blast effects on the other side of the apron. The remaining engines may be started using bleed air from the engines already running.

Proposed LH₂ Procedure

As in a conventional manner, the LH₂-fuelled Twin Boom may be powered by ground power units that are either separate or fixed to the aircraft i.e. APU. Alternatively, a fixed electrical supply installation may be utilised, provided that the aircraft are positioned in the same place each time. These centralised sources of power transmit power via cables to aircraft docking points or hangars and are located adjacent to the aircraft, usually in predetermined positions, so that the power connection can be made with a minimum of interference or requirement from other apron equipment.

However, given the advantages and availability of the LH₂ fuel, it is recommended that LH₂-fuelled aircraft utilise an APU or fuel cell that runs on hydrogen. There has been R&D effort into fuel cells. In a hydrogen fuel cell, the reverse procedure to hydrogen liquefaction is performed. Stored hydrogen reacts with a supply of oxygen to produce

water and electricity. Hydrogen fuel cells have been demonstrated to not only be feasible but also provide advantages such as less noise and higher efficiency, particularly for automobiles. Although, the technology is transferable to aircraft the main requirement here is to minimise the weight. Moreover, it is expected that the ground power requirements, be it fixed or mobile, will be less. This is because cabin air conditioning will be provided by extraction of the LH₂ fuel energy.

For an aircraft engine that operates on hydrogen fuel, the internal thermodynamic cycle may differ as might the internal components, such as the addition of a heat exchanger. However, the method of operation will remain the same. The purpose of an engine starter is, as the name suggests, to provide a means to start the engine by rotation of the fan to ingest air until the point at which the engine becomes self-sustaining. Since this will not change for a hydrogen fuelled engine, the engine starter will remain the same and it is recommended that a conventional unit be used.

6.5.4 Aircraft de-icing/washing

A very small amount of roughness caused by ice, snow or frost, disrupts the air flow over the wing and lift and control surfaces of an aircraft. The consequences of this are lift loss, increased drag, and impaired manoeuvrability. In a similar manner, ice can also interfere with the movement of aircraft control surfaces and/or add weight. Ice can form even when the outside temperature is well above 0°C. An aircraft with wing fuel tanks will have fuel that, after a certain amount of flight time, may reach a sufficiently low temperature to cool the wing temperature below the outside air temperature. This phenomenon is known as cold-soaking. Cold-soaking can also be caused by fuelling an aircraft with cold fuel. If there is rain or high humidity, ice can form on the cold-soaked wing and accumulate over time. This ice can be invisible to the naked eye and is often referred to as clear ice. This ice can be detected by running one's hand over the surface or more normally by using specially designed eye-detecting cameras. Chunks of ice can

be dislodged during take-off, climb or mid-flight and can be ingested by engines potentially causing damage.

Conventional practice

To prevent the accumulation of ice, an anti-icing barrier compound is sprayed onto the aircraft to provide protection for aircraft parked for extended periods. The compound is sprayed from a vehicle with a platform lift and should not be sprayed onto areas of the aircraft such as engine intakes, other air intakes and vents and brake units. The vehicles use a hydraulic platform with adjustable spray nozzles, pumps and mixing and control systems. Tanks provide hot water and anti-icing/de-icing fluid. Some may use the aircraft APU to provide the pressurised air. Some systems in operation are fixed and comprise a travelling gantry which sprays aircraft passing underneath prior to taxiing onto the runway.

It is important to ensure that during winter months, when temperatures are likely to fall below freezing at ground level, the aircraft is cleared of frost, snow and ice before take-off. In these weather conditions, towing and taxiing operations should be carried out with extreme precaution. Just after flight, all covers should be fitted as soon as possible. An inspection should be made of turbine engines for the presence of ice in the air intake, since it could melt when the engine is hot, drain to the lowest part of the compressor and refreeze when the engine cools, locking the lower compressor blades in ice. The presence of frost or ice will both add to the aircraft weight and affect aerodynamic performance, and possibly cause control surfaces to become stuck or inoperative. During flight, the aircraft de-icing system will operate and may use hot air from the main propulsion engines or electrical de-icing.

Washing equipment consists of a mobile power unit with an articulating arm, spray nozzles and cleaning brushes and can be operated by one man. Some employ a laser camera to ensure the rotating brushes do not damage the aircraft skin. Some also have

low emission ethanol engines to aid in hangar operation. Power is usually provided by a local electrical source.

Proposed LH₂ aircraft practices

It is expected that the accumulation of frost or ice on the aircraft skin will be greater due to the very low temperature of the hydrogen fuel and tanks. Despite the thick insulation, the outer skin surface temperature will be less, and the capabilities of present anti-icing/de-icing agents must be checked. This will be especially important in-flight, since the additional outer surface skin temperature coupled with the freezing temperatures at altitude may lead to the formation of ice, which if substantial, may cause damage to rearward parts of the aircraft upon separation, or cause control surfaces to become stuck. The formation of ice however is dependent on the amount of humidity present.

The outside temperature of an insulated LH₂-fuelled tank will depend on the amount i.e. thickness, (as well as type) of insulation. In order for an LH₂-tank to be within the de-icing capability of current fluids with freezing points of around -60°C e.g. UltraTM [Dow Corporation] which is an Ethylene Glycol-based Fluid, sufficient insulation must be used to prevent or eradicate any ice formation with the use of these fluids. *Brewer, 1991* suggests an insulation thickness of 5 in as being sufficient which also agrees with *Colozza, 2002* who shows that the reduction in boiloff for insulation greater than about 10cm is small.

As previously mentioned (Section 3.6.7), the amount of insulation needed will vary and will depend on the insulation properties, the tank size (and shape), and the allowable boil-off rate. In order to estimate the insulation required, the outside surface temperature of the insulation needs to be determined by analyzing the heat flow (comprising convection, conduction and radiation) into the insulation from the Liquid hydrogen tank. Once the outside temperature is known, the boiloff rate may be calculated. The boiloff rate may then be translated to a given flight time for the aircraft

segment to determine the residence time of the LH₂ and the resulting boiloff.

6.5.5 Passenger boarding and embarkation

Once all turnaround operations are complete, passengers can board the aircraft, approximately 10-20 minutes before departure (depending on the number of departing passengers). Factors influencing this time include the number of departing passengers, the cabin layout, the level of service etc.

Immediately after the boarding process, final checks are made by the cabin crew that the cabin is ready, the notice of departure will be handed over and the doors closed. When the boarding bridge is removed, the aircraft will be pushed out by a tractor vehicle and the engines started. Factors influencing the time required include the time to remove the passenger boarding bridge and push back tractor vehicle availability.

6.6 Aircraft Maintenance Requirements and Facilities

Maintainability can be defined as the workload which is necessary or imposed by scheduled and unscheduled maintenance. Maintenance requirements can be reduced by simplification, increasing reliability, and design for ease of maintenance when necessary. The cost of maintenance is significant and may be as high as 25% of the DOC of large, long haul aircraft. Increasing the intervals between maintenance checks results in shorter downtimes consequently increasing aircraft utilisation and revenue earning days.

Hangar space is essential in terms of maintenance of large transport aircraft. The severity of the check that is being performed will determine the extent to which the hangar must be prepared. An intensive 'D check' will require extensive equipment including docking structures, mobile staircases, ladders, steps and servicing platforms.

6.6.1 *Elements of downtime*

Scheduled servicing

The aircraft's maintenance schedule varies between operators for the same aircraft type. Although the maintenance planning document for an aircraft is the same for all operators, an airline with wide experience of a type can have intervals increased for that aircraft and its derivatives. Table 6-3 describes each maintenance check, as well as a time reference for its occurrence based on a relatively young narrow-body aircraft.

A Check is a primary visual inspection from the ground, of aircraft and specific components for general condition and security. This check is usually performed overnight and averages about 60 labour hours.

B Check is an intermediate check requiring inspection and servicing of the aircraft to determine its general condition for assuring continued airworthiness. Labour hours vary between 200 and 500.

C Check intervals depend on the type of programme, varying from one aircraft to another. New generation aircraft have abolished D checks and adopted a progressive maintenance program with multiple C checks, commonly known as heavy maintenance visits (HMTVs). Intervals between checks vary depending on aircraft type. This check requires a thorough visual inspection of the aircraft to ensure continued airworthiness. The check will normally be performed in seven to ten days and will utilise between 3,000 and 12,000 labour hours. A and B checks are often included.

D Check, for those aircraft still under maintenance programmes, is an overhaul which returns the aircraft to its original condition, as far as is practicable. The aircraft is normally on the ground for about 30 days and it will utilise upwards of 20,000 labour hours, depending on the aircraft type.

INTERVAL BETWEEN CHECKS (flight hours)			
Check	Old Generation (707/DC-8/727/737/DC-9)	Mid Generation (737-300/A300/DC-10/747)	New Generation (757/767/777/A320/A310/A330/A340)
A	150-170	200-450	350-600
B	500-625	800-1,700	N/A
C	2,000-3,200	3,500-4,500	3,500
D	17,000 – 20,000	20,000-26,000	N/A

Table 6-3 - Flight hours necessary to perform various maintenance checks for different generation aircraft.

Table 6-4 shows an example maintenance cycle for a Boeing 747 indicating the nature and extent of the checks that were performed as well as the intervals at which they occurred.

Service	Time	Executive	Procedure	Duration
Transit check	Before each flight	2 engineers and flight crew member	Exterior check of aircraft and engines for damage and leakage, including specific checks on items such as brake and tyre wear.	
Ramp 1 check	Daily	4 engineers	Transit check, plus checks on oil level, tyre pressures, aircraft external lighting and cabin emergency equipment, engine health monitoring system and assessment of technical log entries.	
Ramp 2 check	Every 155 flying hours	4 engineers	Transit and Ramp 1 check, plus checks on APU and component oil levels, engine component oil levels, cabin interior condition and windows.	
Ramp 3 check	Every 310 flying hours	6 engineers	Previous checks plus replacement of hydraulic systems filters, checks on cockpit and cabin seats and attachments, sterilisation of the water system and detailed inspection of systems filters.	
Ramp 4 check	Every 625 flying hours	6 engineers	More detailed inspection of above checks carried out including check of avionics system. Checks on standby power systems. Batteries changed.	
Service check 1	Every 1060 flying hours,	50 engineers	All the above plus partial strip down of structure and engines for detailed inspections, replacement of worn components and soiled and damaged cabin equipment and furnishings. Servicing of undercarriage struts.	Around two shifts
Service check 2	Every 2000 flying hours	50 engineers	All the above plus detailed inspections of specific areas of structure over and above those mentioned, external wash of aircraft, system clarification function checks and intense cleaning of cabin water ad waste systems.	Around three shifts
Service check 3	Every 3875 flying hours	50 engineers	All the above plus detailed inspections of flying controls, structure and engines. Fluid levels drained and refilled in major mechanical components. Aircraft washed. Avionics systems integrated checks. Cabin condition assessed and repaired in depth.	Around four shifts
Inter check 1	Every 6250 flying hours	160 engineers	Detailed inspection and repair of aircraft structure, engines, components, systems and cabin, including operating mechanism, flight controls and structural tolerances.	Seven to eight days

Inter check 2	Every 2500 flying hours	160 engineers	All the above plus additional system function checks.	Between 8 and nine days
Major service	Every 24000 flying hours (every five years)	180 engineers	Most intensive inspection, involves major structural inspections including attention to fatigue corrosion. Aircraft is virtually dismantled, repaired and rebuilt as required, with systems and parts tested and repaired or replaced as necessary.	Between 20 and 25 days

Table 6-4 - Boeing 747-400 Maintenance cycle (*Chudoba, 1995*).

Determination of the maintenance demand expressed in maintenance hours involves three key parameters:

Aircraft Utilisation

Aircraft utilisation for each aircraft type establishes the actual intervals between scheduled maintenance visits. It is the number of hours an aircraft flies in revenue service over a 24-hour period and varies by aircraft type, age, and region of the world. Older aircraft types usually have lower utilisation rates.

Intervals Between Scheduled Maintenance Visits

These are specified by the civil aviation authorities within which the aircraft are certified and operated and is usually expressed in terms of number of “flying hours” between C and D checks or HMs.

Labour Hours per Scheduled Maintenance Visit

This is simply the number of hours required at each maintenance visit.

6.6.2 Maintenance Station Equipment

Conventional practice

Maintenance Vehicles

These are electric, petrol or diesel powered self-propelled mobile units usually having electrohydraulic platforms designed to transport cargo, baggage, supplies, equipment or personnel to or from the aircraft. Some also have a compressed air system for operating maintenance tools at platform level.

Engine Compressor Washing Unit

The engine compressor washing unit uses a pneumatic system comprising a combustion engine-driven air compressor. The compressor is used to generate the pressure required for delivering washing liquid to the engines.

Fuel Tank Repair Trolley

Self-contained mobile trolleys are used containing equipment necessary for fuel tank repairs. The trolleys can also be used for the recovery of pools of residual fuels which may be left in the fuel tanks, and includes a controllable venting facility. Leak detection and tracing is also carried out using pressure or a vacuum.

Miscellaneous equipment and systems maintenance

Other types of equipment which are also used include electrohydraulic work stands and docks, electrohydraulic aircraft jacks, electrically-operated aircraft wheel stands, various trucks and platforms used for loading/unloading heavy equipment to/from the aircraft cabin, inspection of the aircraft structure, engine and APU, mobile column lifts for ground support vehicles, tyre/wheel servicing units with electrically operated boom and height variability, electric powered engine transporters and positioners using hydraulic driving and steering systems, and engine test cells.

Various access, lifting and handling platforms are used and operated by electric motors. Some platforms have remote control and electromagnetic sensors to enable automatic steering. Some installations are fixed to the hangar ceiling using overhead cranes providing a ground area clear of vehicles and equipment.

Test and servicing equipment are also used including ultrasonic cleaning systems, aircraft weighing systems, undercarriage maintenance platforms, electric-motor-driven hydraulic and pneumatic test units, electrical system test stands, fuel system test stands, jet fuel nozzle cleaning systems, pressurised cabin leakage test units, aircraft instrument testing equipment, dry-stripping paint machines, oxygen/nitrogen replenishment units, air recovery equipment, portable lighting equipment, battery chargers, and fluid dispensers.

Some specialised equipment are used for maintaining the runways, taxiways, apron areas etc. These include sweeper/scrubber vehicles, airport de-icers, runway snow-clearing machines, runway grip testing vehicles, and line marking vehicles.

As an example, engine maintenance may be carried out in the hangar, whilst mounted on the aircraft, or taken away to a special installation in the hangar. Specific equipment required for such an operation includes:

- Engine test cells plus engine control and measuring devices.
- exhaust silencers, blast deflectors, and special insulation walls used to reduce jet noise.
- units designed for transport and hoisting of engines
- cranes for removal/fitting
- engine assembly stations and systems
- engine compressor washing unit
- engine nozzle cleaning unit

Structural maintenance

Large aircraft require the use of sophisticated equipment to provide access to all parts of the structure. The equipment is usually mobile, may be designed for use with a

particular aircraft type and may also be provided with built-in power points and other facilities for aircraft maintenance.

There will also be fire protection systems usually consisting of two separate operating systems with associated controls and indicators. One system is for fire and overheat detection, and the other is for fire suppression. The requirements for fire protection in aircraft are set forth in the regulations which specify the system required in accordance with the classification of the aircraft. The system must:

- provide an immediate warning of fire/overheat by means of a light and/or audible signal in the cockpit.
- accurately indicate that a fire has been extinguished and indicate if a fire reignites
- be durable and resistant to damage from all environmental factors which may exist in the location where it is installed
- include an accurate and effective method for testing to assure system integrity.
- be easily inspected, removed and installed.

Proposed LH₂ aircraft procedures and equipment

Changes to maintenance facilities and hangars will be necessary to eliminate the possibility of hydrogen gas accumulation in confined areas. Further modification may be needed to hangars to be able to accommodate the large Twin-Boom fuel tanks. Although still within acceptable limits, its relative size will increase even further for larger, long range types. Nonetheless more space will be required to manoeuvre around the aircraft.

Overall, during the maintenance procedures, the risk of sparks will be greater due to the many operations going on simultaneously involving the use of various tools, machinery and operating personnel. The many personnel working in a confined area makes for a

dangerous environment, and hence operator training and higher levels of safety will prove vital.

Some altogether new equipment will be required including test equipment which will need to be specially adapted to service LH₂ components. Fuel tank repair equipment will be new because of the new fuel tank structure formed of separate tank walls, insulation etc. The problem of air getting into the tank makes things more complex with purging equipment required. There will be entirely new systems such as the venting facility. New methods of leak detection will be vital, although many methods may be obtained from space installations, e.g. such as the use of infra red detectors. Due to its specialist properties, technologically advanced systems will be needed to ensure a safe environment.

Maintenance vehicles are subject to the same stringent safety requirements relating to spark ignition as stated in the turnaround phase. They will also probably need a certain degree of modification to their physical structure to be able to accommodate new tools and test equipment for the Twin-Boom. There may also be different maintenance vehicle configurations which are set-up to repair and maintain the Twin-Boom aircraft, for example, special access equipment to get up over around the large extending tanks.

A new unit will need to be developed which can be used for the recovery of residual or spilled liquid hydrogen, and/or to perform a clean-up operation. Repairs to the hydrogen fuel tanks is a particularly specialised area and will need developed equipment and tools and test rigs which is likely to be more complex than for kerosene. In addition to this, purging of the fuel tanks will be required before the tank can be defuelled and this will require special equipment.

In case of fire, hydrogen will need special fire-fighting procedures and equipment, although the same requirements apply here as they do for conventional kerosene fuelled aircraft.

6.6.3 Inspection, Maintenance and Repair of Fuel Systems

Conventional practice

Kerosene fuel tank inspections involve visual inspection for any evidence of leaks. An identification dye is added making fuel leakage easier to spot. Generally, any leak in an enclosed area is considered a fire hazard and the aircraft should not be flown.

The fuel vapours present in all empty tanks is explosive, therefore caution should be observed in their repair. Purging of fuel tanks filled with kerosene may be accomplished with an inert gas by first filling the tank with water, and then introducing inert gas into the tank as it is drained. Even if a fuel tank has been empty for a long time and appears to be dry inside, it is still likely that enough fumes can be released, e.g. by the heat of welding in fuel tank repair, to create an explosive mixture.

The maintenance and repair of fuel lines and fittings are the same as those practised in the maintenance and repair of hydraulic systems and other systems requiring plumbing. Fuel lines must be kept separate from electrical wiring if at all possible, and clamped securely to the aircraft structure. During the assembly of fuel lines and hoses, it is important that certain standard practices be followed.

Proposed LH₂ aircraft procedures

Since any fuel is dangerous, many safety and precautionary measures as described will still be necessary since many current operating practices will remain the same. However, some properties of hydrogen can make any operation which involves contact with the cold LH₂ more difficult. Mobile and fixed leak detection systems will be

required while the operation is being performed and purging of hydrogen fuel tanks will be different.

If a hydraulic component or line is in close proximity to the hydrogen tanks, it is mandatory that the hydraulic fluid used and the fuel tank insulation be completely compatible. The structure and systems could be adversely affected if material choices are made without considering hydrogen embrittlement.

6.6.4 *Other aircraft maintenance operations*

Some unscheduled checks which may be reported by the flight crew include:

- hard or overweight landings leading to systems and items checks of nacelles and pylons, wing and flaps, landing gear and fuselage shell.
- severe turbulence or buffeting conditions leading to structural inspection.

Some defects may be deferred and unscheduled maintenance can be combined with scheduled work. In some cases repair must be immediate, and if the time required to complete the repair exceeds the aircraft turnaround standard, a change of aircraft has to be made. Other potentially hazardous tasks (not directly affected by the transition to hydrogen) include such operations as aircraft painting, since the fumes are highly flammable. All those involved with aircraft painting must keep in mind that many solvents, lacquers and other materials used are highly flammable. Dry sanding of certain finishes can create static charges which can ignite nitrate flames. The interior of a freshly painted wing or fuselage contains vaporised solvents. If a static discharge should take place in this atmosphere, it is most likely that there will be an explosion and fire. It is recommended that wet sanding be performed in every case possible because the water is effective in dissipating static charges. For example, spray dust or sanding residue can be ignited by static discharge or by a person walking over them. It is usually recommended that floors be washed down with water frequently to prevent

build-up of flammable residues. The use of drill motors to drive operating tools should be avoided since arcing at the motor brushes can ignite flammable fumes.

Special equipment for ramp service includes the major equipment described but also attention must be paid to the provision of all smaller items such as spark resistant wrenches, flame resistant clothing, and hydrogen leak detection systems.

Personnel and Training

Training must be a continuing function for all personnel involved in the turnaround procedure, and particularly the fuelling/defuelling procedure. Training must be given with respect to the handling of LH₂ as well as its associated properties and hazards. Knowledge must also be gained in how to recognise and deal with unsafe situations.

Air Transport System Impact

Overall, the basis for evaluating the broader implications that the introduction of LH₂ would have on the airport have been evaluated however, focus for a particular airport should be the next step and would require evaluation of the following:

- Identity of airports that could be likely candidates for adapting to LH₂ operations
- Characteristics of LH₂ transports and ground support systems that are critical and lend themselves to initiation and build-up to a fully functioning system
- Potential methods by which LH₂ transport operations could develop from one airport and mature to the complex system required to encompass the domestic and worldwide route network
- The timing involved to bring various system elements together considering the required R&D effort and implementation periods.

Although several scenarios could be postulated as to how all, or a portion of, air transportation could convert to operating on LH₂ fuel, there are fundamental factors that would affect any that are considered. These include:

- To warrant serious consideration, the portion of the air transport system devoted to the use of LH₂ must be large enough (in terms of minimizing the impact of cost and/or shortage of kerosene) to attract the large capital required for implementation.
- A well coordinated plan of implementation would be necessary because of the large financial costs involved and the long lead time to provide the necessary infrastructure and fuel production. Because of these factors it is unlikely that a single operating airline would unilaterally adopt LH₂, but instead, a joint effort is required between airlines.
- Implementation should be based on a gradual process that is time-phased to a schedule consistent with facilities and aircraft production rate.

7.0 HYDROGEN PRODUCTION, STORAGE AND DELIVERY

A major challenge in introducing LH₂ into operation is the development of efficient, safe and cost effective production, transport and storage methods. There are comprehensive regulations in existence for conventional aircraft and air transport that deal with safety and the transport of fuel; however all these apply to kerosene fuel. As yet, no regulations exist for Liquid Hydrogen fuel. Nonetheless, the conventional regulations form an excellent basis on which to adapt new regulations.

Hydrogen production, storage and delivery are key issues for the entire hydrogen technology and its successful introduction. Airlines must be satisfied that system failures and/or maintenance requirements do not result in major disruption in their schedules, e.g. redundancy must be provided in case of distribution system failure. The impact of the transition to hydrogen on the air terminal facilities and airline operation must be limited. Only when there are a sufficient number of airports with means for distribution and supply, will LH₂ aircraft be possible.

7.1 *Hydrogen production methods*

One of the key advantages of liquid hydrogen as a fuel for future aircraft is that it can be manufactured using almost any energy source and by many different processes. Methods for producing hydrogen can, in principle, be divided into two groups. The first group concerns processes where water is the sole raw material which is decomposed into hydrogen and oxygen by supplying energy (*Williams, 1980*). In the second group, other raw materials are used (in addition to water), producing hydrogen as well as other by-products.

i. Hydrocarbons

Steam reformation of hydrocarbons is the most popular method today to produce the largest quantities of hydrogen needed. The most desirable feedstock for hydrogen

production is methane from natural gas, because of the higher hydrogen content of the methane molecule compared with other hydrocarbons.

ii. Coal

Hydrogen can also be produced from coal, which has even less initial hydrogen than residual oils and does not have a uniform composition. The CO₂ produced is 188% more than with residual oils and 400% more than methane. Coal resources are very limited and have a large environmental impact, the very reasons other energy resources are being sought.

iii. Electrolysis

An electric current is run through water, decomposing it into hydrogen at the –ve charged cathode and oxygen at the +ve anode, making only two inputs required – water and electricity. Electrolysis is not used on a much wider basis because electrical energy is 3-5 times more expensive than the same quantity of energy derived directly from fossil fuels. Most of the largest electrolytic hydrogen production facilities are sited next to the large hydroelectric facilities that provide reasonably low-cost electrical power.

Hydrogen production by electrolysis has other benefits in that it lends itself to renewable hydrogen production methods such as solar energy and biomass-based production of electricity for water splitting by electrolysis. In reality, there are only certain technologies close to realisation or ready for large-scale hydrogen production.

Energy required for hydrogen production

Steam reforming of Natural Gas and partial oxidation of crude oil are the methods most commonly used to day to produce hydrogen (*Pohl, 1995*). The thermal efficiency is defined as the energy content of the hydrogen divided by the overall energy content of the feedstock plus any supplemental energy sources which are involved.

The net thermal efficiency of steam reforming is about 70%, that of coal gasification is between 61-66% depending on the process used, and that of water electrolysis is an estimated 70% (*Spath and Mann, 2001*).

For example, the energy required to produce hydrogen via electrolysis (assuming 1.23 V) is about 32.9 kW-hr/kg (*Spath and Mann, 2001*). Because a Watt is Voltage x Current (i.e. $P = VI$), this is equivalent to Power x Rate x Time. The power in this case is the voltage required to split water into hydrogen and oxygen and rate refers to the current flow (and how fast hydrogen is produced). Time is the length of reaction time. To run the water splitting reaction at a higher rate (generating more hydrogen in a given time); more voltage must be applied (similar to pushing down on the accelerator of a car, adding more petrol to make the car go faster.) For commercial electrolysis systems that operate at about 1 A/cm², a voltage of 1.75 V is required. This translates into about 46.8 kW-hr/kg, corresponding to an energy efficiency of 70% (i.e. 32.9/46.8) (*Spath and Mann, 2001*). Lowering the voltage for electrolysis, which will increase the energy efficiency of the process, is an important area for research.

Although many different renewable energy technologies exist, in considering the future viability of these sources, it is important to weigh the benefits against their costs. This type of evaluation often takes the form of energy efficiency analysis — a measure of the amount of energy that must be invested to obtain a quantity of energy for use.

Fossil fuels

Currently, most electricity is produced from fossil fuels. A coal-fired power station has three main types of equipment – (i) a boiler, (ii) a turbine and (iii) a generator. In the boiler the energy in a fuel is used to convert water into steam at high temperatures and pressures. The type of fuel used for producing steam from water defines the type of power station, thus a coal-fired plant burns coal for this purpose. The steam drives the turbine which in turn drives the generator to produce electricity.

Typically, a coal fired power station converts 3.45Mw of chemical energy from coal into only 1.2Mw of electrical energy. The difference (2.2Mw) is lost as heat. The effect of this low efficiency ($\approx 35\%$) can be reduced if the lost heat is re-used e.g. by pumping hot water around a house for heating. If the energy is used in this way, the power station becomes a Combined Heat and Power (CHP) station and the energy efficiency rises (to $\approx 70\text{--}80\%$) because the heat is no longer wasted but provides additional energy utilisation. Generally, greater efficiency is obtained the fewer the energy conversions. For high efficiency conversion, the steam temperature and pressure must be as high as possible. Currently, power plants can now be designed and constructed to operate with increasing efficiencies to around 55% or more.

Steam reforming

Hydrogen can also be extracted or "reformed" from natural gas. A two-step process at temperatures reaching 1100°C in the presence of a catalyst makes four parts hydrogen from one part methane and two parts water ($\text{CH}_4 + 2 \text{H}_2\text{O} \ggg 4 \text{H}_2 + \text{CO}_2$). It is a relatively efficient and inexpensive process, and can be made still more efficient with harvest of the waste heat which makes steam-methane particularly attractive for local use.

While this process is well understood and can be implemented on a wide scale today, it produces moderate emissions of CO_2 . This byproduct need not be pumped into the atmosphere as it can also be profitably re-sequestered at the wellhead, providing a greater yield.

Unlike renewable electrolysis, steam-methane reformation depends on the fluctuating price of natural gas – a non-renewable consumable. Nonetheless, steam-methane reformation is poised to be the near-term hydrogen production method of choice on the road towards completely renewable methods.

A life cycle assessment (LCA) of hydrogen production via natural gas steam reforming can be performed to examine the net emissions of greenhouse gases, as well as other major environmental consequences. In order to quantify the emissions, all the operations required to transform raw materials into useful products should be analysed e.g. natural gas lost to the atmosphere during production and distribution. This LCA can then be compared to other production technologies to compare on a like-for-like base the environmental benefits and drawbacks of alternative systems.

For natural gas steam reforming, CO₂ is emitted in the greatest quantity (in terms of total air emissions) accounting for 99% of the total air emissions. The CO₂ accounts for 89.3% of the system's global warming potential (GWP), defined as a combination of CO₂, CH₄, and N₂O emissions expressed as CO₂-equivalence for a 100 year time frame. Methane accounts for 10.6% of the GWP (*Spath and Mann, 2001*).

Other than CO₂, methane is emitted in the next greatest quantity followed by non-methane hydrocarbons (NMHCs), NO_x, SO_x, CO, particulates, and benzene as shown in Figure 7-1.

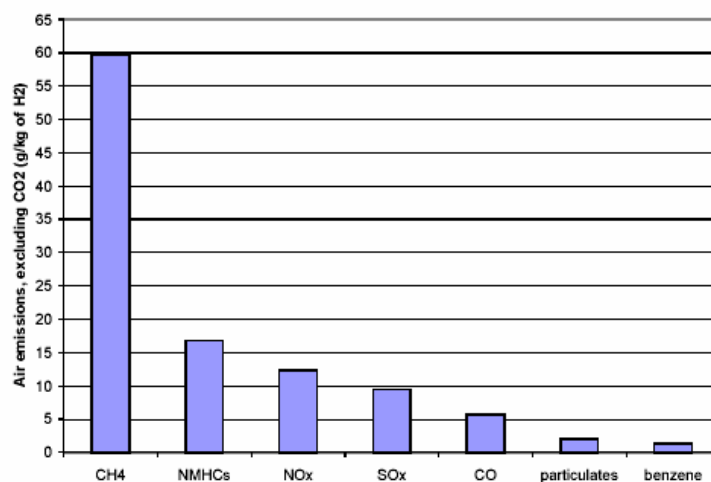


Figure 7-1 - Air emissions (excluding CO₂) for hydrogen production via Steam Reforming (*Spath and Mann, 2001*)

Most of these air emissions are a result of natural gas production and distribution. It should be recognized that upstream processes required for the operation of the steam methane reforming plant also produce pollutants and consume energy and natural resources.

Although CO₂ is the most important greenhouse gas and is the largest emission from this system, quantifying the total amount of greenhouse gases produced is key to examining the GWP of the system. As mentioned, the GWP of the system is a combination of CO₂, CH₄, and N₂O emissions. The capacity of CH₄ and N₂O to contribute to the warming of the atmosphere is 21 and 310 times higher than CO₂, respectively, for a 100 year time frame. Thus, the GWP of a system can be normalized to CO₂-equivalence to describe its overall contribution to global climate change. The GWP, as well as the net amount of greenhouse gases, are shown in Table 7-1. It is evident from this table that CO₂ is the main contributor, accounting for 89.3% of the GWP for this specific system. However, it is important to note that the natural gas lost to the atmosphere during production and distribution causes CH₄ to affect the system's GWP.

	Emission amount (g/kg of H ₂)	% of greenhouse gases in this table	GWP relative to CO ₂	GWP Value (g CO ₂ - equivalent/kg H ₂)	Contribution to GWP (%)
CO ₂	10,621	99.4	1	10,621	89.3
CH ₄	60	0.60	21	1,256	10.6
N ₂ O	0.04	0.0003	310	11	0.1
GWP	N/A	N/A	N/A	11,888	N/A

Table 7-1 - Greenhouse Gases Emissions and Global Warming Potential (*Spath and Mann, 2001*)

Table 7-2 gives the major performance and design data for the hydrogen plant.

Design parameter	Data
Plant size (hydrogen production capacity)	1.5 million Nm ³ /day (57 million scfd)
Hydrogen purity	Industrial grade (>99.95 mol% H ₂)
Average operating capacity factor	90%
Natural gas consumed @ 100% operating capacity	392 Mg/day (feed) 43 Mg/day (fuel)
Steam requirement (2.6 MPa or 380 psi) @ 100% operating capacity	1,293 Mg/day
Steam production (4.8 MPa or 700 psi) @ 100% operating capacity	1,858 Mg/day
Electricity requirement @ 100% operating capacity	153,311 MJ/day
Hydrogen plant energy efficiency (higher heating value (HHV) basis)	89%

Table 7-2 - Steam Methane Reforming Hydrogen Plant Data (*Spath and Mann, 2001*)

The hydrogen plant energy efficiency (quoted as 89% in Table 7-2 above) is defined as the total energy produced by the hydrogen plant divided by the total energy into the plant.

In extracting, processing, transmitting, storing, and distributing natural gas, some is lost to the atmosphere e.g. due to leaking compressor components,. The remaining losses come from other sources such as dehydrators, purging of transmission/storage equipment, and meter and pressure regulating stations in distribution lines.

It is important to note that when estimating the resource consumption, emissions, and energy use, care should be taken in scaling results to larger or smaller facilities as normally they are functions of the size of the plant and the technology.

A large amount of the energy consumed in natural gas production is predominantly from extraction of the natural gas and transportation.

7.2 Resource Consumption

Fossil fuels, metals, and minerals are used in converting natural gas to hydrogen. Natural gas is used at the highest rate, accounting for 94.5% of the total resources on a weight basis, followed by coal at 4.1%, iron (ore plus scrap) at 0.6%, limestone at 0.4%, and oil at 0.4%. The iron and limestone is used in the construction of the power plant and pipeline. The majority of the oil consumption comes from natural gas production and distribution while most of the coal is consumed to produce the electricity needed by the hydrogen plant.

7.3 Water Emissions

The total amount of water pollutants was found to be small compared to other emissions, and come primarily from the material manufacturing steps required for pipeline and plant construction.

7.4 Solid Waste

The waste produced from the system is miscellaneous non-hazardous waste.

7.5 LH₂ infrastructure

The overall hydrogen fuelling system infrastructure requires consideration of the following concepts:

- ◆ Liquefaction facility
- ◆ LH₂ distribution and transfer
- ◆ Vent gas
- ◆ Hydrogen Storage
- ◆ System Safety

At this stage, hydrogen is then converted into liquid by a liquefaction plant. The modular hydrogen liquefier plant size may depend on available land space as well as the output requirements. According to Linde (*CRYOPLANE, 2000*), currently the largest plant produces just over 50 tons/day of liquid hydrogen. The estimated requirements for LH₂ aircraft vary between 40 tons/day for a small airport and 4000 tons/day for a major site. The initial plan, shown in Figure 7-2, is to use a small number of plants which can then be increased to provide the required output.

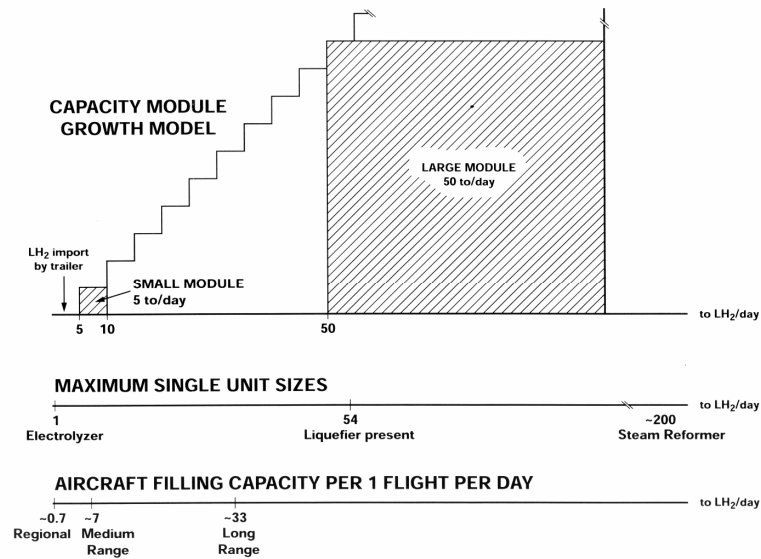


Figure 7-2 - LH₂ liquefier plant capacity growth model. (*CRYOPLANE, 2000*)

However, in the long term, large plants will be required which will be costly yet technically feasible as shown by the simplified hydrogen storage, production and distribution model (Figure 7-3). They will also require a large area of available land

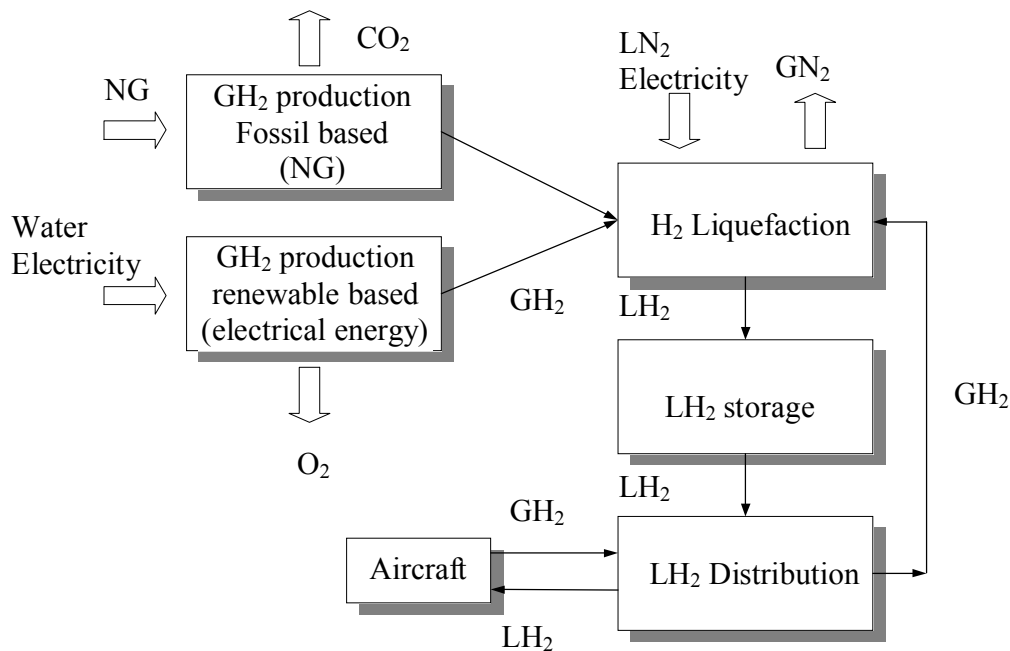


Figure 7-3 - Simplified hydrogen storage, production and distribution model
(CRYOPLANE, 2000)

7.6 Transport of Hydrogen

The techniques needed to transport hydrogen (either gas or liquid) are very much the same as those applied to the transport of natural gas (methane). Gaseous hydrogen may be supplied via pipelines but requires very good insulation. Several lines up to 1 km or more in length exist in the refinery industry and short lengths of vacuum-insulated pipelines have been used in space programs for many years and in LH₂ production plants. The problem with using long pipelines is that not only does cost quickly increase since the more pipelines you have the more insulation you need, but also boil-off will increase. GH₂ may also be transported in cylinders at high pressures (20Mpa), but this method is very inefficient due to cylinder weight. Other transportation alternatives include trucks and shipping.

It is therefore highly advantageous to locate the liquefaction plant as close as possible to the airport.

7.7 Hydrogen storage

As in the case of hydrogen transport, gaseous hydrogen can be stored in much the same manner as natural gas. For mobile storage, capacity can be increased by increasing pressure. Hydrogen can also be stored as a liquid, with the major requirement being insulation. The fuel storage capacities at the airport should be enough to supply fuel throughout the year, accounting for peak demand of $\approx 60\%$ higher in certain months. Provision must be made to ensure that boil-off is minimised.

Different processes are carried out on the fuel before delivery, in order to maintain quality level e.g. filtering, water separation, anti-static additive addition, micro-filtering etc. It is important to discharge static electricity accumulated in the fuel due to the friction from the pipe walls.

7.8 LH₂ distribution and GH₂ collection system

There are two methods of delivering fuel from the storage tank to the aircraft fuel tanks

- ◆ transporting it by self-propelled/towed vehicles, or “fuellers” that directly pump the fuel into the Twin-Boom aeroplane
- ◆ hydrant systems, based on buried pipelines connecting storage tanks to hydrant pits at each Twin-Boom aircraft loading bay

It is preferable that a hydrant system is installed at the airport because of the reduced operating costs associated with fuel tankers as well as increased safety. Fuel tankers occupy a large space around aprons causing obstruction and increase the possibility of spillage due to increased movement around the already busy ramp areas. Although mobile dispensers/tankers are many times cheaper than fuellers, their operating costs are higher and service life shorter. On the other hand, the fixed location of the hydrant

pits limit flexibility with respect to the aircraft position. All insulated piping can be located underground to minimise possibility of damage. However, ventilation must be provided to ensure a combustible hydrogen-air mixture does not accumulate.

8.0 AIRCRAFT ECONOMIC ANALYSIS

Having also examined conceptual design, aeroplane safety, airworthiness certification, and the ground support and infrastructure necessary to support the Twin-Boom aircraft, we finally arrive at the final juncture in the study and one which is of utmost importance – **the economic analysis**. This begs the question *how much will the Twin-Boom cost to buy and operate?*

Direct Operating Costs (DOC) is a factor of predominate interest for airlines. A small difference in DOC, amounting to only a few hundredths of a cent, calculated for the millions of passengers flown by airlines each year, can make a tremendous difference in the bottom line financial statement. Accordingly, it is important that the subject of DOC be examined very closely when considering the prospects of a new fuel, especially one with very few characteristics of the those fuels such as kerosene currently being used.

This chapter introduces the methods by which the Twin-Boom aircraft operating costs are estimated. The total aircraft unit cost and the direct operating costs are estimated. This involves the summation of all cost elements associated with purchasing, operating and supporting the aircraft throughout development and production based on a fixed production quantity and production rate, and average utilisation per year.

Calculating the operating cost of an aircraft in general is fraught with difficulty for several reasons. Values for costs are highly time-dependent and the long timescales involved means that all the factors influencing the costs are difficult to account for, such as political issues.

These calculation methods are based on today's prices, i.e. **YEAR 2005** prices and are used to enable comparisons to be made between the Twin-Boom (operating on liquid hydrogen fuel) and an equivalent aircraft operating on kerosene fuel. Although, for

civil aircraft a lot of data is available from past aircraft and operations on which to base such analysis, an unconventional configuration such as the Twin-Boom will involve a degree of uncertainty, estimation, assumptions and best engineering judgement. Although assumptions are made, a very useful comparison is presented providing the *relative* cost benefits of using LH₂ fuel. Furthermore, every effort has been made to utilise current prices for the various elements that make up the operating costs and where necessary the prices have been 'factored' to account for 'current year'.

8.1 Operating Costs

Most standard cost methods only estimate the DOC of the aircraft; however, in reality the total cost of owning and operating an aircraft is the sum of indirect operating costs (IOC) and DOC. It is common practice, however, to consider the two cost components separately.

8.1.1 Indirect Operating Costs

Indirect operating costs (IOC) are those airline costs not directly connected with the actual flight of the aircraft. IOC are sometimes more difficult to separate and define but in general include the following:

- Aircraft Ground Handling
- Landing Fees
- Aircraft Service
- Cabin Attendants
- Food and Beverage
- Passenger Handling
- Reservations and Sales
- Baggage/Cargo handling
- Marketing/Advertising/Sales
- General and Administration

As these costs are generally independent of the type of aeroplane they are classified as *indirect* items.

8.1.2 *Direct Operating Costs (DOC)*

The evaluation of the DOC of an aircraft involves consideration of all parameters associated with the airframe, engine, avionics etc. and is fully described in the DOC model below (Figure 8-1).

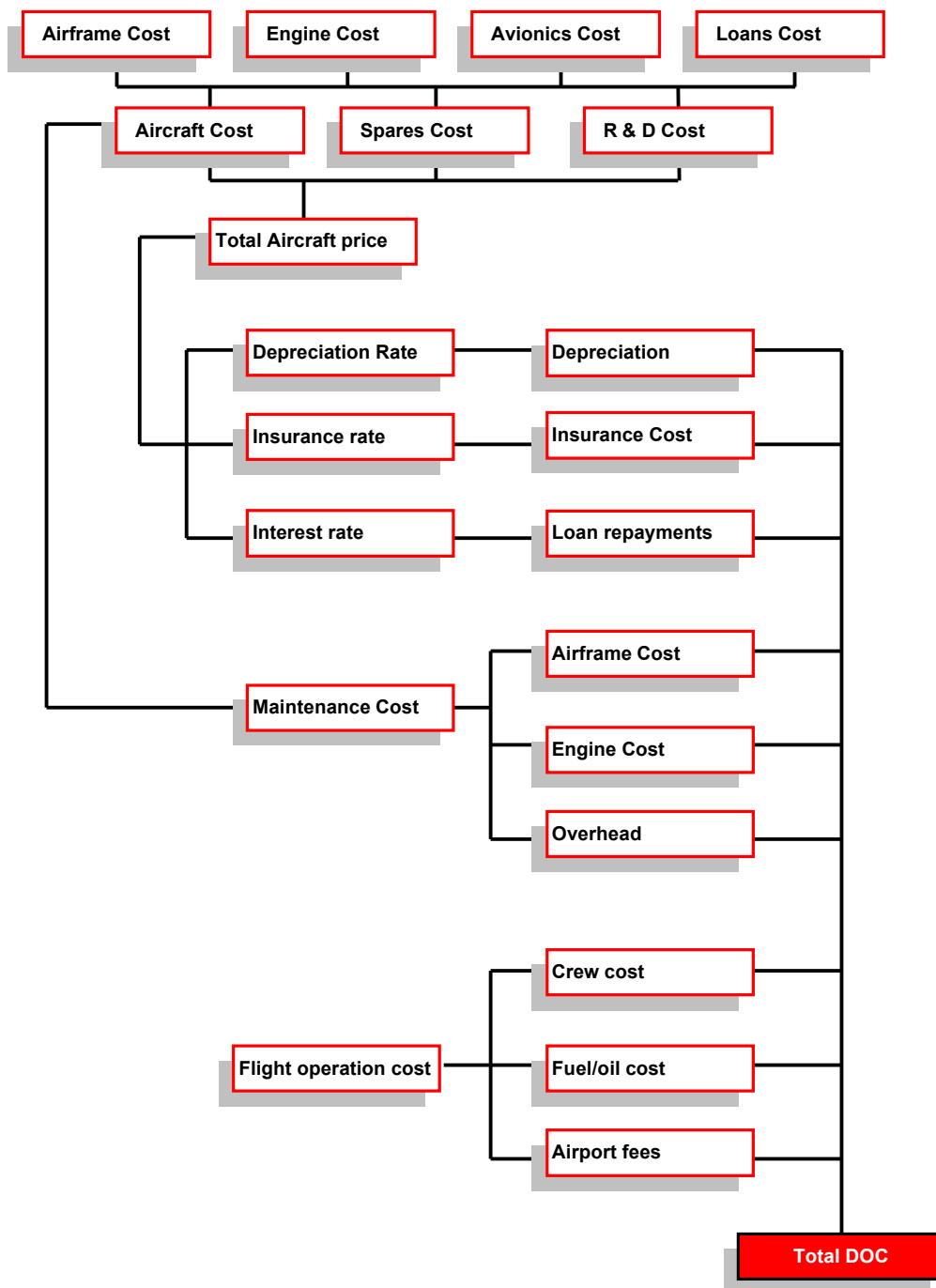


Figure 8-1 – Components of aircraft DOC (*Jenkinson, Simpkin, Rhodes, 1991*)

There are different ways of representing DOC, although in general DOC is dependent on the following factors:

- ◆ Aircraft weight
- ◆ Maximum speed
- ◆ Production rate and quantity
- ◆ Engine thrust
- ◆ Advanced technology and materials
- ◆ Labour rate
- ◆ Maintenance costs
- ◆ Fuel cost

During the later phase of any aircraft preliminary design, the design team will consider “*how much should we spend per pound for weight reduction?*”. That is, it is possible to spend more money on expensive materials and manufacturing processes to drive down weight but this will also drive the aircraft cost up. For example, advanced materials generally increase engineering effort as well as tooling, materials cost and fabrication, although for some materials such as composites there are life cycle cost benefits e.g. they are less prone to corrosion and so lead to reduced maintenance costs.

Thus, many factors need consideration when deciding how much to invest in weight reduction such as competitor aircraft weight, range, and price. Current aircraft are containing greater amounts of advanced materials and technology than their older generation predecessors e.g. Airbus A380, Boeing 787 ‘Dreamliner’.

8.2 DOC methodology

The methodology contained in this chapter is predominantly based on J Wayne Burns, Vought Aircraft Company, cost estimation (*Burns, 1994*) which is primarily intended for use on new development aircraft rather than derivative aircraft which suits our purposes.

8.2.1 Life Cycle Cost

The Life Cycle Cost (LCC) can be defined as the total cost of an aircraft from initial concept through to retirement of that aircraft type and includes the total cost of

- R&D
- Test and Evaluation
- Acquisition
- Operation and Support
- Retirement and decommissioning

The total LCC can be estimated by:

$$LCC = C_{DDTE} + C_{ACQ} + C_{OPER} + C_{DISP} \quad \text{Eq 8-1}$$

Where:

C_{DDTE} = Design, development, test and evaluation cost

(includes Airframe Engineering and Design, Development Support and Testing, Flight Test, Tooling, Manufacturing Labour, Quality Control, Manufacturing Material, Engine & Avionics)

C_{ACQ} = Acquisition cost

C_{OPER} = Operations and support cost

C_{DISP} = Disposal cost

8.2.2 Development & Acquisition Cost

Engineering Hours

The total airframe engineering hours for development, E_{HD} , and production, E_{HP} , can be estimated using the following equations.

$$E_{HD} = 0.066A^{0.796}S^{1.538}Q_D^{0.183}A_{TF}C_{AMC} \quad \text{Eq 8-2}$$

$$E_{HP} = 0.066A^{0.796}S^{1.538}(Q_D+Q_P)A_{TF}C_{AMC} - E_{HD} \quad \text{Eq 8-3}$$

Where:

A_{TF} = judgement factor to account for advanced technology features. For commercial transport and business jets, $A_{TF} = 0.9$ (Burns, 1994).

C_{AMC} = Judgement factor for cost of advanced material relative to conventional metal designs.

S = maximum speed (kts) at best altitude

Q = quantity of aircraft that will be produced (Q_D for DT&E phase, $Q_D + Q_P$ for production)

A = AMPR (airframe unit weight in lbs)
= weight empty minus wheels, tyres, tubes & brakes, Engines, Rubber or nylon fuel cells, Starters, APU, Instruments, Batteries & electrical power, Avionics equipment, Air-conditioning, anti-icing and pressurisation

Most aircraft costing methodology is based on AMPR or airframe unit weight, and generally AMPR is estimated for a specific aircraft after empty weight is estimated. Airframe cost is directly dependent upon airframe weight. Thus DOC depends upon total thrust, airframe weight and fuel burned, and since these three items are the variables in take-off weight, a minimum take-off weight is a good 'first' guess criterion for minimum D.O.C.

With a given set of engines, the least take-off weight will be very close to the minimum D.O.C. Since weight empty is known, AMPR can be estimated using the following equations.

$$AMPR = 0.431(WE_{CT})^{1.05375} \quad \text{Eq 8-4}$$

Where:

WE_{CT} = weight empty of transport aircraft

The engineering hourly labour rate varies with different airframe manufacturers but can be estimated as being approximately \$95 per hour (*Burns, 1994*).

Engineering cost for the development phase can be estimated using the following equation:

$$C_{AED} = E_{HD} * E_{RATE} C_S \quad \text{Eq 8-5}$$

Where:

E_{RATE} Engineering hourly rate

C_S Cost factor = 1.0 for commercial aircraft (*Burns, 1994*).

Development Support Cost

Development support is the non-recurring manufacturing effort undertaken to support engineering design during the DT&E phase of the aircraft program. It includes the cost of manufacturing labour and materials required to support mock-up, test components and all else required for airframe design and development.

The development cost can be estimated using:

$$C_{DSC} = 0.0356 A^{0.903} S^{1.93} Q_D^{0.346} C_{PI} A_{TF} C_S \quad \text{Eq 8-6}$$

Where:

C_{DSC} = development support cost

A = AMPR weight

S = Maximum speed (kts) at cruise altitude

C_{PI} = cost escalation factor (= ratio of CPI for “then year” and CPI for 2005)

Flight Test Operations (DT&E)

Any aircraft will need to be flight tested as part of its evaluation and eligibility for an

airworthiness certificate. For the Twin-Boom, flight testing activities will be more extensive due to its unique configuration.

Flight test activity costs include all costs incurred by the aircraft manufacturer to complete flight test (except the cost of the actual flight test aircraft itself). The cost of flight test operations can be estimated using the following equation.

$$C_{FTAR} = 0.00558A_{1.19}S_{1.401}S_{1.401}Q_D^{1.281}C_{PI}A_{TT}C_S \quad \text{Eq 8-7}$$

Where:

C_{FTAR} = cost of flight test operations

ATT = judgment factor (0.8-0.9 for conventional commercial aircraft (Burns, 1994))

Tooling (DT&E and production)

Tooling includes hours required for tool design, fabrication, production test equipment, etc. Tooling hours are dependent on production rate and construction materials used for the aircraft components. Higher aircraft production rates result in a higher tooling cost and will cause the unit flyway cost to be slightly higher for a given production quantity.

Tooling hours for development and production can be estimated using the following equations:

$$T_{HD} = 5.083A^{0.768}S^{0.899}Q_D^{0.18}R^{0.066}C_{AMC} \quad \text{Eq 8-8}$$

$$T_{HP} = (5.083A^{0.768}S^{0.899}(Q_D+Q_P)^{0.18}R^{0.066}C_{AMC})-T_{HD} \quad \text{Eq 8-9}$$

Where:

T_{HD} = Tooling hours for development

T_{HP} = Tooling hours for production

R = Production rate (aircraft per month)

C_{AMC} = Judgement factor for advanced materials tooling and manufacturing cost relative to % advanced materials

Tooling cost for development C_{TD} and production C_{TP} can be estimated with the following equations:

$$C_{TD} = T_{HD}T_R C_S \quad \text{Eq 8-10}$$

$$C_{TP} = T_{HP}T_R C_S \quad \text{Eq 8-11}$$

Manufacturing Labour

Manufacturing labour hours, as the name implies, include those hours necessary for machining, fabrication, and assembly of the major structure.

Manufacturing labour hours for development M_{HD} and production M_{HP} can be estimated with the following equations:

$$M_{HD} = 43.61A^{0.76}S^{0.549}Q_D^{0.554}C_{AMC} \quad \text{Eq 8-12}$$

$$M_{HP} = 43.61A^{0.76}S^{0.549}(Q_D+Q_P)^{0.554}C_{AMC}-M_{HD} \quad \text{Eq 8-13}$$

Manufacturing labour cost for development (C_{MD}) and production (C_{MP}) can be estimated with the following equations.

$$C_{MD} = M_{HD}M_R C_S \quad \text{Eq 8-14}$$

$$C_{MP} = M_{HP}M_R C_S \quad \text{Eq 8-15}$$

Where:

M_R = hourly rate used for manufacturing cost estimation.

C_S = Cost factor = 1.0 for commercial aircraft (Burns, 1994).

Manufacturing labour rates are estimated to be **\$70** (Burns, 1994).

Quality Control

Quality control includes the task of inspecting fabricated and purchased parts, sub-assemblies, and assembled components for standards specified by process standards, drawings and specifications. The quality control man-hour requirement for development (Q_{HD}) and production (Q_{HP}) can be estimated with the following equations:

$$Q_{HD} = 0.13M_{HD} \quad \text{Eq 8-16}$$

$$Q_{HP} = 0.13M_{HP} \quad \text{Eq 8-17}$$

Quality control labour cost for development (C_{QD}) and production (C_{QP}) can be estimated with the following equations.

$$C_{QD} = Q_{HD}Q_R \quad \text{Eq 8-18}$$

$$C_{QP} = Q_{HP}Q_R \quad \text{Eq 8-19}$$

Where:

Q_R is the average hourly rate for quality control.

Manufacturing Material and Equipment

Manufacturing material and equipment includes the raw material and hardware required for the fabrication and assembly of the airframe (with the exception of engines and avionics). The cost of manufacturing materials for the development program (C_{MMD}) and the production program (C_{MMP}) can be estimated using the following equations.

$$C_{MMD} = 96.677A^{0.692}S^{0.639}Q_D^{0.803}C_{PI}C_{AMC}C_{LO} \quad \text{Eq 8-20}$$

$$C_{MMP} = (96.677A^{0.692}S^{0.639}(Q_D+Q_P)^{0.803}C_{PI}C_{AMC}C_{LO}) - C_{MMD} \quad \text{Eq 8-21}$$

Where:

C_{PI} Cost escalation factor

C_{AMC} Advanced materials cost

C_{LO} judgement factor for low observable materials = 1.0 for conventional aircraft (Burns, 1994)

C_{AMC} represents the amount of advanced materials used, expressed as a percentage of total structure material, and the increased cost of advanced materials and tooling relative to conventional metal construction. This is estimated to be **1.08** for conventional aircraft and **1.2** for the Twin-Boom to reflect the fuel tank structure and the advanced technology standard (as specified in Section 3.4.1 combined with best engineering judgement)

Engine Costs

For the Twin-Boom, engine cost has been estimated since, although similar in design to conventional engines, will still have unique aspects, therefore, a 10% increase in engine cost is assumed relative to the conventional aircraft engines to account for the increased R&D based on past trends of increases in engine cost.

The conventional aircraft engine cost data may be derived from the following equations but does not include initial engine development cost.

$$C_E = 121.5 T_{SL}^{1.00161} N_E C_{PI} \quad \text{Eq 8-22}$$

Where:

$$\begin{aligned} C_E & \quad \text{Cost of engine} \\ T_{SL} & \quad \text{Sea level maximum thrust} \\ N_E & \quad \text{Number of engines per aircraft} \end{aligned}$$

Avionics Cost

The avionics cost per pound varies with the type of equipment used which also varies with the type and quantity of aircraft. The following equation can be used as an estimate for uninstalled avionics cost.

$$C_{AV} = W_{AV} (\$3950) C_{PI} \quad \text{Eq 8-23}$$

Where:

- C_{AV} Avionics cost in then year dollars
 W_{AV} Avionics weight
 C_{PI} ratio of cost escalation factor for year of interest and 1983.

The avionics cost for the Twin-Boom has been factored by 10% to account for the more sophisticated system required for the unconventional configuration relative to conventional aircraft (increased technology level in Section 3.4.1).

Interior Cost

This is a substantial cost and includes seats, ceiling and flooring materials, lavatories, IFE etc. The following equation can be used for commercial production aircraft.

$$C_{INT} = F_{INT} N_{PAX} N_{PAC} (C_{PI} / C_{PI1990}) \quad \text{Eq 8-24}$$

Where:

- C_{INT} Cost of interior
 F_{INT} Interior cost factor in US\$ per passenger (based on 1990 \$)
= \$2000 for jet transport
 N_{PAX} Number of passengers
 N_{PAC} Number of production aircraft
 C_{PI} Cost escalation factor for current year

8.3 Development Cost

The total development cost for commercial programs can thus be determined with the following equation which is a summation of the development items:

$$\boxed{C_{DDTE} = C_{AED} + C_{DSC} + C_{FTAR} + C_{TD} + C_{MD} + C_{QD} + C_{MMD} + C_E + C_{AV}} \quad \text{Eq 8-25}$$

8.4 Production Cost

The production cost can be estimated using the following equation:

$$\boxed{C_{PROD} = C_{AEP} + C_{TP} + C_{MP} + C_{QP} + C_{MMP} + C_E + C_{AV} + C_{INT}} \quad \text{Eq 8-26}$$

8.5 Acquisition Unit Cost

The acquisition unit cost and recurring flyaway cost can be estimated with the following equations:

$$\boxed{\begin{aligned} C_{UA} &= \left(\frac{C_{DDTE} + C_{PROD}}{Q_D + Q_P} \right) \\ C_{RF} &= \frac{C_{PROD}}{Q_P} \end{aligned}} \quad \begin{array}{l} \text{Eq 8-28} \\ \text{Eq 8-28} \end{array}$$

Where:

- C_{UA} *Acquisition unit cost*
- C_{DDTE} *Development cost*
- C_{PROD} *Total production cost*
- Q_D *Quantity of development aircraft*
- Q_P *Quantity of production aircraft*
- C_{RF} *Recurring flyaway cost*

The AMPR cost per pound that will be used for value of a pound guidelines can be estimated with the following equation:

$$C_{AMPR} = (C_{RF} - C_E - C_A) / A \quad \text{Eq 8-29}$$

Where:

- C_{AMPR} *AMPR cost per pound*
- C_E *Cost of engines*
- C_A *Cost of avionics*
- A *AMPR weight*

8.6 Cost Estimation – Twin-Boom and conventional aircraft

The prices have been based, where possible using today's prices to prevent ambiguity and uncertainty in the values. Although the values are estimates they provide an insight into some of the relative costs. However, it should be borne in mind that not all development costs have been taken into consideration, e.g. engine R&D.

Table 8-1 below indicates recurring flyaway unit cost, cost per pound, and AMPR cost per pound for the assumed production quantities and rates.

			TWIN BOOM		CONVENTIONAL	
		UNITS	DEVELOPMENT	PRODUCTION	DEVELOPMENT	PRODUCTION
Judgement factor to account for advanced features	ATF		1.1		0.9	
Weight Empty	OWE	lb	136154		136154	
AMPR	A	lb	110780		110991	
Max Speed	S	kts	350		350	
quantity for development phase	Q _D		2		2	
development + production	Q _D +Q _P		1000		1000	
Engineering labour rate	E _{RATE}	\$	95		95	
Consumer Price Index	C _{PI}		180		180	
Security Cost factor	CS		1		1	
ATT -judgement factor for advanced technology aircraft testing	ATT		1.5		0.85	
Production rate per month	R		1	4	1	4
Tooling Hourly Rate	T _R	\$	80		80	
Manufacturing Labour Rate	M _R	\$	70		70	
Quality Labour rate	Q _R	\$	80		80	
Advanced Materials Cost Factor	C _{AMC}		1.2		1.08	
Low Observable Materials	C _{LO}		1		1	
Interior Unit Cost	per aircraft	\$	498461		498462	
Avionics Weight	W _{AV}	lb	1540		1540	
Avionics Unit Cost	C _A	\$	12044340		10949400	
Sea Level Thrust	T	lb	26764		25000	
Number of Engines	N _E		2		2	
Engineering Hours	E _{HD} /E _{HP}	hrs	8382499.537	17756264.54	6172567.841	13075067.52
Engineering Cost		\$	796337456	1686845131	586393944	1242131415
Development Support Cost	C _{DSC}	\$	261499397		213954052	
Flight Test Operations	C _{FTAR}	\$	135134012		76575940	
Tooling hours	T _{HD} /T _{HP}	hrs	10017274	66528947	9015546	59876052
Tooling Cost		\$	801381939	5322315795	721243745	4790084215
Manufacturing hours	M _{HD} /M _{HP}	hrs	13062348	395492757	11756113	355943481
Manufacturing Cost		\$	914364381	27684493020	822927943	24916043718
Quality Control man-hours	Q _{HD} /Q _{HP}	hrs	1698105	51414058	1528294	46272652
Quality Control Cost		\$	135848422	4113124677	122263580	3701812210
Manufacturing Material and Equipment	C _{MMD} /C _{MMP}	\$	47635433	6954057144	42871890	6258651430
Interior Cost	per aircraft	\$		497464615		497464615
Engine Cost		\$	26180674	13064156776	22229488	11092514678
Avionics Cost		\$	10949400	10927501200	10949400	10927501200
TOTAL COST			\$3,129,331,117	\$70,249,958,359	\$2,619,409,985	\$63,426,203,481
Acquisition Unit Cost				\$73,379,289		\$66,045,613
Cost per lb				\$539		\$485
Recurring Flyaway Cost				\$70,390,740		\$63,553,310
Recurring Cost per lb				\$517		\$467
\$/lb of AMPR weight				\$418		\$375

Table 8-1 - DOC results of Twin-Boom and conventional aircraft.

The development and production cost comparisons between the Twin-Boom and conventional aircraft are shown graphically in Figure 8-2 and Figure 8-3.

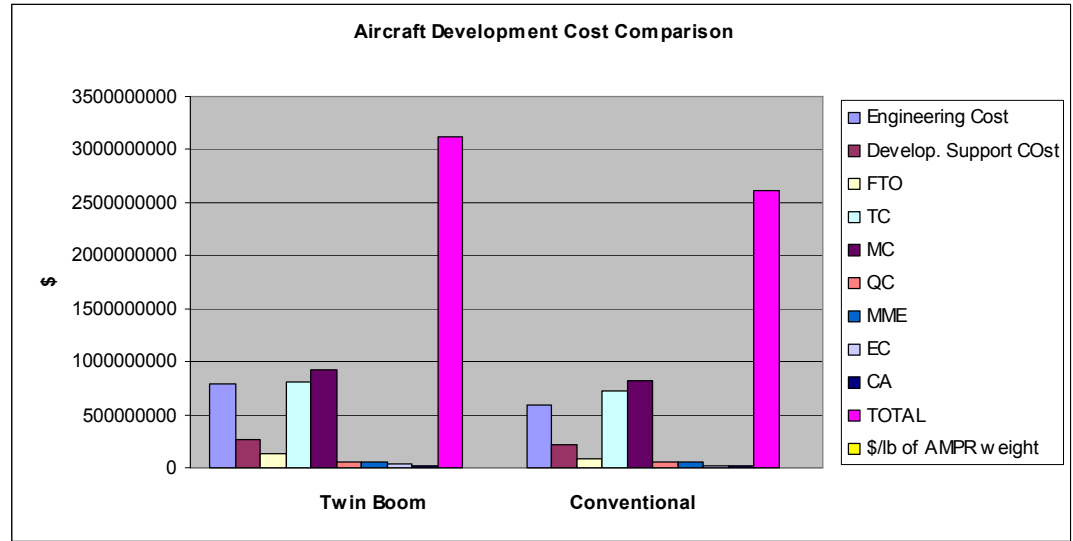


Figure 8-2 - Development cost comparison between Twin-Boom and conventional aircraft.

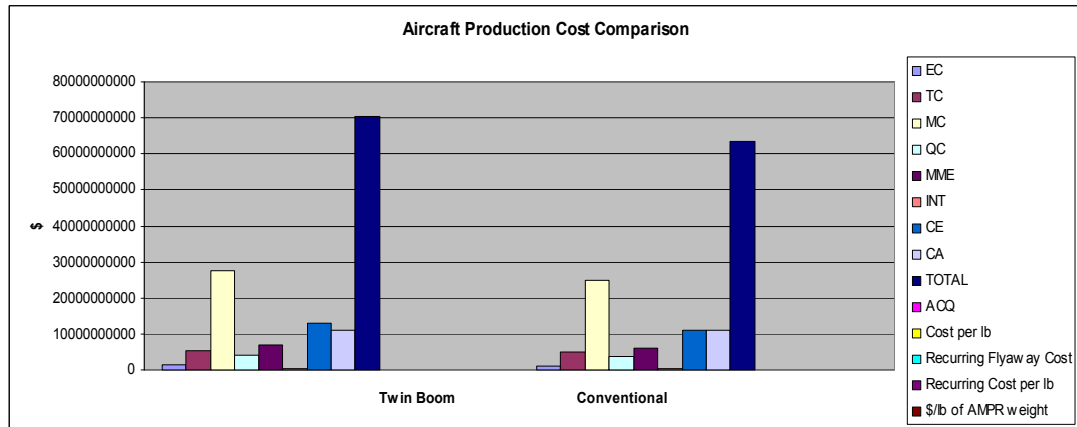


Figure 8-3 - Production cost comparison between Twin-Boom and conventional aircraft.

8.7 Operation Fuel Cost

Operation cost includes fuel oil, maintenance, crew salaries, depreciation etc. For the purposes of this study, only those operating costs that are affected by weight, which is primarily fuel, will be addressed.

We assume:

- ◆ Constant fuel fraction
- ◆ Constant planform efficiency (composite L/D)
- ◆ 10% of total fuel is used for takeoff, climb and descent

$$T_{FUEL} = 1.1x \left[\left(\frac{(K_{FF} TO_{GW})}{L / D} \right) sfc \right] FH_{YR} Y_S \quad \text{Eq 8-30}$$

Where:

T_{FUEL} Total pounds of fuel used during the aircraft life

K_{FF} Fuel fraction life

0.85 for 30% fuel fraction

0.80 for 40% fuel fraction

L/D Lift to Drag ratio

TO_{GW} Take-Off gross Weight

sfc specific fuel consumption (lbs of fuel per lb of thrust per hour)

FH_{YR} Flight hours per year

Y_S Years of service

The L/D for a given aircraft varies for different mission segments however the L/D for the Twin-Boom has been estimated as being approximately **15** whereas for the conventional aircraft L/D can be estimated as being **20**. For a given weight and propulsion efficiency, aircraft with higher L/D and span/area ratios require less fuel for a given range.

Total life cycle fuel cost (per aircraft) can be estimated with the following equation:

$$TC_{FUEL} = \left(\frac{T_{FUEL}}{F_{DEN}} \right) C_{FUEL} \quad \text{Eq 8-31}$$

Where:

TC_{FUEL} *Total life cycle cost of fuel per aircraft*

F_{DEN} *Fuel density (lb/gal)*

C_{FUEL} *Price per gallon of fuel*

This equation can also be used to evaluate the approximate life cycle fuel cost effect of changes that affect aircraft gross weight, L/D, and sfc. It is important to understand that 1lb of weight empty translates to more than 1lb of gross weight change because of the gross factor effect. In fact, it has been estimated that adding 1lb to airframe weight increases the overall weight by 3lb. Conversely it has been estimated that a 1lb weight decrease results in a corresponding decrease of ≈ 0.5 lbs in other structure, and a fuel weight decrease of ≈ 0.75 lbs, although the net aircraft gross weight effect of component weight changes varies with the type of aircraft, configuration, wing and tail loading etc. Unfortunately, we cannot apply the same weight change sensitivity to unconventional configurations such as the Twin-Boom.

8.7.1 Life Cycle Fuel Cost

The following graph (Figure 8-4) illustrates the yearly cost effect (per aircraft) of excess take off gross weight with different engine sfc and fixed fuel cost.

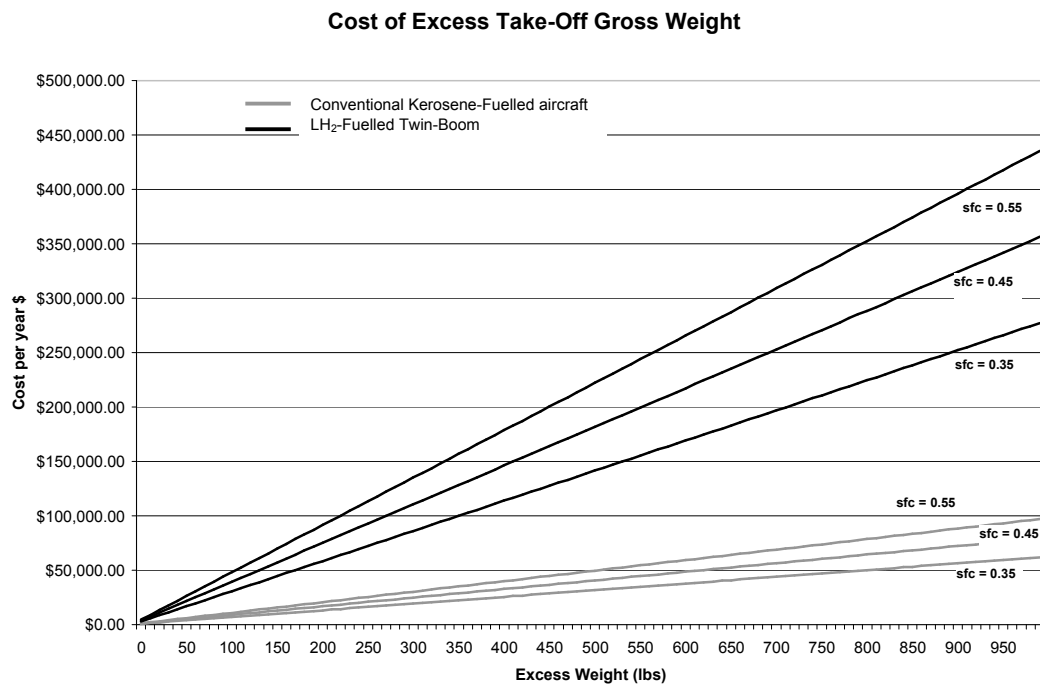


Figure 8-4 – Effect on cost effect of excess take off weight for the Twin-Boom and conventional aircraft.

A final summary of the DOC for the Twin-Boom and Conventional aircraft is shown in Table 8-2.

	Twin-Boom	Conventional Aircraft
OWE	61888	61888
Total Aircraft Price	73379289.48	66045613.47
Aircraft Spares	23064683.83	17590735.21
TOTAL INVESTMENT COST	96443973.3	83636348.67
Annual depreciation costs/year	4339978.799	4177635.616
Interest/year	5207974.558	4516362.828
Insurance	513655.0263	330228.0673
Total Standing Charge/Year	10061608.38	9024226.512
Standing charge/flying hour	\$1,698.2	\$1,523.1
STANDING CHARGES		
Airframe Cost	\$60,288,952	\$54,930,869
Engine Cost	\$13,090,337	\$11,114,744
Spares cost	\$11,554,486	\$8,827,510
Total Investment Cost	\$84,933,775	\$74,873,124
Depreciation costs/year	\$3,822,020	\$3,369,291
Interest/year	\$4,586,424	\$4,043,149
Insurance/year	\$587,034	\$330,228
TOTAL ANNUAL STANDING CHARGE/year	\$8,995,478	\$7,742,667
Standing charge/hour	\$1,518	\$1,307
FLYING COSTS		
crew costs/hour	\$1,260	\$1,260
Landing charge	\$543	\$543
Navigational charges (per flight)	\$4,000	\$4,000
Ground Handling	\$1,980	\$1,980
TOTAL AIRPORT CHARGE (per flight)	\$6,523	\$6,523
Cruise time	6.25 hrs	6.25 hrs
Block time	6.97 hrs	6.97 hrs
airport charges/hour	\$936	\$936
Fuel cost per hour (based on energy content)	\$434	\$120
MAINTENANCE COSTS		
Total Maintenance Cost	\$1,258	\$1,258

TOTAL DOC		
DOC per hour	\$5,406	\$4,880
Total Stage Cost	\$37,681	\$34,017
Mile Cost	\$19	\$17
seat mile cost	10.47¢	9.45¢

Table 8-2 - Summary of operating costs for Twin-Boom and Conventional aircraft.

8.8 CONCLUSIONS

Weight has a direct influence on the overall acquisition and also operating costs. It was shown that the Twin-Boom has a similar take-off weight to a conventional aircraft. The reason being that the lower weight of the hydrogen fuel is offset by the tank and insulation weight (as well as increased drag leading to an increased fuel requirement) ultimately resulting in very similar take-off weights. For this reason, and for the purposes of the cost analysis, the Twin-Boom and the conventional aircraft have been assumed to have identical take-off weights. This therefore results in similar results for many elements of their production and development costs (Figure 8-5 and Figure 8-6) and indeed ultimately results in a ‘similar’ overall acquisition and recurring flyaway cost. The results show that the Twin-Boom will cost approximately 19% more to design, develop and 11% more to manufacture than an equivalent aircraft operating on conventional fuel which is to be expected.

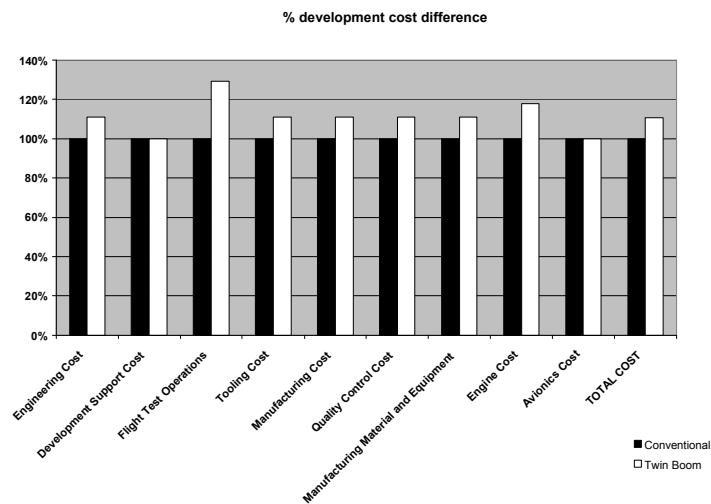


Figure 8-5 - Percentage difference in various development cost parameters between Twin-Boom and conventional aircraft.

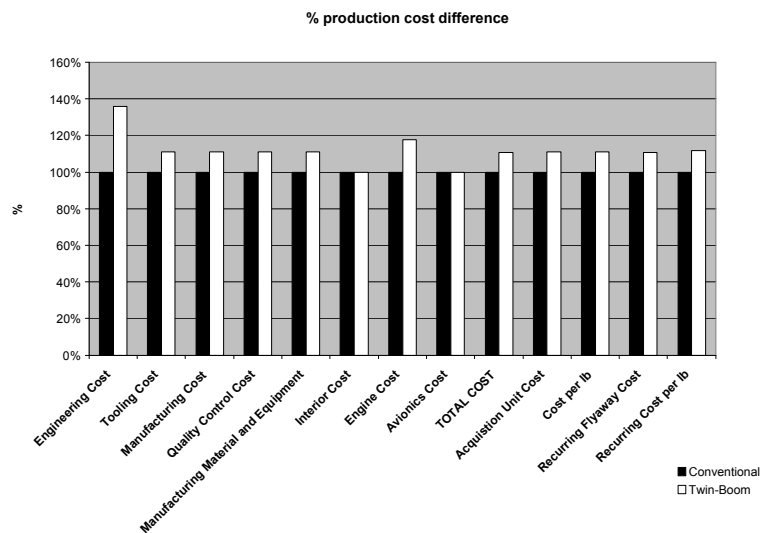


Figure 8-6 - Percentage difference in production cost parameters between Twin-Boom and conventional aircraft.

Where the Twin-Boom and conventional aircraft differ significantly is in their technology status. Although the Twin-Boom aircraft will be of a similar technology standard (and weight) to conventional aircraft, the Twin-Boom fuel tanks and their safe

integration will require extra design effort as well tooling, and manufacturing material design and development. This will lead to an increase in development costs which will translate into other areas such as flight testing. The judgement factor is used to account for advanced technology features. For the conventional commercial transport aircraft in this example a judgement factor is suggested (*Burns, 1994*). However, for the Twin-Boom, a judgement factor of 1.1 has been used which assumes a 2010 technology standard (Section 3.4.1). Based on best engineering judgement this increase was deemed a practical figure by the author (as well as peers of aircraft design at Cranfield University) as a reasonable estimate of the increase in technology required and the extra design effort that this would entail.

The graph shown in Figure 8-4 demonstrates the sensitivity of a weight increase for the Twin-Boom and conventional kerosene-fuelled aircraft for a range of engine sfc. The graph shows that the LH₂-fuelled Twin-Boom is more sensitive to any weight increases and the difference in cost per year increases with increasing weight and worse sfc. Thus, the Twin-Boom must be subject to a far stricter weight control program to prevent weight (and costs) spiralling out of control. The cost of fuel used is \$18 per GJ for LH₂ and \$5 per GJ for kerosene (*Hydrogen Technical Advisory Panel, 1999*).

The main difference between the Twin-Boom and the conventional aircraft rests in the life cycle fuel cost. As the cost of kerosene fuel inevitably increases, the cost of liquid hydrogen fuel will decrease albeit at a lower rate. This will result in a 'break-even' point whereby in a certain year the cost of both fuels will be equal. After a further period of time the cost difference will be great enough to offset the increased design, development and production costs of the Twin-Boom and the lifecycle and operating costs will be equal.

Table 8-2 illustrates the cost differences in operating the two aircraft. The main difference is due to the fuel cost but there are also other factors which adversely

influence the cost of the Twin-Boom operating costs including insurance, and maintenance.

This ultimately results in a seat mile cost for the Twin-Boom some 11% greater than the conventional aircraft. This is a significant amount and over the assumed 20 year operating life of the aircraft amounts to an additional **\$43.50M** (based on a load factor of **0.7**).

9.0 DISCUSSION OF RESULTS

LH₂-fuelled aircraft concepts

This Thesis has shown in Chapter 3.0 that an unconventional aircraft concept is indeed technically feasible. Estimates of the mass and performance have been provided. It is evident that the main properties of hydrogen that affect the aircraft configurations are the high heat of combustion, effectively reducing the fuel weight by a factor of $\approx 2-3$, and the low density of the fuel. Despite the large fuel volume, the results show that the unconventional LH₂-fuelled Twin-Boom aircraft offers much promise particularly if the designs are optimised with particular emphasis on detailed local design. The benefits of the hydrogen fuel can be exploited even further and could enable overall weight savings to be achieved.

The Twin-Boom has proved an excellent basis on which to base the conceptual design because it possesses conventional and unconventional characteristics enabling valid and credible estimates to be made of its mass, size and performance. In monetary terms, it also offers less development risk – a significant consideration given the cost of developing and manufacturing new aircraft today.

The Twin-Boom has offers a good structural solution combining the structural bending relief of the booms with their fuel storage ability. The disadvantage is the increased wetted area which increases the profile drag which becomes significant at high subsonic speeds.

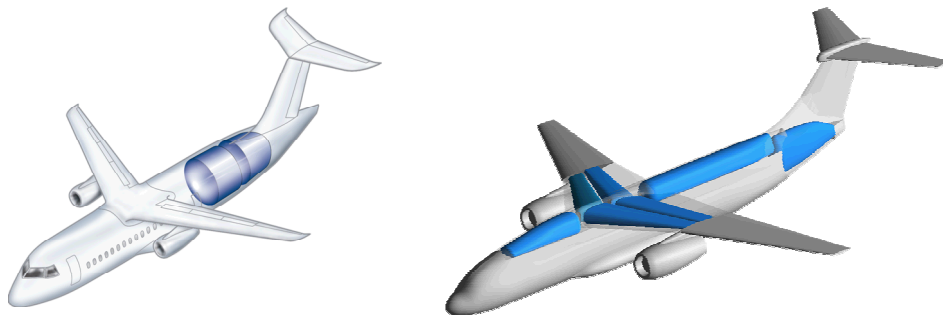
The Twin-Boom is structurally efficient but is less aerodynamic favourable as well as possesses a large cg travel range (as fuel is used).

Although the configuration concerned a medium-range aircraft, it is estimated that a shorter range LH₂-fuelled aircraft would be expected to yield better results for the

Twin-Boom. This is mainly because the lower fuel required would mean more slender booms, and therefore less drag. However, the shorter cruise segment means the benefits of the LH₂ fuel are less pronounced.

Unconventional configurations have a lot against them – many decades along with billions of pounds have been spent designing, producing and operating the classical configuration. This has resulted in a very well refined machine offering excellent efficiency, against which any new design must compete. A major problem is the lack of experience in certification, operation and construction of novel aircraft resulting in a lack of understanding of what makes a “good” design. While any novel configuration may prove to be more efficient and environmentally friendly, there are many challenges to be overcome before the design can become operationally successful.

As kerosene is transitioned to liquid hydrogen, initial configurations of hydrogen fuelled aircraft are expected to be ‘conventional’ (Figure 9-1).



Regional Aircraft (Fairchild Dornier)

Medium Range Aircraft (EADS Airbus)

Figure 9-1 - ‘Conventional’ LH₂-fuelled aircraft (CRYOPLANE, 2000).

LH₂ aircraft ground operations

Chapter 6.0 provided a thorough definition of the ground operations that would be required at an airport to support a LH₂ aircraft. The turnaround and maintenance operations have been explained comparing current procedures with those that would be required to support a LH₂ aircraft. As expected, modifications and new ground support

equipment, as well as new operational procedures will be required, to sufficiently support the aircraft during turnaround and undergoing maintenance. So far there appears to be some obvious areas where the activity will change, and there are those areas which will depend on the system employed as well as more detailed specifications and safety issues.

Not surprisingly, among all the turnaround activities, the refuelling procedure will be subject to the most change. Nonetheless, based on average refuelling times and the condition that the aircraft is refuelled while passengers are disembarking, the time to refuel is minimised. Refuelling requires consideration of boil-off – a requirement that did not exist. Changes in the rest of the turnaround equipment/procedures are small by comparison. Some minor modifications may arise because of a particular configuration or because of the availability of a new fuel e.g. fuelling all ramp vehicles using LH₂.

It is so far evident that LH₂-fuelled aircraft can be refuelled at gate positions exactly like conventionally fuelled aircraft, i.e. while turnaround operations are performed, passengers loaded, and baggage is loaded. Turnaround time should also be of a similar order as existing times.

Most procedures will remain the same, such as aircraft parking and towing, passenger disembarking, cleaning, catering and galley services, baggage and freight handling, toilet and potable water servicing, and ground power. For all procedures there are common requirements such as the necessity to negate any spark emission vehicles from the immediate area. Most equipment currently used to perform these service functions are common to many different aircraft due to their flexibility. Therefore, the same equipment and hence the same procedure may be adopted for the changeover to LH₂ fuel and even to the Twin-Boom aircraft. The various access, lifting and handling platforms will thus on the whole remain much the same.

The current interface between the kerosene fuel supply and the aircraft fuel tanks will change as will most, if not all, of the fuel system components. Additionally, consideration is required concerning what to do with the boil-off, the importance of insulation, and the need to provide venting without allowing direct contact of the fuel with oxygen.

Some changes will be necessary regarding eliminating the possibility of hydrogen gas accumulation in confined areas in maintenance facilities i.e. in hangars. Some new equipment will be required including test equipment which will need to be specially adapted to service LH₂ components. Fuel tank repair equipment will be new because of the new tank structure formed of separate tank walls, insulation etc. They will also probably need a certain degree of modification to be able to accommodate new tools and test equipment for the LH₂ aircraft and their components.

Based on knowledge of the required turnaround procedure, a final turnaround diagram can be drawn as shown below in Figure 9-2.

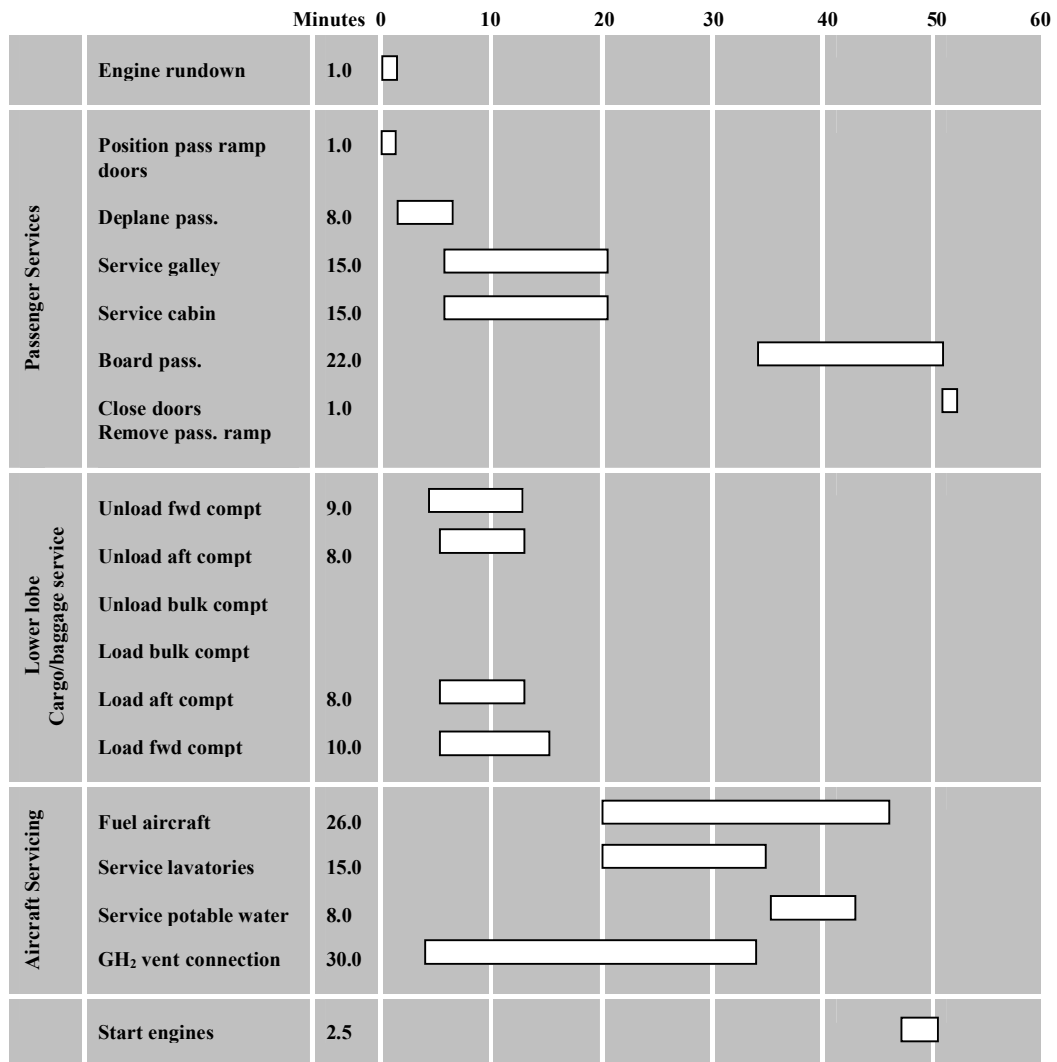


Figure 9-2 - Turnaround diagram for LH₂ aircraft.

We can compare this turnaround time of just over 50 minutes to current ground times for selected European airports as shown in Table 9-1.

<u>Airport</u>	<u>A320</u>	<u>737-400</u>
Frankfurt	0:50	0:50
Munich	0:35	0:35
Berlin	0:40	0:35
London Heathrow	0:55	0:50
London Gatwick	0:50	0:45
Paris	0:45	0:45
Amsterdam	0:50	0:50
Brussels	0:40	0:40
Madrid	0:50	0:50

Table 9-1 - Minimum ground times (MGT) for selected European airports (*Sanchez, 2001*).

Overall, the turnaround time is $\approx 5/6$ minutes longer than a standard turnaround of ≈ 45 minutes. This caters for connection/disconnection of GH_2 vent recovery, configuration difficulties e.g. high location of fuelling tanks, more awkward access etc., and added safety measures for the hydrogen fuel.

Overall, the demand for totally new and unique facility/equipment concepts is not extensive, but the use of LH_2 fuel in air transport service will clearly require some special facilities and equipment considerations relative to operation of the LH_2 fuel system, the aircraft ground support services, and aircraft maintenance.

Modification of an existing airport to incorporate the capability of servicing transport aircraft fuelled with liquid hydrogen is practicable, and if proper safety measures are observed, it is expected that the turnaround will be as safe and efficient as it is now with kerosene aircraft.

LH₂ aircraft certification

Chapter 5.0 highlighted those airworthiness regulations that would be subject to change as a result of the change to LH₂ fuel. For unconventional aircraft configurations, aviation authorities prescribe **special conditions** to assure an adequate and appropriate safety standard. These special conditions are agreed upon between the manufacturer and aviation authorities. Concorde, which is unique in its category, was certified by making use of a very large number of special conditions. Currently, hydrogen is mainly used in space applications where engines and aircraft have a limited (sometimes one) number of flight cycles, unlike civil or military applications where a large number of flights must be scheduled.

Unsurprisingly, the main certification issues to arise involve those issues concerning the fuel and associated systems and tanks. Not only must it be proven that the tanks can withstand impact, i.e. their structural integrity proved, but also it must be known what the effect of such an impact is. Hydrogen leak detection is vital around all systems. Certain properties of the hydrogen have highlighted the need for new regulations, and these should be developed and refined over time as operational experience is gained.

The following can be concluded:

- Special requirements must be taken into account concerning tank design. The tank must withstand defined vibrations and loads and pressurisation loads, and bird impact prescribed in the regulations. These should all be matters for extensive testing.
- Operational aspects are critical, such as ground vehicle collision damage and safety issues when on the ramp area.
- The effect of hydrogen on fatigue life and embrittlement of metal and aircraft components and requirements concerning the tank insulation are a critical area for concern and require testing.

- Early warning hydrogen leakage detection means must be developed for airport operators.
- Safety is an extensive area for consideration concerning all stages from production at the liquefaction plant right through to delivery to ramp areas and maintenance hangars.
- Hydrogen requires a very small minimum amount of energy for ignition and a shock wave caused by a temperature change, or resulting from a tank rupture can be sufficient to ignite hydrogen.
- A rise in the fuel tank temperature may cause a large pressure increase that can result in rupture and tank explosion.
- The temperature of the hydrogen fuel must be low enough to avoid autoignition **and** minimize boiloff. In addition, we can have no stagnant cross-feed lines (hydrogen will evaporate). We therefore need a different system architecture achieving the same purpose.
- Ice will form at the very low temperatures causing a hazard if it accumulates since it may separate in-flight, perhaps with enough mass or inertia to cause structural damage.
- Regulations prescribe amount, type and temperature of contaminants in kerosene fuel but not for LH₂ fuel which needs evaluation. Vents are also mentioned, but must be updated for specific hydrogen problems and properties.
- Adequate instrumentation needs to be provided encompassing additional sensors required to sense the necessary hydrogen properties, indicative of normal operation.

Hydrogen production, storage and delivery

Chapter 7.0 has provided a discussion of the size of today's hydrogen liquefaction facilities. It has been shown that the size of current liquefaction facilities are inadequate to meet demand for today's air transport network; however it has been shown that larger facilities are technically feasible based on an incremental increase in the size of modular liquefaction facilities. Thus, a short-term possibility is to build a number of

modular facilities to satisfy the total requirement. A cost analysis is required to decide whether to recycle the boil-off gases or dispose of them. Land availability also poses an issue.

Hydrogen supply to/from the airport may initially be by trucks/tankers and then over time by pipelines and hydrants similar to those used to transport and supply NG. A possible arrangement involves receiving GH_2 via pipeline at the airport boundary, installing a liquefaction and storage complex, and piping LH_2 through pipes in a closed loop around the terminal area to provide means for fuelling aircraft at gates.

The risk level with hydrogen is more or less equal with kerosene, but the nature of the hazards are different. Hence, the safety precautions and operational procedures, in some cases will be different. The following need to be considered:

- Liquefaction plant and storage facilities at the airport must be separate and located far enough from active runways, to avoid hydrogen ignition in the event of a crash during take-off/landing - a critical time in the aircraft flight.
- Storage tanks should preferably be protected by a surrounding dyke or pit. Minimum distances between tanks and dykes and buildings should also be observed.
- Clearances between liquefaction, storage plant and process equipment, passenger terminal, ignition sources, public ways, buildings etc. must also be observed.
- Vacuum loss detectors and heat sensors should be installed along pipes particularly in enclosed areas.
- Over-stressing and excessive pressure build-up in the distribution and collection piping should be avoided e.g. pressure relief valves.
- The best method for hydrogen fire protection is to interrupt the supply. The LH_2 tanks should be equipped with remotely controlled isolation valves as close as possible to the tanks.

- Dyes can not be added to hydrogen fuel at 20K because all additives would solidify so leak detection systems are necessary.
- Fuel system must be grounded during refuelling.
- Establish a safety exclusion zone. Metal-wheeled equipment should be prohibited in this zone. There should be a clear path for the bowsers in case of an incident.
- There should be emergency-stop buttons on hydrant stands, emergency phones, and a person responsible for the operation present.
- In the event of a spillage, all persons must be evacuated, established fire fighting measures carried out, and electrical equipment in use in the aircraft, e.g. Radar, HF equipment, turned off and connection and/or disconnection of electrical equipment prevented.
- Fuel zones established 6m around fuel vents, fuelling hoses and fuelling equipment. Any naked flames, such as matches, lighters, welding equipment etc. must be switched off.
- Vehicles must not be parked under or in close proximity to the aircraft fuel tanks.
- Hydrogen may be distributed to hydrants along the ramp or it may be supplied directly to fuelling tankers which provide the interface for aircraft refuelling. It is more advantageous to install a hydrant system at an airport because of the reduced operating costs, the increased safety, and the reduced likelihood of contamination during refuelling. On the other hand, pits are fixed in location, limiting aircraft position and offering little flexibility. Although the investment cost of constructing hydrant system are several times higher than purchase of several tankers/mobile dispensers, its operating costs are lower and its service life longer.
- GH_2 may be supplied via pipelines. Several lines up to 1 km or more in length exist in the refinery industry. Alternatively, it may be transported using tankers or rail.

It has been shown that LH_2 fuelled aircraft are a practical way not only to reduce the emission of the greenhouse gas carbon dioxide, but to avoid it completely, and despite

their larger emission of water vapour, will contribute to the greenhouse effect by magnitudes of order less than kerosene fuelled aircraft.

Safety

Chapter 4.0 provided an in-depth qualitative discussion of aircraft and airport specific safety aspects. Hazards relating to the LH₂ production, storage and distribution have been analysed. The main hazards of the hydrogen fuel relate to failure of pipes, tanks and connections which may result in hydrogen leakage and which poses an additional hazard by the formation of a flammable mixture with ambient oxygen. To avoid this, venting and the use of hydrogen gas leakage sensors are crucial safety measures. In addition, redundancy and material compatibility must be observed to ensure safe continued operation in case of a fault or hazard.

Hydrogen release alone does not cause accidents, since it always requires an ignition source. Therefore, potential sources of sparks must be removed from the immediate area and equipment grounded. Elimination of ignition sources is not entirely practical so the hydrogen system needs to be designed such that the potential for a leak is minimised, particularly in those areas which are critical. Even if there are no tank leaks visible there may still be a hydrogen discharge.

Properties of the fuel such as its low temperature can cause embrittlement and therefore poses a hazard to systems and components should there be a leak. Fuel temperature in the tanks must be limited not just to the auto-ignition temperature but also to prevent boil-off as far as possible which would cause high pressure rises and a potential risk.

The low temperatures are likely to cause ice accretion with the risk of freezing of equipment and degraded operation of valves, and operating systems. There are many potential problems which could occur due to leakage at valves, joints etc., causing an

increase in pressure and danger of explosion. A leak resulting in a sustained fire is primarily governed by flame radiation. Unfortunately, contrary to hydrocarbon fires, pure hydrogen flames are not visible.

The main issues regarding hazard prevention includes provision of:

- i. adequate insulation and ventilation
- ii. system protection by safety cut-off valves
- iii. monitoring and leak detection of pressure, temperature etc.
- iv. inerting equipment
- v. system redundancy
- vi. electrical grounding and safety area excluding potential spark sources

Hydrogen fuelled aircraft will be at least as safe as conventional kerosene aircraft, and the chance to survive a post-crash fire will be much better;

10.0 CONCLUSIONS

It is a truism that the operating costs of liquid-hydrogen fuelled aircraft will one day be competitive to that of fossil fuels. Many other 'external' issues lean favourably towards hydrogen fuel which offers the prospect of a cleaner, renewable energy source and one which, in the future, is potentially cheaper. Clearly, there is indication that use of Liquid Hydrogen, produced on the basis of renewable energy, has the potential to reduce the impact of civil aviation upon the atmosphere, both locally and globally (greenhouse effect).

The main policy drivers for change in the energy and transport sector and technology mix are the worldwide need to respond to a perceived threat by man-made climate forcing, and the need of western economies to ensure the security of their energy supply. Both of these requirements pose significant strain on key economic sectors such as aviation, being vulnerable to disruptions of the energy supply chain.

To a certain extent the initial price of the aircraft (and engine) is set at what the customer will pay (rather than their true cost) since it is a well established policy of aircraft manufacturers to set a low initial price when introducing a new design to enable the manufacturer to gain market penetration. The price of an aeroplane seems to suit the market and is not simply calculated from the design and production cost. The LH₂ Twin-Boom may well be more desirable to operators who may subsequently be willing to pay extra.

As domestic oil supplies diminish and prices escalate, aviation will need to consider the implications of relying on liquid hydrogen for its aviation fuel needs. Fuel is a prominent factor in the direct cost analysis. Next to depreciation, fuel costs represent the most significant cost parameter in the design.

In order to successfully introduce the Twin-Boom into service, advances in technology and the inherent properties of the fuel must be exploited. Much technical effort is required into building confidence in new designs or methods before they are accepted for production, particularly as aircraft design decisions have a significant influence on the initial aircraft cost and the operating expenses over its lifetime. An important starting place however is to identify the outstanding technical issues that require further R&D as listed in Chapter 11.0.

A brainstorming session in Chapter 3.0 yielded the Twin-Boom configuration which was developed from a blank sheet of paper and underwent conceptual design providing estimates of mass, size and performance. This has shown that not only is an aircraft that operates on LH₂ fuel technically feasible from a design aspect but that the benefits of the LH₂ combined with the unconventional configuration offers potential for the future. The benefits of such a combination will no doubt be improved upon as the design is optimised further. Expectedly, there is a need for much more R&D work to make the technology ready for routine commercial operation. Under today's economic conditions, hydrogen is not yet economically competitive. Furthermore, the DOC was estimated and it was shown that the unit cost increased. This was as a result of the increased R&D including flight testing activities necessary but was mainly due to the increased fuel cost. Despite this, however, the Twin-Boom offers a good solution (and potential) bridging the gap between unconventional and conventional. The technical challenges have been understood, and known conceptual design principles can be applied for new components.

The equipment and procedures necessary to support a LH₂-fuelled aircraft at an airport was defined and in addition it was demonstrated that the additional equipment required to support such an LH₂-fuelled aircraft on the ground is by no means extensive. This is a very important result since if the capital cost outlay of providing additional support

equipment for LH₂ fuel is minimised then this serves to strengthen the argument of using LH₂ fuel.

The safety analysis and the evaluation of the certification requirements requiring change when switching to LH₂ fuel has also shown that although inevitable changes will be required, these changes will be minimal with hydrogen fuel expected to be at least as safe as kerosene. This is supported by the fact that LH₂ has been in successful and safe use with the Space industry for many decades. The main hazards were identified and it was seen that there is a trend whereby similar hazards are present for different areas of the infrastructure. Many of these hazards relate to leakage or rupture of seals and pipes.

11.0 RECOMMENDATIONS & FUTURE WORK

11.1 *Hydrogen Safety*

- As an initial approximation, a 100-metre radius represents a satisfactory estimate of the hazard distance of a medium-range LH₂-fuelled aircraft with full tanks during normal operation.
- Reliable containment and transfer equipment, ventilation systems and leak detection devices in hydrogen systems are the first step in preventing serious accidents.
- The fuel system should be designed and arranged to prevent the ignition of fuel and fuel vapour within the system. Sparks by the process of conduction or induction should be prevented by all means in areas with flammable vapours.
- Vent outlets and the jettisoning system should be designed and located such that they will not experience electrical discharges. The vent outlet should be located in a zone with low possibility of direct contact.
- Each zone containing fuel system components should be protected against ignition.
- Possible sources of ignition including electrical faults, overheating of equipment and malfunctioning of protective devices should be located and eliminated. If electrical equipment may come into contact with flammable vapours it should be so designed that the risk of ignition under both normal and fault conditions is minimized.
- All surrounding structure and vital systems pertinent to the fuelling systems should be adequately protected against structural damage.
- Thorough and extensive operator training is vital, as are clearly marked areas and safety bulletins

There are many different possible scenarios as well as many possible sources of accident-related hazards occurring whether within the system or elsewhere. This indicates the magnitude of identifying all the safety-critical areas and addressing them

with preventative and protective methods. The very first step is to identify where those areas may lie. Taking this a step further has shown some possible scenarios of what may happen in the event of an accident occurring.

11.2 *LH₂ aircraft configurations*

- In the short-term transition to hydrogen, aircraft will have a more or less “conventional” appearance, although the internal systems will be very different.
- Longer-term, hydrogen-fuelled aircraft will be designed from the outset with the large fuel volume in mind and so will be more unconventional. This will maximize benefits of both fuel and configuration, particularly as experience would have been gained in the operation of LH₂-fuelled aircraft.
- From a safety point of view, the fuel tanks should not be placed in close proximity to the passenger cabin. This is also important from a passenger acceptance point-of-view.
- Several tanks are required for redundancy.
- The biggest challenge in the design of LH₂-fuelled aircraft is the fuel tanks. Efficient tank design will prove critical in terms of safety and performance by keeping weight and wetted area down, and providing structural protection, insulation and venting.
- The resultant increase in profile drag and reduced L/D drag ratio adversely affects the Twin-Boom performance.
- A substantial weight saving is possible due to the higher the low specific energy of LH₂ despite the increase in volume.
- Careful local design and optimisation is crucial in the minimisation of drag and reduction of weight if achievement of a configuration design that can not only meet but exceed today’s well refined designs is to be developed.

11.3 *Hydrogen aircraft certification*

Present regulations need modification to adequately account for all the differing aspects of operating LH₂ aircraft and include the following aspects:

- Fatigue of all aircraft components is critical. The fail-safe approach is recommended, unless design complications dictate this to be unfeasible or economically unsatisfactory.
- In terms of the tanks, tests are required to confirm the strength and ability of the tank to withstand impact.
- Temperature effects need to be controlled and lightning protection provided (and certified).
- Insulation is also a critical issue for concern as not only must leaks be prevented, they must also be detected to prevent hydrogen boil-off or the formation of ice, this includes onboard hydrogen leak detection. Appropriate measures must be fully specified to eliminate a fire should one occur.
- Adequate venting and instrumentation is needed.
- Because of the large surface area of the tanks, they are more susceptible to damage or rupture which could be catastrophic; therefore the regulations need to ensure more measures are taken in the aircraft design to provide adequate protection.

Some properties of the hydrogen will dictate requirements recommended by airworthiness regulations; however, many current regulations will apply in the transition to either conventional or unconventional aircraft configurations such as the Twin-Boom. It remains to be seen whether it will be more difficult for the unconventional aircraft to meet the requirements which may favour a more conventional layout.

11.4 *LH₂ aircraft ground operations*

- It is recommended that parking and fuelling LH₂-aircraft be performed close to the terminals to ensure lower turnaround times.

- There may be a degree of flexibility regarding the type of refuelling concept used, whether hydrant or trucks, and will depend on infrastructure, cost impact etc.
- In order to reduce surface traffic across the apron and improve apron utilisation and reduce ground time, fixed ground ‘systems’ can be used with the added benefit of increased apron safety. Possible installations of this concept includes: LH₂ hydrant dispensers, ground power, potable/non-potable water supply, compressed air, air conditioning. Local environmental impact is lower, due to lower noise and exhaust emissions.
- New equipment required to service an unconventional aeroplane configuration such as the Twin-Boom is limited since most current equipment can be adapted to aircraft of different heights and to a certain extent, different shape.
- Nose-in parking is recommended for LH₂ aircraft where guiding and gate operating systems remain the same.
- To prevent build-up of static electrical charges, onboard electrical equipment should be grounded throughout the turnaround procedure.
- Before shutting down the engines, LH₂ fuel flow must be cut-off to avoid hydrogen remaining in pipelines. Consequently, ice could build up or hydraulic fluid could become very viscous making engine starting difficult.
- LH₂ aircraft should use existing terminal facilities where possible. However, major reconstruction of the terminal may be required to accommodate LH₂-fuelled aircraft, particularly those with an unconventional configuration.
- Currently the APU which operates on kerosene is only allowed in some airports for engine starting. A LH₂-APU would eliminate most, if not all environmental disadvantages associated with current APUs.
- De-icing/anti-icing operations may require some changes. Current methods consist in using hot air or heated fluids to remove ice from surfaces and avoid future accumulation. There are alternatives involving the use of special chemicals, which react to the ice. However, in general these fluids are generally not environmentally friendly.

- Airport and liquefaction plant and distribution system personnel should be trained to be highly competent in LH₂ system operation and learn to recognise failures, malfunctions, know emergency procedures etc. Training must be a continuing process for all personnel involved in refuelling/defuelling operations and in general hydrogen handling. Only trained personnel should be allowed to work in these areas, and should receive training on the characteristics of hydrogen, potential hazards, how to recognise unsafe conditions and procedures for emergencies. Specific training for each hydrogen distribution phase must be developed.
- Maintenance of the LH₂ distribution system should ideally be performed by the same persons operating the liquefaction, storage and distribution systems.
- If vacuum jacketed pipes are used then new equipment will be required for testing and maintenance to ensure the integrity of this insulation.
- The required servicing and testing of system valves and pumps indicates a need for a small cryogenic test facility.
- Minor maintenance is carried out in the same way as current aircraft, although extra special care must be taken in the detection of fuel leaks.
- Alteration to hangars to accommodate LH₂ aircraft should not be great, although ventilation is required. There may also be a need for a GH₂ recovery line connected to the liquefaction facility. If the quantity of GH₂ is not so large, then the excess gas could be ‘burned’ off. Economics will dictate the method used.
- Spark ignition engines or any device that could create ignition of a GH₂-air mixture resulting from a spill or leak should be excluded from an area of certain radius of any components involved in the fuel transfer. Alternatively, diesel powered, air started GSE should be used to avoid ignition sources in the vicinity of the fuelling operation.

11.5 *Hydrogen production, storage and delivery*

- Redundancy must be provided in case of distribution system failure to prevent any disruption and limit the impact of the transition to hydrogen on the air terminal

facilities and airline operations.

- Long term developments will need to use production methods from renewable sources.
- Liquid hydrogen is to be stored at the airport in tanks which should possess structural protection.
- Initial hydrogen transportation may be via tankers or fuellers which offers a low cost initiative. This should then be replaced with fixed fuel hydrant systems supplied by pipelines, offering lower operating costs and better safety.
- Minimum distances must be observed between tanks and buildings, liquefaction and storage plant and process equipment, passenger terminal, ignition sources, public ways, buildings etc..
- Fuel zones established 6m around fuel vents, fuelling hoses and fuelling equipment. Any naked flames, such as matches, lighters, welding equipment etc. must be switched off.
- Vehicles must not be parked under or in close proximity to the aircraft fuel tanks

11.6 FUTURE WORK

Because the scope of introducing LH₂ into full airline operation is very wide, there are many further areas of work which need to be explored. Some of these are suggested below:

Aircraft Design

- ❑ Further study into **family** concepts for unconventional aircraft
- ❑ Detailed design particularly of aerodynamic and performance data.
- ❑ Study into effects of increasing engines to 3 on Twin-Boom.
- ❑ Practical Configurations for **all** categories of airliners identified – no “standard solution” but logical sequence of solutions depending on design range.
- ❑ Detailed design and evaluation of tanks.

- ❑ DOC need to be evaluated as accurately as possible. The calculated DOC will be time dependent, since the cost of oil will rise in the future making the cost of LH₂ production more attractive. Allowance needs to be made for changes in design, and other technical and operational issues.

Transition

- ❑ Detailed scenarios analysed, including worldwide/regional/local aspects, political/legislative aspects
- ❑ Detailed study into the environmental effects of a typical configuration.

Safety/Certification

- ❑ Safety needs experimental confirmation e.g. testing structural integrity of fuel tanks by firing bullets at tank, experiments with drop weights and fire engulfment (made in the past on LH₂ tanks for cars). It is by no means obvious that tank penetration by engine or propeller debris will cause a tank explosion as there is no air in the tank. The tank will leak heavily if damaged, and the hydrogen leaving the tank will be ignited, but will there be an explosion?
- ❑ The fuel jettisoning system will perhaps be a more difficult to design since the fuel can not be simply pumped out of the tanks. One possibility is to ‘burn’ the fuel via a catalytic combustor either in addition-to or instead-of fuel jettisoning depending on the achievable rates.
- ❑ Lightning discharges will be strong enough to ignite any sort of fuel provided there is air/oxygen available but a hydrogen tank contains just hydrogen liquid and gas no oxidizer. Will this reduce risks from lightning?
- ❑ It is certainly true that evaporating LH₂ could rupture the tank if safety devices do not relieve pressure. But is this strictly an “explosion”?
- ❑ Is a hydrogen engine more sensitive to bird strikes than a kerosene engine?

- ❑ In a LH₂ system, we can have no stagnant cross-feed lines (hydrogen will evaporate). We therefore need a different system architecture achieving the same purpose. How is this issue to be resolved?
- ❑ Feasibility of infrastructure aspects demonstrated.
- ❑ Practical engine layout identified and feasibility of Low NO_x combustion.
- ❑ Experimental investigation into contrail formation/characteristics.

11.6.1 Final remarks

It is not feasible to establish a fixed hard time schedule for introducing hydrogen into aviation, but initial transition may be estimated to begin in 2025.

The introduction of liquid hydrogen as a new fuel for aviation would be, and still is, a challenging concept. This thesis highlights many of the issues which need consideration before a mid/long term plan of action is taken. It also shows on a conceptual basis that there are no show stoppers. Political actions aimed at protecting the environment or events leading to the disruption in oil imports will create economic conditions prompting airlines to introduce the new fuel. Rather than wait for such events, which at the very latest will happen due to the depletion of fossil fuels, it is the aim (and hope) that the technical issues are addressed providing a solid foundation to initiate larger scale activities for developing safe aircraft using liquid hydrogen as a fuel.

This thesis has provided an understanding into the conflicting requirements and improved the understanding of the technical issues and challenges faced in the introduction of LH₂ as an aviation fuel. More importantly, this thesis has demonstrated the technical feasibility of LH₂ aircraft and clearly defined the enormous potential and advantages to the economy and environmental sustainability that is to be gained.

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Appendix A LH₂ Fuel Tank Example

The net effect of the increase in fuel tank weight compared against the lower fuel weight can be demonstrated by an example.

The Airbus A310-300 uses 61100 litres (61m³) of fuel (*Jenkinson, Simpkin, Rhodes, 1999*). The density of kerosene is 0.811 g/cm³ (from Table 2-2) which is equivalent to 811 kg/m³. Therefore the fuel mass = 49471 kg, since mass = density x volume.

Now if we switch to LH₂ fuel, we would approximately need 2.8 times less fuel or 17688 kg; a weight saving of over 31800 kg. Whereas the kerosene fuel is stored in the aircraft wings, the LH₂ fuel must be stored in separate tanks requiring a volume of 17688/71 (kg/m³) = 249 m³. Increasing this by 10% to allow for extra boiloff and unusable fuel means we would require a net volume of 274 m³.

Let us assume we have two external tanks, each with a fineness ratio of 7 (i.e. length/diameter = 7). This fineness ratio provides a favourable aerodynamic shape for fuselages (*Howe, October 2000*) and we can assume this for the slender and cylindrical fuel tank booms each formed of a cylinder with half a spherical shell at each end. This results in each tank having a length 19.8 m and diameter of 2.8 m (i.e. to provide a total fuel volume of 274 m³ for two tanks). The surface area, S, of each tank equals 133.5 m².

As the tanks are made of Aluminium Alloy, their weight can be simply estimated just as that for a fuselage since they are pressurised cylinders using the following formula (*Howe, October 2000*):

$$M_F = \frac{P}{f} S(9.75 + 5.84B)$$

Where

P = limit pressure = 1.4 bar

f = the allowable working stress to 100MN/m^2 . A value of 1.0 is reasonable (*Howe, October 2000*)

B = diameter = 2.8

S = surface area = 133.5 m^2

Therefore, $M_{\text{TANK}} = 6098\text{ kg}$ (each)

Using Polymethacrylimide insulation with a density of 2.2 lb/ft^3 (16.018 kg/m^3 *Colozza, 2002*) and assuming we require 5 inches of insulation (*Brewer, 1991*) or (0.127 m) means that the total volume of insulation required would be 17 m^3 including the spherical ends of the tanks. This results in an insulation mass of 272 kg for each tank.

Thus, the total mass for each tank including insulation = $6098 + 272 = 6370\text{kg}$ or 12740kg for both tanks empty weight; or $30,428\text{ kg}$ for fuel and tank weight – a weight saving of 19043 kg . Factoring this by 15% to account for uncertainties and unknowns (e.g. increase in LH_2 fuel system mass) would still mean a fuel + fuel tank weight saving of $14,478\text{kg}$ for a medium-range LH_2 aircraft.

Appendix B GROUND OPERATIONS – CONVENTIONAL PRACTICE

Aircraft Parking and Docking

Immediately after landing, the aircraft will be docked under the aircraft's own power and moved out by a tug or towing tractor vehicle under responsibility of the ramp marshal or automatic guiding system. Tow tractors are available to handle aircraft up to 10⁶ lbs gross weight. The push-back procedure allows aircraft to be parked much closer to each other all "nose-in" to the terminal buildings. Jet efflux is directed across the apron and taxiway to minimise the effect on passengers and staff.

Towbars

Aircraft are generally moved by connecting a towbar to the front of the nose wheel. At crowded gate positions the tractor can be positioned behind the nose wheel enabling the aircraft to be pulled back from the terminal. Towbars are produced in wide and narrowbody configuration which use a common undercarriage design employing integral hydraulic pump, reservoir and actuator cylinder to adjust the operating height. Towheads can be designed to break free from the tow bar under failed conditions or to remain attached.

Tow tractors

These low profile (1.58m height) self-propelled vehicles can either have petrol, diesel, or electric powerplants. The limited height enables manoeuvrability beneath the aircraft fuselage. The purpose-built towing vehicles may also have a cab at either end for greater manoeuvrability and propulsion in either direction. During towing operations, the aircraft nosewheel is lifted hydraulically and locked in position close to the tractor's centre. The towing tractors can also carry accessories such as wheel chocks, fire extinguishers, snow ploughs etc. Towbarless tractors (TLT) dispense with the need for a tow bar by docking with and lifting the nosewheel, enabling one-man push back and towing.

Docking Guidance Systems

Aircraft parking and information systems provide accurate guidance information to the aircraft flight deck and flight information to ramp personnel. The system confirms the aircraft position to related equipment such as boarding bridges, fuel and other services.

A “push-pilot” is also currently in operation which runs on special tracks embedded in the apron surface to automatically move the aircraft nosewheel using electrohydraulic power. No towbars are needed and the complete operation is controlled by the operator.

Disembarking

There are several methods of transporting passengers to/from the terminal/aircraft. The passengers may walk from the aircraft to the terminal, powered mobile transporters or lounges (electric, diesel or petrol -powered) may be used, or most commonly used is the pier or satellite system which supports an extending passenger bridge. Stairs may be used which maybe self-propelled, truck-mounted or towable with diesel, electric or petrol engines. Many have an extendable top platform and incorporate stabilising jacks to operate in high winds. Some stairs automatically align with the fuselage contour using IR sensors, after which bumper limit switches prevent further horizontal movement. Passenger bridges link the terminal and aircraft and can move horizontally and laterally using a telescoping action. Some have T-sections enabling connection to both aircraft doors simultaneously.

Factors which affect the boarding of passengers include aircraft layout (seating arrangement and aisle width), number of exits, and passenger behaviour. It is common practice to use the aircraft exit at the front even though most aircraft have more than one exit. Due to the relatively fast times with which passengers can be offloaded, this does not form part of the critical path for turnaround times.

Cleaning, Catering and galley service, Baggage and freight handling, Toilet servicing, Water servicing, and General aircraft servicing

High-Lift Vehicles

These high lift vehicles can also be used for cleaning, catering and cabin service operations as well as transfer of baggage, equipment, passenger seats etc. when servicing aircraft. The number of teams assigned these turnaround tasks in general depends on the number of aircraft seats. The tasks may be dependent on the individual contracts with the ground handling company. Factors which influence the time required to perform the duties include type of service e.g. long haul, short haul, service offered by the airline, cabin layout, and manpower available.

Because of the height and weight involved in the scissors lift units, it is necessary to provide stabilising jacks on the chassis as the van sides expose a large area to prevailing winds and jet blasts which have the potential of tipping over high lift equipment.

Fresh water is carried on the aircraft for washing and drinking purposes and must comply with health regulations. Water is supplied from a trolley towed by a tractor or a self-propelled unit via a standard connection. The water is usually drawn from main pressurised water tanks, passed through filters cooled by dry ice or other means, and delivered to the drinking points.

General servicing includes minor faults that have been reported in the technical log and that do not necessitate withdrawal of the aircraft from service. Aircraft heaters are used and are trailer-mounted units designed to recover heat. They are used to maintain the internal temperature of aircraft to $\approx 5^{\circ}\text{C}$ overnight or 20°C during operations. They can also be used to heat iced exterior surfaces, portable accommodation, hangars etc. Power is supplied via petrol or diesel engines and can be incorporated as self-contained units

or by connecting to an AC power source using the electric prime movers. Additional equipment includes rubbish trucks, centralised preconditioned air systems, brake cooling carts etc. Since it is not practical to transport all motorised GSE to a refuelling depot, a small refuelling vehicle may be used which tours the apron area checking and refuelling the equipment even while the equipment is in use at the aircraft stand. General purpose transport vans or vehicles may be used to transport people rapidly from rest rooms to aircraft or from one aircraft to another frequently carrying spares or equipment.

Appendix C ENVIRONMENTAL ISSUES

Aside from providing an alternative resource to the fast-depleting resources of fossil fuels, a major advantage of hydrogen fuel is that it is much 'cleaner', mainly producing water as a by-product. It is therefore instructive to briefly look at some of these environmental advantages and to what extent aviation contributes to the global pollution problem. This appendix provides a useful insight to the main causes and possible solutions to the environmental concerns of the present and of the future.

Aircraft Pollution

Two reasons make aircraft pollution of particular concern. Firstly aircraft cause pollution in sensitive layers of the atmosphere. For example, engine emissions introduced in the stratosphere will typically have long persistence times and their effect will therefore be amplified significantly by comparison with the effects of the same pollutants injected in the troposphere. The greatest uncertainty, however, lies in predicting the extent to which aviation generates high altitude cloud. Although the effects of line shaped contrails (which presently cover $\approx 0.1\%$ of the Earth's surface) are well understood, the extent to which contrails promote large expanses of cirrus clouds are not. In order to sustain the ever-increasing growth in air traffic there must be a substantial reduction in the pollution.

C1 Global warming

There is evidence of significant increases in the atmospheric concentrations of several active greenhouse gases, almost certainly due to the use of fossil fuels and increases in transport (both land and air). It is estimated that the most significant and dominant greenhouse gas is CO₂ which is responsible for about two thirds of the direct radiative forcing. There are many other greenhouse gases, which like CO₂, remain in the atmosphere for a long time, and therefore have a long term effect.

	Source	Lifetime	Relative contribution to global warming
CO ₂	Fossil fuels, land use changes	100 years	63%
Methane	Agriculture	10 years	24%
NO _x	Combustion	150 years	10%
Chlorofluorocarbons	Production	100 years	< 10%
Ground level ozone	Transport, industry	3 months	<10%
Aerosol	Power generation, transport	2 weeks	

Table C-1 - Lifetime of different atmospheric pollutants (US DoE, Energy Efficiency and Renewable Energy)

What is the role of aviation in climate change and how should industry respond?

To answer this, we need to ask three further questions:

1. What are the likely levels of growth in aviation?

Predicting the long term growth in aviation traffic is difficult because it depends on many factors including global economic development, fuel prices, legislation, and development of infrastructure. The predicted growth in aviation assumes that air traffic is dictated by demand and not limited by development of infrastructure.

2. How do aircraft emissions affect climate as distinct from ground based emissions?

It isn't possible to separate out the impact of any single human activity, and to state its effect in terms of mean global temperature change. The most useful method of comparing possible impacts is to use radiative forcing which is estimated to be 0.05 W_m^{-2} for aviation measured in 1992. Although this does not sound very much, we should consider that the total radiative forcing of *all* human activities is estimated to be only 1.4 W_m^{-2} . Therefore, aviation accounts for 3.5% of the present human impact on mean global temperatures. However, it is predicted that by 2050, total forcing due to

aviation will rise by a factor of 4 to 0.2 W_m^{-2} , constituting 5% of the total effect of all human activities (*Jenkinson, Simpkin, Rhodes, 1999*).

3. What mitigating options are available to us?

The only option to reduce emissions is to use a cleaner and more efficient fuel. However, reductions in sfc and engine efficiency have just about reached a plateau with further reductions not being worthwhile in terms of the cost in achieving them.

The main impact from aircraft is at a cruise altitude of 9-13km which encompasses the upper troposphere and lower stratosphere and includes the boundary, known as the tropopause. At this altitude, aircraft emit various gases including NO_x , hydrocarbons, CO_2 , water vapour and SO_2 as well as soot particles.

NO_x emitted from aircraft can lead to the formation of ozone. Emissions of SO_2 and water vapour can lead to destruction of ozone in the lower stratosphere. Aircraft contrails may contribute to the formation of cirrus clouds which have the potential to affect the climate system because they absorb longwave radiation emitted by the Earth and absorb and scatter solar radiation.

C2 Airline emissions of CO_2

The main areas offering a potential reduction of airline pollution include technology, and improvements in air traffic control and management. By improving navigation and flight planning equipment, the shortest route and the most fuel-efficient flying techniques can be achieved by reducing the time to top of climb, cutting fuel consumption, and decreasing noise.

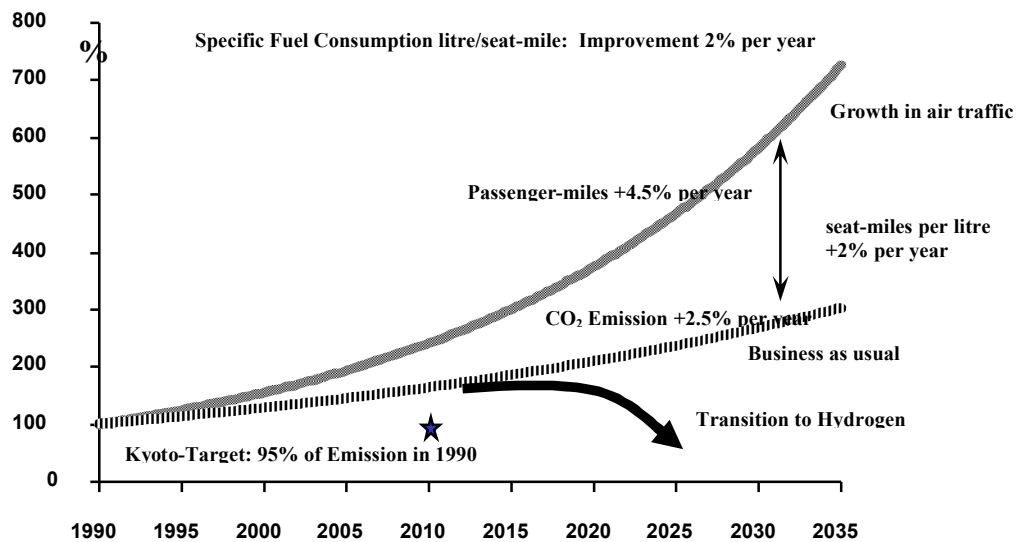


Figure C-1 - Three different scenarios illustrating possible future fuel usage by airlines
(CRYOPLANE, May 2000).

The solid black line estimates the trend when transition is made to hydrogen fuel. As more and more of the aircraft fleet transition to using hydrogen, then the CO₂ levels gradually decrease as time progresses due to less CO₂ production and existing CO₂ in the atmosphere disappears.

The vertically dashed line shows continued production of CO₂ by aviation leading to an increasing atmospheric level, based on today's requirements and negating the effect of air traffic growth.

The grey line shows the steep increase of CO₂ produced taking into consideration the predicted growth in air traffic.

One way to force operators to lower emissions is to use taxation. Aviation fuel taxes already exist in Japan at a significant level and in the USA at a lower level. However, this is not a long term solution and only serves to delay the increase of CO₂. It will also be met with opposition, particularly by airlines.

C3 Civil aviation noise

As well as pollutants, aircraft noise is also considered environmentally detrimental as it disturbs a significant number of people who live close to airports. It is tolerated due to the economic and social benefits that aircraft bring to society as a whole. However, the levels that are tolerated from individual aircraft must reduce to compensate for increases in increase of air traffic. The potential means of reducing disturbances are threefold:

- i. design of new aircraft and engines to significantly reduce noise
- ii. invoking a steeper approach path to reduce approach noise
- iii. directing greater proportion of aircraft movements to remote airports

The noise levels allowed by airworthiness rules are affected by both M_{TOW} and the number of engines. Aircraft have been able to meet more stringent requirements without significant economic penalty by using advanced materials and by reducing jet velocity from the nozzle by increasing optimum mass flow through the engines while maintaining thrust.

Acoustic absorbing material is used in the intake and exhaust. Blade and vane numbers have already been optimised and acoustic liners exploited, therefore engine design has evolved to a point where significant reductions in noise can only be invoked by novel engine designs. Modern aircraft are typically 20dB quieter than the first generation of jet aircraft.

C4 Renewable energy sources

Percent of primary energy

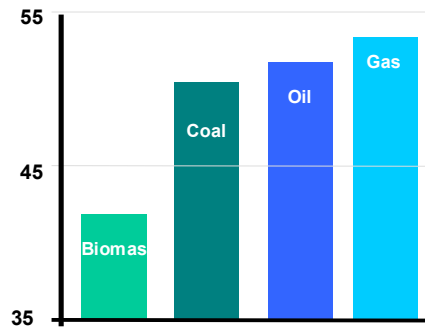


Figure C-2 - Percentage of different types of fuel contributing as a primary energy source (*CRYOPLANE, 2000*).

The figure above shows what percentage different energy sources contribute as a primary energy source. Renewable energy is still far from cost effective and at best is intermittent in its supply. However, the cost of renewable energy will decrease as time passes due to improved technology and more widespread use and they will become more attractive in their use, not just as a primary energy source, but also to be used in the production of hydrogen using electrolysis, which at the moment is far more expensive than using fossil fuels. As fossil fuel reserves are depleted they will become more expensive. The figure below shows the estimated decreases in cost for various types of renewable energy sources as time passes.

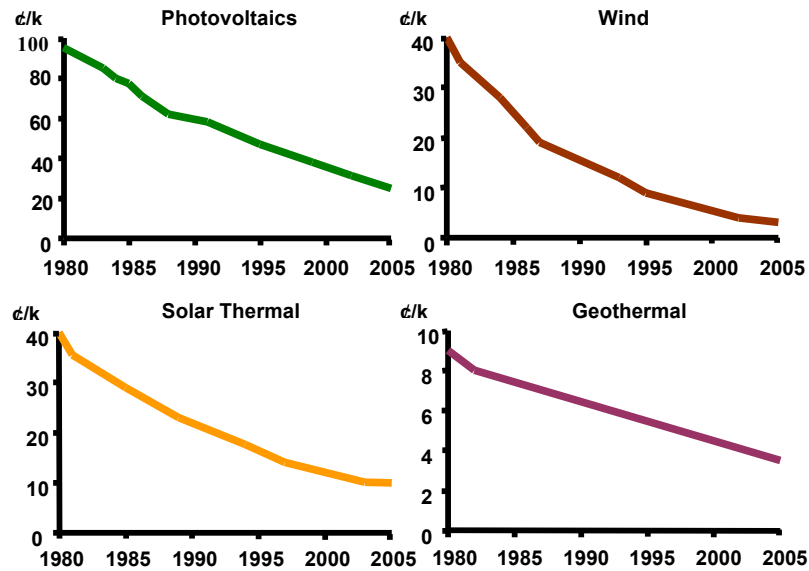


Figure C-3 - Renewable energy cost improvements for photovoltaic, wind, solar, and geothermal (*CRYOPLANE, May 2000*).

C5 Global warming potential

Before renewable energy can be used, it must be converted into a useful energy such as electricity and although the conversion process may not have any environmental impact, the actual distribution will. This is illustrated in the charts below.

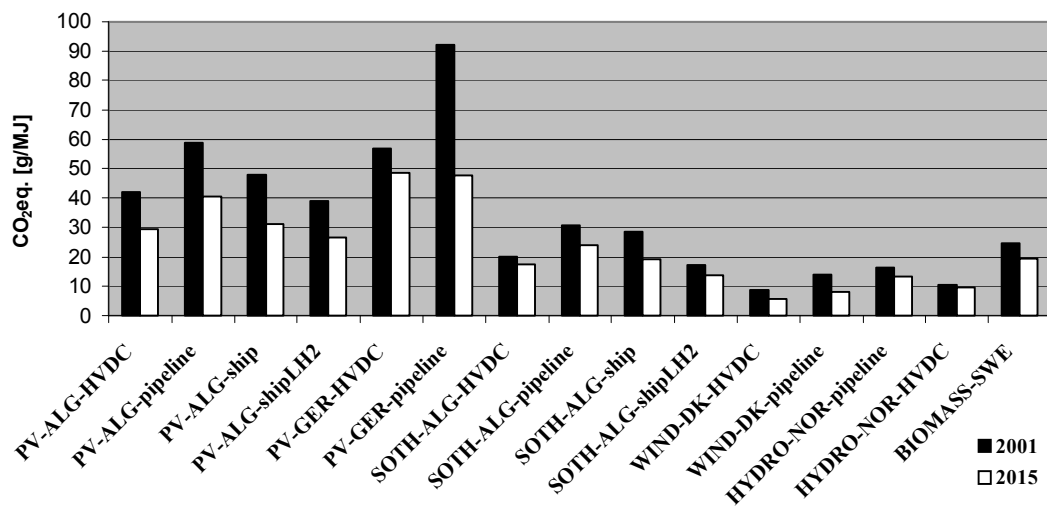


Figure C-4 - CO₂ emissions for different types of distribution methods and renewable energy types (*CRYOPLANE, May 2000*).

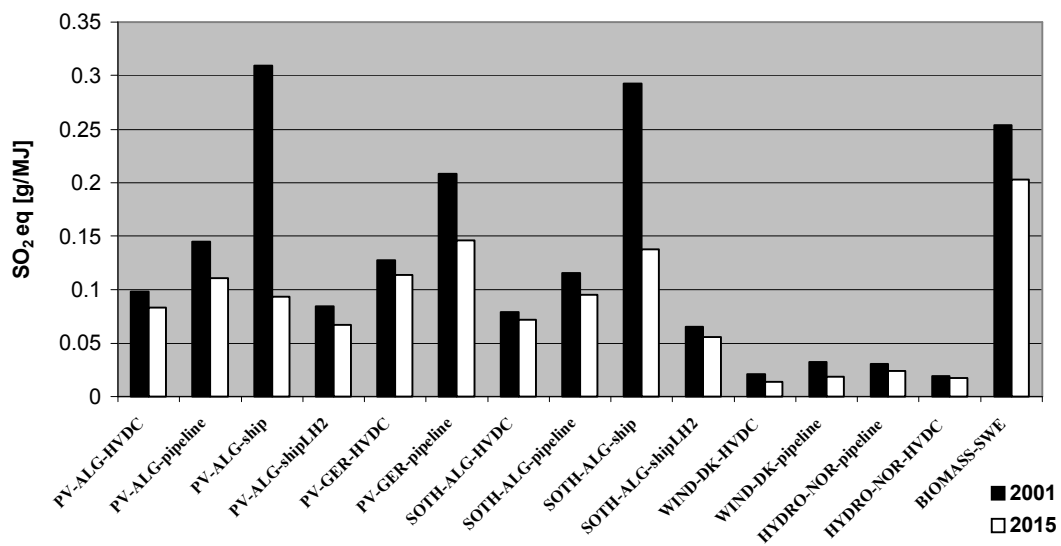


Figure C-5 - SO₂ emissions for different types of distribution methods and renewable energy types (*CRYOPLANE, May 2000*).

Key

PV	photovoltaic	ALG	Algeria	Ship	shipping
SOTH	Solar thermal	Ger	Germany	HVDC	High voltage DC
Wind	Wind power	NOR	Norway		
Hydro	Hydropower	DK	Denmark		
		SWE	Sweden		

This shows us that solar energy based technological systems for liquid hydrogen production including long distance energy transportation is more favourable in terms of greenhouse gas emissions and acidification potential. Wind and hydropower energy sources lead to very low emissions, even for long distance transportation. Biomass also leads to very low greenhouse gases but only if the biomass is produced locally to avoid transportation related emissions and with prospective gasification technologies.

C6 Conclusions

Oil resources are concentrated in a few regions, with the Middle East holding over 40% of the total oil reserves. Actual oil supply may never reach the last levels of depletion and may decline much earlier depending on competing fuel prices and environmental conditions. Conversely, oil supply could continue to expand at a slower rate of growth well beyond 2025 if efficiency measures, particularly in vehicles, were widely adopted. Current forecasts of non-OPEC oil production general show a permanent decline by 2010. Once non-OPEC production begins to decline many people expect prices to be increased significantly and permanently due to greater OPEC power (*Mikowsky, 1978*).

As for worldwide gas resources, there is much greater uncertainty as much less exploration effort has been undertaken. Gas prices are widely expected to rise over the

next two decades as more remote sources of supply are required and longer and more expensive pipelines are required.

Thus, the arguments for seeking and utilising renewable energy are overwhelming and as described there are a wide variety of potential methods for obtaining renewable energy. However, there is still uncertainty about the economic extraction of these energy types which will be affected by the available technology as well as other factors such as land availability, despite the fact that renewable energy costs have fallen substantially over the past three decades.

Although there is adequate renewable energy to meet all future energy needs, most of the renewable energy resources are intermittent, and so major advances in energy storage will be required for this potential to be useable. Hydrogen would be one potential solution.

Appendix D LH₂ SYSTEM SYNERGIES

Aside from the basic properties of hydrogen that make it very useful as a fuel, we can study whether there are any other useful properties of hydrogen which may be used for other ‘secondary’ functions. This chapter looks even further into the possibilities of using the inherent properties of hydrogen in gaining some benefits for any other part of the aircraft and/or its systems i.e. **synergism**. Upon examination of the hydrogen properties we can extract four useful properties (including by-products) which may be utilised, namely:

- electricity
- heat
- cold
- water

Most aircraft systems need electricity, but by cooling them to a low temperature, an effect similar to superconductivity occurs which can reduce power requirements and improve performance.

Although from a safety point of view, it’s not advisable to locate heat exchangers containing liquid hydrogen as cooling liquid, inside the passenger cabin, they may be placed in the tail, and the cooling ability be adopted to double as cabin and galley air conditioning.

D.1 Environmental control

If the water by-product of hydrogen fuel cell is consumable, it may serve as a means for water supply, bearing in mind that this will be at a high temperature. Because of the high temperature, the water is not useable without cooling down to a temperature suitably low to mitigate any risk of scolding.

If a fuel cell is used, the water vapour can be used for heating up the air and the hydrogen transported to the fuel cell to generate boil-off which could be large enough to provide environmental control. For aircraft with a flexible cabin layout, e.g. BWB, and for larger aircraft with multiple galleys, there may be less benefit overall to be gained from using liquid cooling, since this means that larger distribution is required and hence heavier piping combined with increased insulation, cost and boil-off losses.

D.2 Relaxed stability with tail tank

It may well be the case that since all LH₂ aircraft will have relatively large fuel tanks, managing c.g. travel becomes a likely and useful option, particularly with the Twin-Boom. This helps reduce trim drag and therefore save fuel. This system is already used in present aircraft and is a feature of many designs. Although the density of hydrogen is much lower than kerosene, the tank size/length could provide enough scope to use c.g. management.

D.3 Water of fuel cell anti/de-icing and for drinking/galley services

Instead of using hot bleed air from the engines, water vapour from the fuel cell might be used for the anti/de-icing system, since it will be at a high temperature. The system may also remain operational during overnight stops as the liquid hydrogen always boils-off at a steady (but low) rate even with insulation. However, it must be determined whether the capacity is large enough to de-ice the aircraft and so eliminating the anti-icing by the ground operators just before startup. Using water vapour also demands extra precautions to prevent corrosion or ice forming in the system. This requires testing and quantification.

As mentioned previously, the water by-product may be used in the galley for potable purposes subject to filtration and further processing, however, it has already been shown to be feasible in space programs.

D.4 Surface cooling with liquid nitrogen for drag reduction

A potential benefit of using boundary layer control (BLC) to reduce drag has been achieved on an experimental basis by several methods, the most popular of which involves putting holes or slots in the wing surface and applying suction. With adoption of LH₂ as fuel for aircraft, another option for achieving BLC is available using cryogenic wall cooling which doesn't possess some of the disadvantages of using holes in the wing such as clogging of the holes, but instead is able to utilise the low temperature already available and inherent in the fuel.

Theory shows that reducing the surface temperature of the nose section of an aerofoil reduces the drag by a few percent leading to reduced fuel consumption. For a kerosene-powered aircraft the additional power and weight required for cooling outweighs the possible gains. But a LH₂ aircraft possesses significant cooling capacity in cold fuel with the addition of an entirely new system. It is also possible that the surface cooling system be combined with the anti/de-icing system.

A more detailed study regarding the possible amount of drag reduction obtainable by cooling and a more detailed study about the risk of temporary icing conditions needs to be performed.

D.5 Summary

Overall, the most promising solution seems to be the replacement of the APU with fuel cells. It is also at a stage whereby it is technically feasible and would improve aircraft operation since it would run on the same fuel as that which supplies the engine. Water is also produced as a useful by-product which may save having to carry extra water for the galleys and toilets. If the APU is replaced with a continuously operating fuel cell it is possible to reduce overall power requirement since for example, the hot bleed air normally extracted from the engine can be eliminated by using an alternate anti/de-icing system with the hot water by-product from the fuel cell.

Using a hydrogen powered environmental control system can possibly replace the conventional system with hot bleed air use and an air conditioner. A more detailed analysis regarding the required cooling, heating and electrical power is needed to quantify the advantages in terms of power and cost.

The available power from boil-off hydrogen should, in most cases, be larger than the power required by all the aircraft systems, therefore it may be possible to design and convert systems to use this “freely available” boil-off hydrogen fuel and use it to provide extra power. Of course, it must be remembered that during the system design, that the availability of boil-off hydrogen is not 100% available all of the time.

Theoretically, surface cooling is still very promising for the use on a LH₂ aircraft (particularly long range aircraft). The aerofoil could be designed with this in mind to encourage laminar flow and therefore utilize this advantage.

The following synergies are recommended for some more detailed analysis in the future.

- Reducing the installed power losses
- Replacement of APU with hydrogen fuel cell
- Replacing the environmental control system
- Drag reduction by surface cooling combined with anti-/de-icing system
- Tank cooling by boil-off gas