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LNG AS AN ALTERNATIVE AVIATION FUEL: INCORPORATING MEMBRANE TYPE CRYOGENIC WING TANKS WITH A CENTRAL CRYOGENIC PRESSURE VESSEL FOR AIRBORNE LNG STORAGE AND FUELLING

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ABSTRACT

The growth in air traffic and the prevention efforts against global warming and pollution are forcing the establishment of new alternative fuel technologies in aircrafts. Apart the usage of biofuels, cryogenic liquefied hydrogen (LH2) is focused on in order to assure sustainable green aviation. However there are open items regarding the storage of LH2 in cryoplanes: The cylindrical pressure vessels are bulky; not appropriate to be stored in the wings, and together with the required thermal insulation they are heavy. Instead of having a zero emission aircraft with LH2, the usage of liquefied natural gas (LNG) is proposed herewith in combination with lower pressure membrane type tanks and submerged cryogenic pumps in wet wings, connected to a central pressure vessel in the fuselage; allowing the reduction of unwanted emissions, the utilization of the space in the wings, the compensation of the boil-off gasses and the prevention of the pressure drop due to sloshing within the LNG tank. Finally this approach is validated by a hazard and operability study (HAZOP) delivering the conceptual framework for future development of detailed cryogenic storage & fuelling system design for cryoplanes.

KEYWORDS: Air Transportation, Green Aircraft, Cryogenic Aircraft, Liquefied Natural Gas, LNG, cryo-compressed LNG

INTRODUCTION

The passenger–kilometer performed (PKP) in air travel grew yearly by about 5.9 per cent on average [Mazraati, 2010] and the load factors of airlines is above 80% [Harned et al, 2007], resulting in four times higher forecasted fuel demand in year 2050 compared to today [ICAO, 2010]. Since kerosene powered aircraft emit several gases such as CO2, H2O, NOx (= NO + NO2), CO, SO2 and unburned hydrocarbons and aerosols [Marquart et al, 2001], new technologies are focused on to reduce these gasses. The European Union (EU) enforces CO2 trading [Meltzer, 2012] and the United States (US) signed the Copenhagen Accord drafted in December 2009 [Lau et al, 2012] for the reduction of emissions. The projected shortage of traditional fuels result that e.g. the US can supply only less than the half of its energy needs by its own [DOE, 2013] and the conventional aviation fuel is expected to become increasingly expensive [Kivits et al, 2010].

As a result alternative aviation fuels according to the fuel standard ASTM D1655 [Hendricks et al, 2011] are being developed, mainly synthetized from biological substances such as coconut oil, babassu oil, jatropha oil, algal oil and camalina oil [ICAO, 2009]. In addition to that hydrogen and natural gas are considered as alternative fuelling media as well. They both promise a clean burn with a low SO4 emission as sown below.

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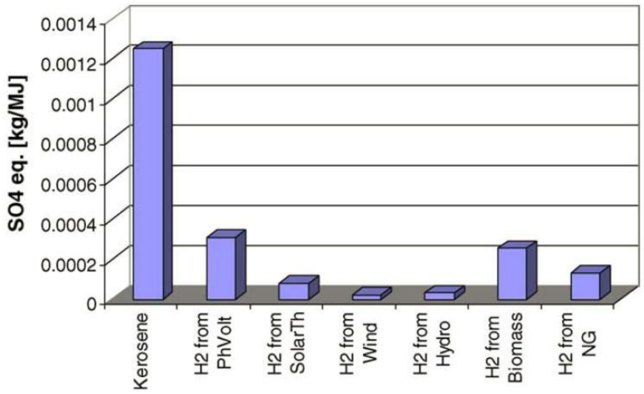

Figure 1: *SO4 equivalent emissions of aviation fuel production [Koroneos et al, 2005]*

In order to assure an efficient storage, these gasses are compressed and liquefied in cryogenic conditions. Due to the low cryogenic temperatures liquefied hydrogen (LH2) and liquefied natural gas (LNG) are subject to be kept in thermally insulated systems. As shown in Figure 2, any temperature increase over the vaporization point will result in the expansion of the gas volume by 848 and 600 times for hydrogen and natural gas respectively [Lanz et al, 2001].

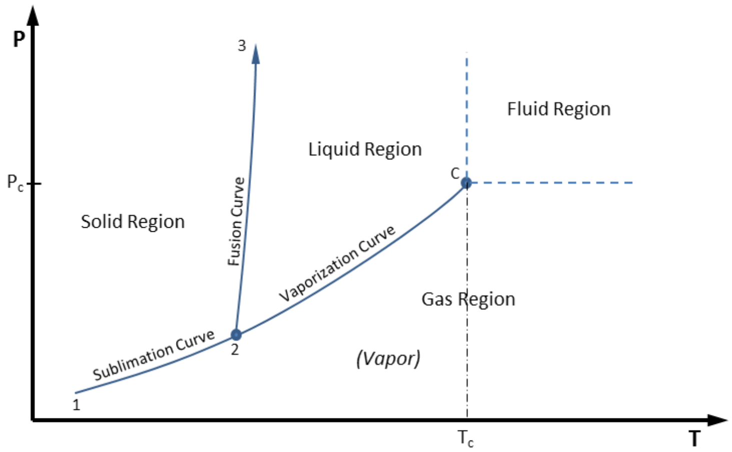

Figure 2: *Pressure – Temperature (PT) Phase Diagram for a pure substance based on [Flynn 2005, p 79]*

Cryogenic fuels are first tested in aircrafts in the 1940s in the US. After the energy crisis of 1973 NASA sponsored alternative aviation fuel programs [Contreras et al, 1997] and in 1988 the Russian hydrogen fuelled aircraft Tu-155 successfully passed tests, converted into LNG usage with around 100 successful demo flights later on [AKO, 2006]. Deutsche Airbus started cooperation with the Russian Tupolev Design Bureau and in 2000 the Cryoplane project started in the EU for the LH2 usage in civil aviation [Khandelwal et al, 2013]. Currently also Boeing in the US is developing within the Subsonic Ultra Green Aircraft Research (SUGAR) alternatives for the implementation of cryo-fuels [Bradley and Droney, 2012].

Fuel	Calorific Value [MJ/kg]	Density [kg/m3]
LH2	119.95 ± 0.13	70.85
LNG	45.86 ± 3.95	422,8
Petrol / Gasoline	44.15 ± 0.74	700
Kerosene	43.69 ± 0.51	780
Diesel	42.91 ± 0.46	800

Table 1: *Calorific values and densities of various fuels based on [Staffell, 2011; Lanz et al, 2001; NIST, 2011]*

The weight of the total cryogenic fuel required on board is lower than the traditional fuels as indicated in the table above. However the common approach for the storage is the usage of double walled vacuum insulated pressure vessels (see Figure 3). Such tanks are non-integral tanks, but also integral tanks (see Figure 4) carrying the loads as a part of fuselage can be adopted [Khandelwal et al, 2013].

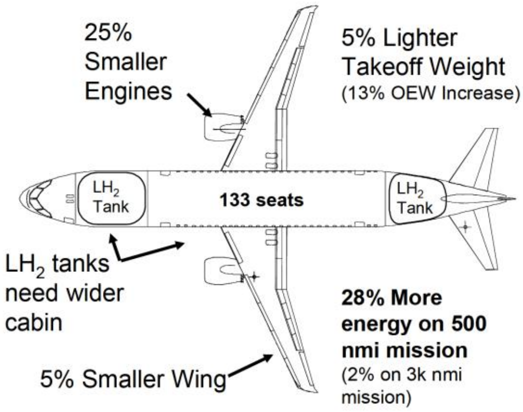

Figure 3: *Cryogenic Plane Layout [Daggett et al, 2006]*

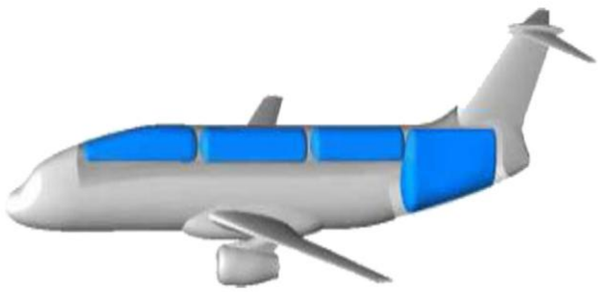

Figure 4: *Example Layout [Khandelwal et al, 2013]*

Whichever construction is used, the thickness of a pressure vessel is driven by the level of the pressure of the cryogen and it determines together with the insulation the weight of the system. Consequently the research for cryoplanes in the literature concludes in a decrease of energy efficiency due to the heavy weight of the equipment [Daggett et al, 2006].

MULTI-PRESSURE TANK GRID

Cryogenic media can be kept in several pressure levels with a saturated gas phase above the liquid phase in the tank. When the pressure of the cryogen is higher, the temperature of this mixture is higher as well. [Bradley and Droney, 2012] define the cryogenic storage in an aircraft to be a low pressure system between 1 and 3.44 bar. Also according to [Khandelwal et al, 2013] LH2 storage in cryoplanes is made in a thin wall pressure vessel with a maximum working pressure (MAWP) range of 1 bar to 3.5 bar. The result is an extreme low boiling point of LH2 at -253°C requires a high insulation capability.

Therefore the vacuum area between the two tanks of the pressure vessel is filled with perlite, glass spheres of 3M, Cryogel or there is a thin multilayer aluminum wrapping around the inner tank to minimize radiation. Altogether the result is a self-carrying, independent tank system, which is heavy. Moreover the inner tank is attached to the outer tank with supports and since the pressure vessel is subject to accelerations, the fatigue requirements make the system even heavier.

There are also several design approaches involving composite layers around a metallic liner, which is the membrane for the liquid containment. Since materials tend to have an embrittlement in cryogenic temperatures [Schmidtchen et al, 1997] and have a special low temperature ductility [Flynn, 2005], it is not easy to find suitable durable composites considering also fatigue. This work is still going on and many composites not mentioned in [BS EN 13458:2002] are being studied in detail before usage. Despite the advancements in composite insulated tanks, even with composites such systems are not light enough and the total thickness and thus the weight is still a function of pressure and thermal insulation. As a result independent pressurized systems remain heavy compared to kerosene tanks in aviation.

Considering LH2, which is extremely cold, this independent tank arrangement is appropriate; however in the short run LNG can be used as a cryogenic fuel as well. LNG has a higher calorific value than kerosene (see Table 2) and its boiling temperature is around -166°C to -157°C at atmospheric pressure [Bernatik et al, 2011]. As a result the insulation requirement is lower than LH2. Moreover LNG has a wide availability and an existing supply chain. On the top of this there are already LNG fuelled green ships in the market [Ucler, 2013].

Looking on the existing LNG carrier ships, the LNG is carried in membrane type tanks embedded in the ship structure. E.g. GTT MARK III and NO96 types are the most common membrane type insulation systems employed for LNG carriers [Chun et al, 2009], wherefore even the dynamic crack propagation is studied in detail. As shown in Figure 5 there is no vacuum insulation, but instead polyurethane foam is attached on the structure for the insulation and there are primary and secondary metallic barriers for the enclosure of LNG.

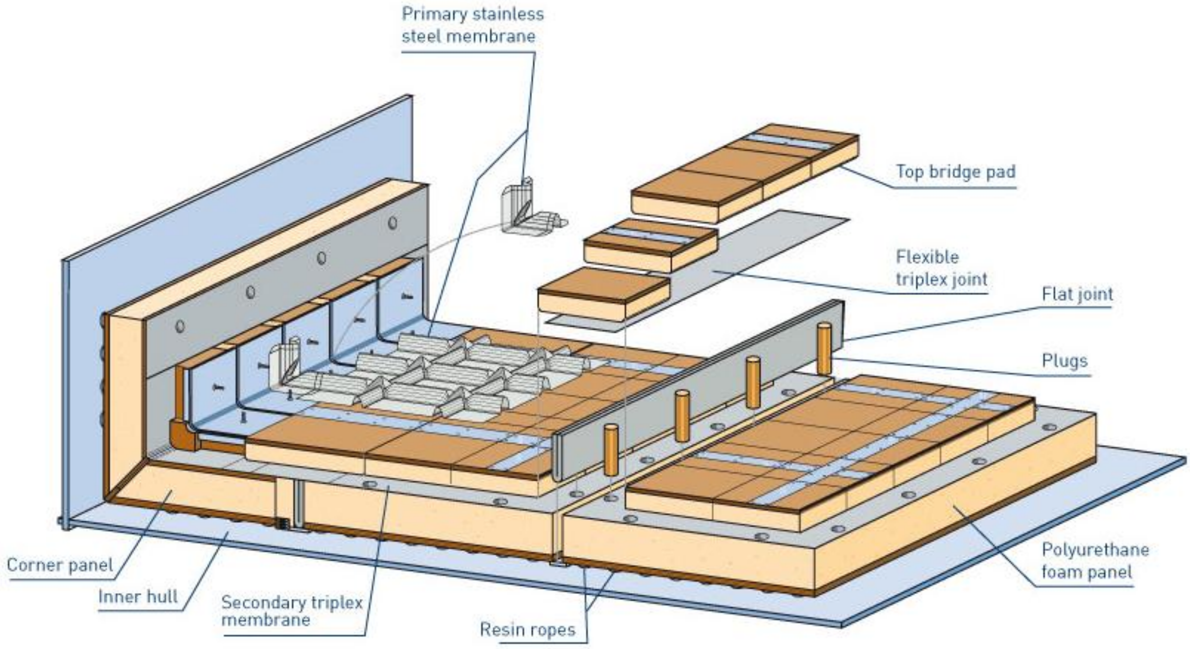

Figure 5: *GTT MARK III type LNGC insulation system [GTT, 2013]*

When the aircraft is fuelled with LNG, such tanks can be incorporated into the wings and instead of foam insulation; composite vacuum panels can be used for weight reduction as well. When increased bending resistance in the membrane is required also the composite fuel tank insulation assembly for space vehicles [US 7,296,769 B2] can be used as a guideline (see Figure 6). This enables the traditional set up of the fuel tanks.

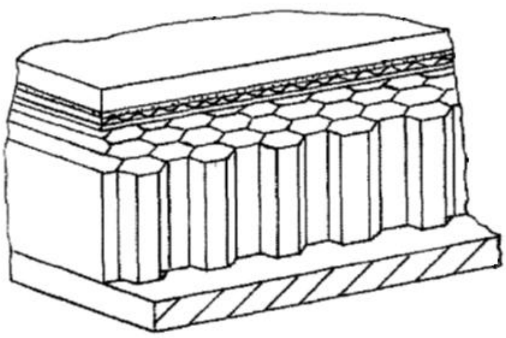

Figure 6: *Composite fuel tank insulation assembly [US 7,296,769 B2]*

Whatever methodology is used the insulation capability of membrane type tanks will be still below a standard pressure vessel. This will lead to a higher thermal leak, resulting in the evaporation of the LNG called the boil-off gas. Moreover warming the liquid decreases its density, leading to volumetric growth, also resulting in a pressure rise.

The proposal made herewith is the usage of a multi-pressure tank grid existing of (i) big membrane tanks in the wings with a small pressure such as 0.4 bar to 0.7 bar, (ii) a smaller central pressure vessel with a higher pressure such as 10 bar and (iii) the necessary connection lines between tanks making use of cryogenic pumps as shown in Figure 7. A cryogenic system must be closed to the atmosphere, i.e. no humidity is allowed to penetrate into the system. Thus there is always an overpressure and nitrogen is used to purge the air with humidity. There are many items for level & pressure measurement, filling and purging due, which are not shown in this simplified piping and instrumentation diagram (P&ID) in order to underline the mechanism of the multi-pressure tank grid. The system automation is achieved by remotely controlled valves and variable pumps.

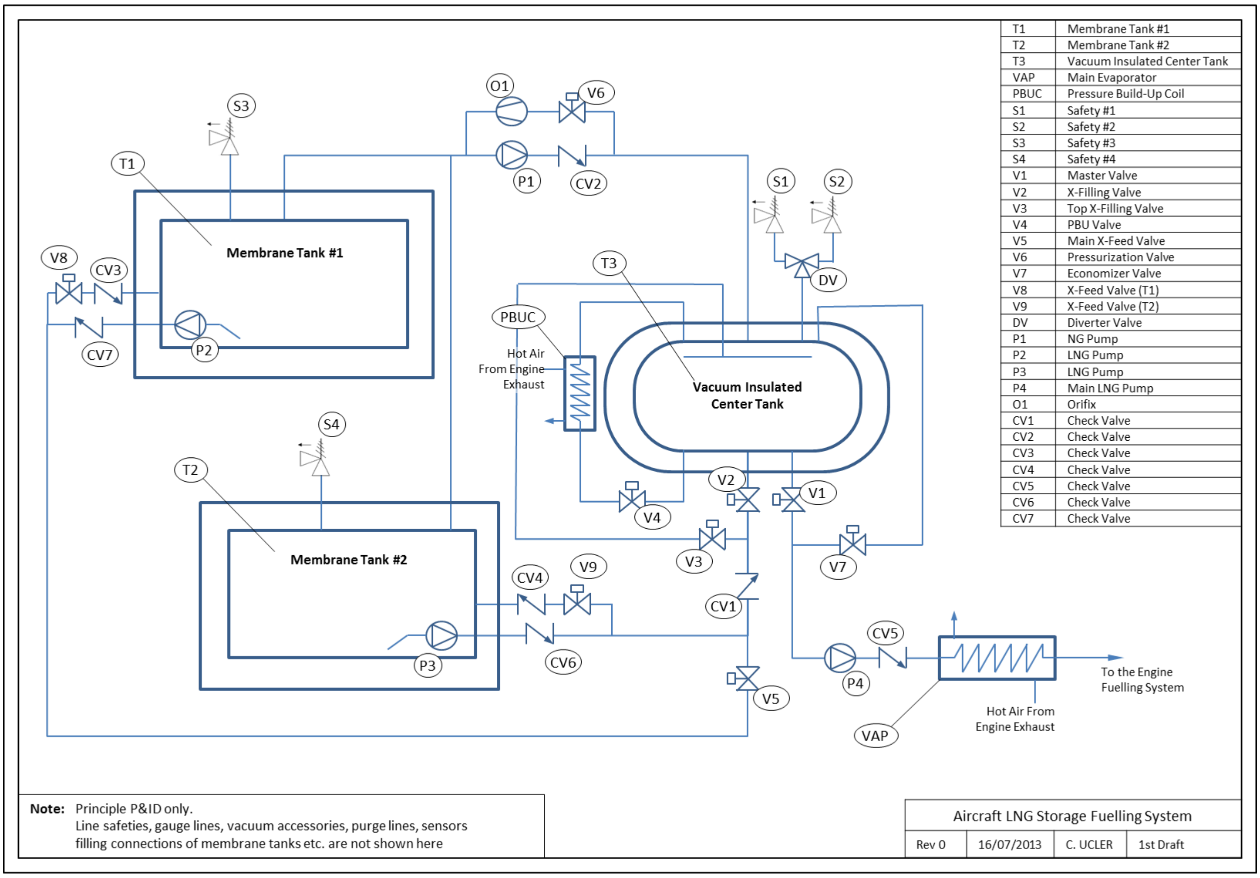

Figure 7: *Simplified P&ID of the Aircraft LNG Storage & Fuelling System*

The logic of the grid is to store most of the fuel in the membrane tanks while making the consumption of the engines over the center tank. The system enables the direct consumption of the boil-off gas from the center tank when opening the economizer valve. As a result the pressure in the tanks can remain stable during flight. For the case of maximum consumption of the engines, supported by the pumps, the pressure build up coil (PBUC) is compensating the volume loss due to the withdrawn fluid by evaporating LNG in the required amount. The high pressure system is also used to increase the pressure of the membrane tanks during withdrawal. Thus a stand-alone PBUC for the membrane tanks is not required. The boil-off gases of the membrane tanks are compressed and pumped to the center tank, which also enables a longer parking time. In the case of a higher pressure than the MAWP, the safeties open and release the extensive pressure to the atmosphere according to [BS EN 13648:2002]. Moreover the center tank is also acting as a buffer during demand fluctuations of the engines. During flight the LNG level in the pressurized center tank is always on a constant level enabling a buffer as well.

The submerged LNG pumps in the membrane tanks are delivering the necessary amount of LNG according to the consumption. The cross-filling of the center tank is either form the bottom or from the top in order to maintain the pressure in the tank, since a fast pressure drop of the tank could trigger the boiling of the cryogen, trying to cool down to reach the saturation point, which might lead to depressurization flash loss and safety issues. The withdrawn LNG from the center tank is fed to the main evaporator by a pump. The evaporator accomplishes the phase change and heats the NG up to the desired temperature range. Both the evaporator and the PBUC make use of hot exhaust gasses. In addition systems such as the air-conditioning can be coupled to the cryo system as given in [US 20120240599 A1] for weight reduction purposes, which is not included in the P&ID. The cryogenic system must operate in a reliable and efficient manner at temperatures well below 173 K (-100°C), [Kerry, 2007, p 318], thus all equipment including NG lines are selected accordingly.

The membrane tanks are to be insulated with composite panels. Such sandwich construction for LNG insulation panels also incorporating aluminum foils in composite structures, however a gas leakage can occur, when the epoxy adhesive is not completely impregnated between the glass fibers, which can be enhanced using adaptive curing methods [Kim and Lee, 2008].

The center tank is supposed to be an aluminum-lined, composite-wrapped vessel with a vacuum shell like the car LH2 tanks as shown in Figure 8. Such composite hydrogen car tanks are capable to withstand even pressures of compressed natural gas (CNG) or compressed LH2 at even 350 bar, by allowing a low weight. By reducing the pressure, a lower weight can be reached even when having a higher diameter, providing sufficient volume for the aircraft operation. A reflective multilayer aluminum wrapping is to be used in order to reduce thermal leak.

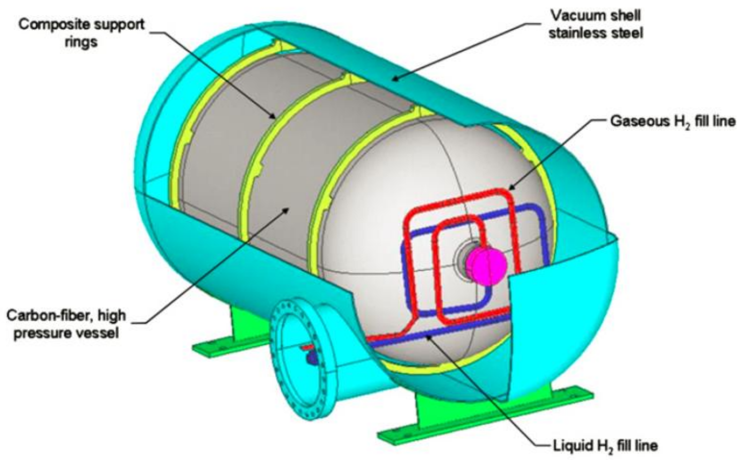

Figure 8: *Generation 2 cryogenic capable aluminum lined carbon fiber wrapped pressure vessel [Aceves et al 2010]*

Another point is the insulation of the cryogenic lines. When un-insulated cold cryo-pipes are subject to atmosphere, this can condense air and cause oxygen enrichment causing an extreme fire hazard or explosive situation. The oxygen-rich air condensate can saturate clothing, rags, wood, asphalt pavement, etc. [Flynn, 2005, p 797]. Thus the transfer lines between tanks in this proposal are Super Insulated Vacuum Lines (SIVLs) consisting of two pipes in each other with a multilayer wrapping of thin reflective material on the inner pipe against radiation and vacuum between two pipes for insulation.

HAZARD AND OPERABILITY (HAZOP) STUDY

In order to evaluate eventual problems during the operation, a HAZOP study is done, which has been adopted worldwide as the most widely used hazard study method in the process industry [Tyler, 2012].

The fallowing HAZOP study is made in general to evaluate possible incidents and associated effects on the storage in the membrane tanks (see Table 2), in the center tank (see Table 3) and on the piping system (see Table 4). It includes the tanks and the piping sectors. This HAZOP is just a preliminary evaluation tool for the principles of operation. As indicated in [Crawley et al, 2000] it is a concept stage hazard review. Upon selection of the specific equipment and finalizing the design several detailed HAZOPs and Failure mode and effect analysis (FMEA) have to be carried out.

During the HAZOP evaluation sections or stages are defined, described and representative parameters for deviations are selected and with respect to their effects evaluated in order to define the protection associated (see Figure 9).

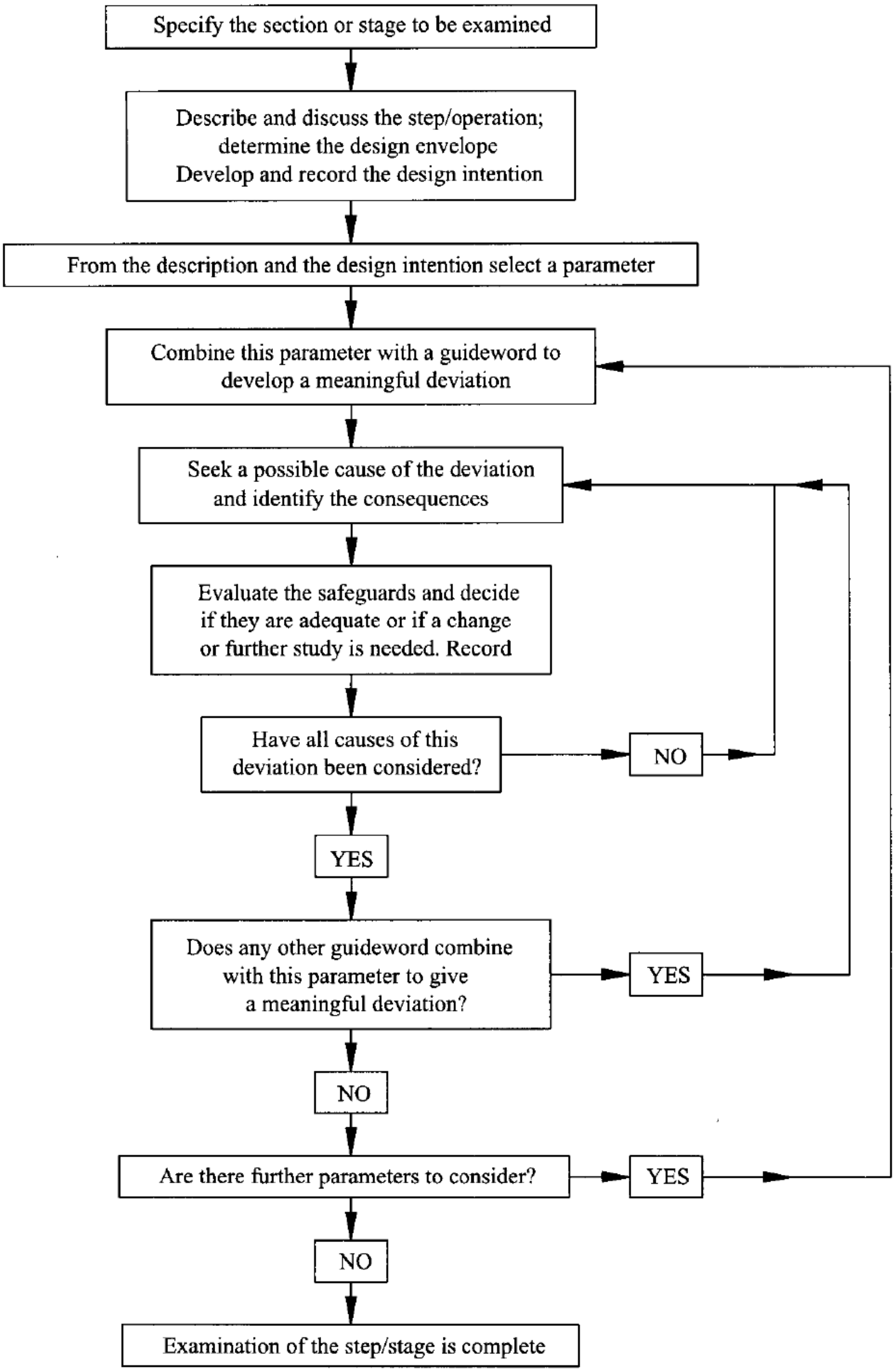

Figure 9: *Flow Diagram for the HAZOP Analysis [Crawley et al, 2000]*

INCIDENT	EFFECT ON SYSTEM	PROTECTION	SYSTEM
High pressure	Failure of tank	NG Pump, Safety valves	High Pressure
Low pressure	Increased buckling and cavitation danger	Pressure building circuit over central tank	Low Pressure
High temperature	N/A		
Low temperature	Embrittlement	Suitable material selection	
High pressure within secondary barrier	Loss of fuel over leak	Sensor	
Low liquid level	Lower Range	Level indicator	Low Level
Water vapor in tank	Freezing and plugging lines under cryogenic temperatures	Drying system with nitrogen and shipping under nitrogen pressure	
Shrinking and contraction of pipes in interspace	Mechanical stress on pipes and installation.	Omega bends	
LNG leak	Explosive atmosphere present	Temperature and gas detection transmitters	Leak
Frost damage of personal	Piping and accessories must be handled according to operating instructions because of harmful low temperatures	Piping and installation is covered by fence to protect from unauthorized reach and pipes containing LNG are insulated	
Pump (P2 & P3) Damage	No LNG feed	Second Membrane Tank (Within Fail Safe logic additional pump has to be implemented)	Pump
Sparks (static electric)	Ignition of possible explosive atmosphere within zones	By using Warning Signs the risk of fire or spark from man-operated equipment is reduced. All electrical equipment used is EEx-proof and ATEX certified.	
Emergency shutdown	In case of emergency liquid and gas lines remotely closed	Center Tank keeps operation as buffer	Emergency
Dangers of LNG	Dangers of LNG are explained in user manual.	User Manual	

Table 2: *HAZOP of Membrane Tank (Excluding filling)*

INCIDENT	EFFECT ON SYSTEM	PROTECTION	SYSTEM
High pressure	Failure of tank	NG Pump, Safety valves	High Pressure
Low pressure	Increased buckling and cavitation danger	Pressure building circuit over central tank	Low Pressure
High temperature	N/A		
Low temperature	Embrittlement	Suitable material selection	
High pressure in interspace	Inner vessel collapse	Outer vessel relief device (RD)	RD Lifting
Low liquid level	Increased buckling, cavitation and flash loss danger	Level indicator	Low level
Loss of vacuum	Thermal Leak: Pressure increase	Safeties	High Pressure
Water vapor in tank	Freezing and plugging lines under cryogenic temperatures	Drying vessel with nitrogen and shipping under nitrogen pressure	
Shrinking and contraction of pipes in interspace	Mechanical stress on pipes and installation.	Omega bends	
LNG leak	Explosive atmosphere present	There are installed transmitters in basins for LNG and fire. In case of high (+60) temperatures, the system will switch to Emergency Shut Down.	Leak
Frost damage of operator	Piping and accessories must be handled according to operating instructions because of harmful low temperatures	Piping and installation is covered by fence to protect from unauthorized reach and pipes containing LNG are insulated	
Sparks (static electric)	Ignition of possible explosive atmosphere within zones	By using Warning Signs the risk of fire or spark from man-operated equipment is reduced. All electrical equipment used is EEx-proof and ATEX certified.	
Emergency shutdown	In case of emergency liquid and gas lines remotely closed	Center Tank keeps operation as buffer	Emergency
Dangers of LNG	Dangers of LNG are explained in user manual.	User Manual	

Table 3: *HAZOP of Center Tank (Pressure Vessel, excluding filling)*

Pos.	INCIDENT	EFFECT ON SYSTEM	PROTECTION	SYSTEM
T1-T2 (gas)	Leak	Low Pressure	N/A	High Pressure
All liquid lines	Oxygen enrichment	Fire	Insulation	Temp-Low
T1-T2 (liquid)	V9 or V8 not opening	No cross feed possible	by-pass to be incorporated within fail-safe logic	Valve Fail
T1-T2 (liquid)	V9 or V8 not closing	High Pressure	back-up to be incorporated within fail-safe logic	High Pressure
T1&2-T3 (gas)	Pump inoperative	No gas burn, high pressure	Safety opens	High Pressure
T1&2-T3 (gas)	V6 not closing	High Pressure	Safety opens	High Pressure
T1&2-T3 (gas)	V6 not opening	Low Pressure, cavitation of pumps	by-pass to be incorporated within fail-safe logic	Low Pressure
T1&2-T3 (liquid)	V2 or V5 inoperative	No liquid feed - engine dies	by-pass to be incorporated within fail-safe logic	LNG Blocked
T1&2-T3 (liquid)	V4 not opening	No top filling, pressure rising	Safety opens by-pass to be incorporated within fail-safe logic	High Pressure
T1&2-T3 (liquid)	V4 not closing	Too much top filling, pressure dropping, flash loss	Safety open	Low Pressure
T1&2-T3 (liquid)	V2 not opening	Too much top filling, pressure dropping, flash loss	Safety open	Low Pressure
T1&2-T3 (liquid)	V2 not closing	Too much bottom filling, pressure rising	Safety opens by-pass to be incorporated within fail-safe logic	High Pressure
T3-PBUC	V4 Not opening	Pressure falls down, pump cavitation	by-pass to be incorporated within fail-safe logic	LNG Blocked
T3-PBUC	V4 not closing	Excessive pressure	Safety open	High Pressure
PBUC	Hot air not coming	Pressure falls down, pump cavitation	Aircraft system to assure hot air	Low Pressure
T3-VAP	V7 not opening	No economizer function	N/A	Eco Off
T3-VAP	V7 not closing	Pressure drop danger	PBUC to be dimensioned overcoming the loss	Eco Fail
T3-VAP	P4 not running	No LNG feed	to be duplicated with fail safe logic	Pump Off
VAP	Hot air not coming	No evaporation, no fuelling	Temperature Element for emergency shut off, Aircraft system to assure hot air	NG Blocked

Table 4: *HAZOP of Pipework*

As resulted in the HAZOP analysis, there is a danger of oxygen enrichment that every line and equipment has to be insulated adequately. Moreover there are many lines and equipment that have to be duplicated to be in line with the fail safe logic increasing the reliability. In addition to that the feed of hot exhaust gasses by the engines must be continuously. For the case of the reignition of all engines this must be evaluated carefully. It might be necessary to add an electrical or chemical heat generator, if the aircraft systems cannot deliver the required heat continuously. Since these modifications are part of the next design iteration, this work is not included within this paper, but has to be accomplished in further research, which also shall develop the bunkering rules and lines, i.e. the filling details, and the alarm and control system including all the required sensors.

CONCLUSIONS

Every consequent year the number of operational aircrafts is rising with respect to the increased need of air travel. Traditional fuel sources for aviation are not satisfying the upcoming environmental requirements and their supply cannot scope with the projected demand as well. As a result alternative fuel sources for aviation are being developed including, but not limited to cryogenic fuelling.

Consequently the usage of Liquefied Natural Gas (LNG) is proposed, which is as of today already being used as a clean energy source in ships. The proposal implements a multi-pressure tank grid on aircrafts successfully, constituting of low pressure membrane type cryogenic wing tanks, a central cryogenic pressure vessel and associated equipment. The philosophy of function is explained and subsequently verified via HAZOP.

As a result using membrane tanks, it enables the weight reduction and fits to the structural design envelope of existing aircrafts. Moreover the LNG usage makes use of already commercialized cryogenic technologies promising fast adaptation. Moreover the wide availability of LNG is commercially beneficial as well.

Further research is required with respect to the adaptation of the cryogenic filing & purging and the aeronautical fail-safe principles to the system. Moreover the detailed designs of membrane tanks, center tank and evaporators have to be completed with respect to the load envelope. However considering the achievements in the cryoplane projects and looking at the LNG adaptation as a fuelling media in process and naval industries, this research is promising.

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