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LNG 연료추진선의 기관실 안전성 확보를 위한 연구

Study on safety analysis of the machinery space for LNG fueled ship

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Study on safety analysis of the machinery space for LNG fueled ship

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Abstract

The abstract has been divided in two parts (1 and 2) as follows:

Part 1. Safety analysis and design concept of LNG fueled ship

The safety and Risk analyses of LNG fueled ship and system carried out, focusing in particular an analysis of the causes and consequences of hazards scenarios for entire LNG fuel system and with objective to evaluate and document the risk level of the design of the vessel compared to a diesel fueled container vessel of equal type. All major hazards have been considered and the risk is quantified in terms of Potential Loss of Lives (PLL) and Fatal Accident Rate (FAR). In total, the personnel risk for the vessel has been estimated to a FAR of 4.30. A similar new conventional diesel fueled vessel will have an estimated personnel risk level of a FAR of 4.16. The net increase of FAR 0.14 corresponds to an increase in risk by 3.4 % compared to the diesel fueled container vessel. The main categories of hazard scenarios are: Fire and explosion initiated from the LNG system, fire and explosion not LNG initiated, dropped objects, collisions, grounding, foundering and occupational accidents. The purpose of the analysis is to identify safety hazards that may represent risks to crew and third parties such as maintenance personnel, yard workers and other ships during operation. The risks and hazards identified following proposed recommendations with comprehensive summary

in term of design and operation. The main result from the safety analysis and HAZID showed that the estimated HAZID increase is mainly due to the presence of the LNG tank and its effect on the risk from fire/explosions due to ship collision. The HAZID results confirm that there is no major HSE showstoppers to carry out construction and conversion on vessel using dual fueled. The main selection criterion was the potential design, worst case scenario for location of LNG tank below accommodation, technical and operational capabilities in conducting such HAZID study and investigations. Several important gaps in mandatory regulations, standards, guidelines or of relevant organizations beyond mandatory regulations have been identified and addressed.

Part 2. Safety analysis of LNG fuel for machinery space

A LNG gas fuel ship is being developed where LNG gas is used as fuel in internal combustion engines (modified diesels). In this concept to investigate possible consequences of a gas leak in the feeding pipe to the engines. Depending on the size of the leak and the time of ignition, different developments of the accident can occur. Two main developments are foreseen; early ignition and late ignition. If the gas is ignited early, there will be a jet fire and no explosion. If the gas is ignited after most of the gas is released, there may be an explosion. The possibility for a strong explosion is dependent of the gas concentration and size of the gas cloud. The main objective is to find the fire and explosion loads caused by a "rupture of high pressure double wall pipe in machinery space". My safety simulations, modelling and analysis includes the following activities:

- Geometry modelling. the entire room is modelled with most details in the area where the leak will start. The geometry is modelled in FLACS v10 so that the geometry model can be applied for ventilation, dispersion, fire and explosion simulations.

- Ventilation and dispersion simulations. The leak is modelled as a transient leak.

The worst case leak size is estimated based on knowledge of the size of the room, ventilation conditions, etc. Two different leak rates in two different leak scenarios are performed. The ventilation in the room is simulated and used as start conditions when the leak starts.

- Explosion simulations. Explosions are simulated in FLACS and explosion pressures on engine room walls are obtained. Total of six simulations are performed with different cloud size, locations and two ignition locations.

- Fire simulations. The leak is modelled as a jet fire assuming it is ignited from the start of the leak. The jet fire is simulated in KAMELEON FIREEX (KFX). Radiation flux on the structure is obtained during the fire. three simulations with different constant leak rates are performed. The extent of the fire when a steady state situation is established is presented. One worst case jet direction is performed based on other fire simulations. Note that the geometry model from FLACS will be converted to KFX.

- Analysis. The obtained explosion and fire loads are compared with typical collapse loads for similar structures. This evaluation is qualitative, and does not include rigorous calculation of structure strength. If the loads are above typical acceptable loads, simulations of the structure strength will be suggested. Possible mitigating measures will also be recommended. Typical mitigating measures are a good gas detection system, start of deluge on gas detection (this may reduce possible explosion pressures), Passive fire Protection (PFP) on critical structure and piping, automatic blow down of fuel pipe system on gas detection, improved air ventilation, reduced ignition sources, etc.

The scope is extended to consider frequency assessment, and full bore rupture calculation. The effect of a smaller ESD segment and shorter ESD closure time are also considered.

KEY WORDS:

LNG fuel, Analysis, Fire, explosion, internal combustion engines, HAZID, Modelling

LNG 연료추진선의 기관실 안전성 확보를 위한 연구

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Abstract (초록)

본 논문은 LNG 연료추진선박의 설계에 대한 안전성을 분석하고 내연기관을 탑재한 LNG연료 추진 시스템의 안전성을 시뮬레이션을 통해 검증 하였다.

주제 1 LNG 연료추진선박의 시스템 설계에 대한 안전성 분석

LNG 연료추진선박에 대한 안정성 및 위험성 분석을 위해 전체 LNG 연료 시스템 중 발생가능한 위험요인 및 결과에 대해 시나리오를 만들고 이를 기존 디젤 연료를 사용하는 선박과 비교하여 위험도를 평가하고 문서화 하였다. 본 논문에서는 대부분의 위험요소에 대해서 검증하였으며 모든 위험요소는 인명피해가능성 (PLL, Potential Loss of Life)과 유해사고율(FAR, Fatal Accident Rate)을 기반으로 정량화 하였다. 결과적으로 LNG 연료추진선으로 인한 인명피해에 대한 위험도는 FAR 4.30이며 이는

디젤연료를 사용하는 선박에 대한 위험도인 FAR 4.16보다 0.14, 즉 약 3.4% 증가한 수치이다. 위험성 분석을 위해 LNG 연료 시스템에서 기인하는 화재 및 폭발 가능성과 충격, 충돌, 좌초, 침몰 등 간접적인 요인으로 인한 화재 및 폭발 가능성을 검토하였다. 본 연구는 선박 건조 혹은 운항 중에 선원 및 선박관리자, 신조 작업자 등 관련 작업자에게 발생가능한 위험요인을 식별하고 각각의 위험요인에 대한 권고사항을 제시한다. LNG 연료탱크 자체는 충돌로 인한 화재 및 폭발 위험성을 증가시키는 주된 요인이지만 종합적인 안전성 및 위험성 평가 결과 LNG 연료추진선박을 신조하거나 개조 시 HSE 분야의 장애요인이 되지 않는다. 본 연구는 가장 위험도가 높은 탱크 배치인 LNG 탱크가 거주구역 아래에 설치 될 경우에 대해서 운영 유지 시 발생 가능한 문제점을 위험성평가를 통해 도출하였다. 또한 관련 국제 법, 규정, 권고 사항들 사이에 존재하는 주요 차이점 및 모순에 대해서도 기술하였다.

주제 2 기관실 내 LNG 연료 시스템에 대한 안전성 분석

LNG 연료추진선은 LNG를 연료로 사용하는 내연기관의 발달과 더불어 개발되었다. 본 연구에서는 엔진에 연결된 연료공급 파이프에서 발생가능한 가스 누설을 분석하였으며, 누설된 가스의 양과 점화 시간에 따라 각각 다른 사고가 발생함을 확인하였다. 누설된 가스가 초기에 점화 될 경우에는 제트파이어(Jet Fire)가 생기나 폭발이 발생하지는 않는다. 하지만 대량의 가스가 누설된 후에 점화가 일어날 경우에는 폭발이 일어날 수 있다. 폭발 가능성은 가스의 농도와 양에 영향을 받는다. 본 연구에서는 기관실 내 고압 이중관이 파열 될 경우 발생할 수 있는 화재 및 폭발 하중을 시뮬레이션을

통해 분석하였으며, 다음과 같은 사항을 고려하였다.

- 기하학 모델링.

  가스 누설이 발생할 공간은 FLACS V10을 통해 실제와 유사하게 모델링 하였으며, 통풍, 기체 확산, 화재 및 폭발에 대한 시뮬레이션을 실시하였다.

- 통풍 및 기체 확산에 대한 시뮬레이션.(일시 적인 가스 누설의 경우)

  설계 공간 및 통풍 용량 등에 대한 기본 조건을 바탕으로 하여 발생가능한 최악의 가스 누설양을 분석하고 두개의 다른 시나리오를 적용하여 시뮬레이션을 시행하였다. 설계 공간 내의 통풍양은 누설 발생 시작 조건을 기반으로 시뮬레이션 하였다.

- 폭발 시뮬레이션.

  FLACS를 사용하여 폭발에 대한 시뮬레이션을 하였으며 기관실 내벽에 작용하는 폭발 압력을 도출하였다. 이를 위해 가스의 누설양과 위치, 점화원의 위치를 바꾸어 총 6번의 시뮬레이션을 시행하였다.

- 화재 시뮬레이션.

  화재 시뮬레이션은 가스 누설 초기에 점화가 되었을 경우를 가정하고 제트파이어를 FLACS에서 설계한 모델을 기반으로 KAMELEON FIREEX(KFX)로 전환하여 시뮬레이션 하였다. 화재 시 구조물의 복사유량을 감안하였으며, 누설양에 따라 세가지의

시뮬레이션을 진행하였다. 화재는 정적 상태에서 화재가 발생할 경우를 가정하였으며, 최악의 경우에 대해서는 제트파이어의 방향을 달리하여 시뮬레이션 하였다.

- 분석

시뮬레이션을 통해 도출한 폭발 및 화재 하중은 유사한 구조의 기존 디젤을 연료를 사용하는 선박과 비교 하여 제시하였다. 본 분석은 정성적인 평가이며 구조강도에 대한 계산은 포함하지 않았다. 만약 하중이 일반적으로 허용가능한 하중을 초과하는 경우, 추가적인 구조 강도에 대한 시뮬레이션이 필요할 것이며 이를 대응하기 위한 권고사항이 제시되어야 한다. 전형적인 대응책은 검증된 가스 누설 감지 시스템 설치, 가스 누설 부위에 살수, 혹은 중요 구조물 및 배관에 PFP(Passive Fire Protection)적용, 가스 감지 시 연료관 자동 블로우오프(Blow-Off), 통풍 시스템 용량 조절, 발생가능한 점화원 최소화 등이 있다.

본 연구는 또한 누설에 대한 발생 빈도 평가 및 이중관의 전체 파열에 대한 계산을 포함하고 있으며 엔진과 ESD밸브(Emergency Shut-down Valve) 사이의 거리와 밸브가 닫히는 시간의 영향 또한 고려하였다.

키워드 : LNG 연료추진선, 분석, 화재, 폭발, 내연기관, 위험성평가, HAZID, Modelling

Chapter 1 Safety analysis and design of LNG fueled ship

1.1 General risk terms

The calculated risk results are compared with similar results derived for a diesel fueled container vessel. The term “risk” is defined as:

Risk = frequency of the hazard considered × consequence of the hazard considered

For the purpose of this study, risk has been measured as the risk of loss of lives and quantified as Potential Loss of Lives (PLL) per year and Fatal Accident Rate (FAR), which is defined as:

- PLL = Average number of persons killed per year

  PLL-values are used in the risk analysis to indicate the frequency for how often it is assessed that life is lost. PLL is short for “Potential Loss of Life” and describes the number of fatalities that are expected due to accidents in an average year. The following formula can be used to estimate the PLL-value of an accident:

  PLL = F (accident) × N (exposed) × Fatality rate

  Where:
  F (accident) = Frequency of the defined event (per year)
  N (exposed) = Number of people exposed by the accident
  Fatality rate = Portion of exposed personnel

- The Fatal Accident Rate (FAR) is the expected number of fatalities per 10^8 hours of exposure:

  FAR = Fatalities per 100 million exposed person hours
  = PLL x 108 / exposure hours per year

= PLL x 108 / (personnel onboard × hours per year

Main points in a risk analysis will therefore be to:

- Identify potential hazardous events
- Assess how often these can occur (probability/frequency)
- Assess the consequences of the identified events

Identification of unwanted events and potential dangers is of course crucial, and should be performed by personnel with practical experience and knowledge of the actual experiences. The hazard identification will always be qualitative.

1.2 Vessel design concept

The Vessel's design data which is complied with IMO interim Guidelines on Safety for Natural Gas Fueled Engine Installations in ships MSC 285(86) is shown in Table 1-1. The deadweight is about 81,000 ton on draught of 13.20m. Design speed (suitable service speed) is about 21 knots. Endurance for using gas fuel is set to 11,200 NM (Nautical mile) for one round trip between Iran/Bandar Abbas and Korea/Busan. In addition, endurance for emergency (using diesel oil) is estimated to be 5,600 NM (Nautical mile).

The accommodation is arranged in the forepart for increased number of containers on deck whilst still being in accordance with IMO visibility requirements. The safety barriers around the bunkering station (i.e. ventilation and shielding, Drip trays, Protection against overfilling, Emergency Shut-Down (ESD) system and other safeguards) are aimed at reducing the likelihood of an accidental spill, but also to minimize the consequence in the event of spilled LNG, where also safety barriers for the "Room for LNG Tanks" (i.e. Ventilation, Gas detection and fire extinguishing, Independent bilge system, LNG tank support, Anti-rolling and anti-pitching chocks) are designed and complied with IMO interim Guidelines on Safety for Natural Gas Fueled Engine Installations in ships MSC 285(86) [1-3].

Table 1-1 Design data of LNG fueled 8,000 TEU container ship –ship design data compared to the reference ship 8,000 TEU.

	Conventional fuel oil design	dual fuel design
Length x Breadth x Depth	280.00 x 46.40 x 24.00m	280.00 x 46.40 x 24.00m
Maine engine	low speed diesel engine fuel engine	low speed dual fuel
Alternator/ Generator	4x diesel generators	4 x dual fuel generators
HFO	6,500 m^3	-
DO	600 m^3	5,000 m^3
LNG	-	6,000 m^3

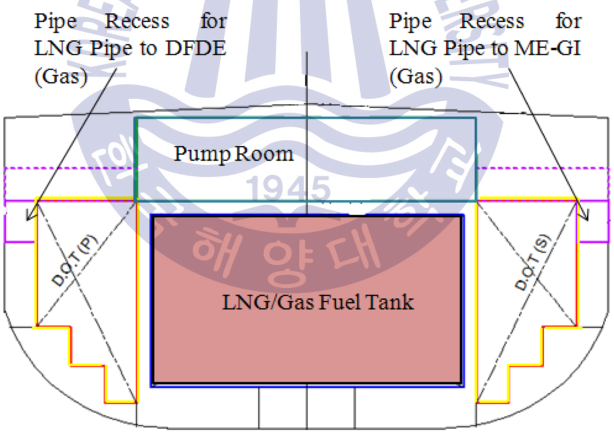


Figure 1-1 LNG fuel tank arrangement

The Vessel has one room for the LNG tank around the mid ship part, under the accommodation area as shown in Figure 1-1, and the general arrangement is shown in Figure 1-3.

The bunker station is located under accommodation space on each ship's side in a semi-enclosed space allowing the Vessel to berth and bunker at any side. The bunker station will have manifolds for liquid gas, vapour gas, nitrogen, and marine diesel oil.

The LNG is stored in one prismatic low pressure insulated tank (A-type). Forced- and natural boil off gas (BOG) is supplied to the main and auxiliary engines. The LNG tank is safeguarded by the B/5 location to the sides according to the IMO Interim Guidelines with additional protection by the double hull and diesel oil tanks, including the structure of LNG tank itself hindering a potential penetration [2-4]. However, when sufficient impact energy exists to defeat all the structural resistance of the outer hull, internal stringers and bulkheads the LNG tank may become punctured. Such high energy collisions are rare events and to this date no collision resulting in loss of cargo on LNG carriers has occurred [5].

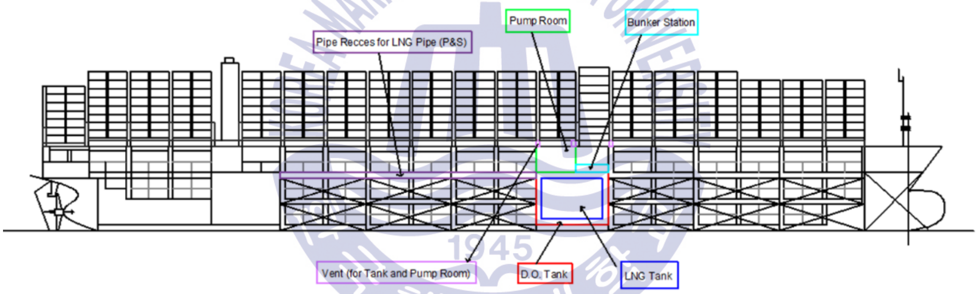


Figure 1-2 General arrangement showing location of bunker station, pump room, LNG tank and pipe recess

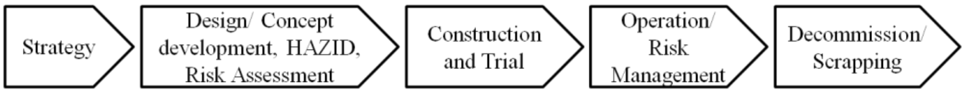


Figure 1-3 Vessel's lifecycle

The pump room is located between the upper deck and the "room for LNG tank". This space is utilized for pumps, heaters, vaporizers, gas heaters and compressors for gas supply system to main engine and auxiliary engines. The air lock space provides the access from under deck passage.

Two pipe recesses for the gas supply system are provided below the underdeck passage on each side of the Vessel between engine room and pump room. The single-wall pipe is arranged in each pipe recess. One pipe recess is arranged for the pipe for main engine, the other is arranged for the pipe for generator engines. The pipe duct for diesel oil pipes, water ballast pipes etc. is provided in the double bottom at centre of the ship.

The high pressure gas supply piping is led to engine room from the starboard side pipe recess and the low pressure gas supply piping is led to engine room from the port side pipe recess. The gas flow to the generator engines is regulated and measured in the gas valve unit (GVU) room located in the engine room. Gas to main engine is regulated by using the high pressure (HP) pump.

The engine room arrangement shall be based on conventional container ships. However, the main engine type is changed from conventional two stroke diesel engine to dual fuel engine. The generator engine type is changed from conventional four stroke diesel engine to dual fuel engine. High pressure gas supply system for main engine and low pressure gas supply system for generator engines are additionally provided.

The Boil-off gas from the LNG tank will be burnt in the ship's main propulsion engine and generators engines. Under normal operating conditions when the ship is at sea, one FG compressor, Gas heater, LP pump, HP pump will be running to supply fuel gas to ship's main propulsion engine and generator engines. The FG compressor then discharges the gas to engines via gas heater. HP vaporizer being used to discharge high pressure gas to main propulsion engine. If the fuel consumption of the main propulsion engine and generator engines cannot be met by the gas supplied by natural boil-off from tank, additional gas can be obtained by utilizing the HP vaporizer via LP pump and HP pump. This is fed by LP pump and HP pump to supply liquid to vaporizer, the outlet gas from vaporizer controlled by gas heater.

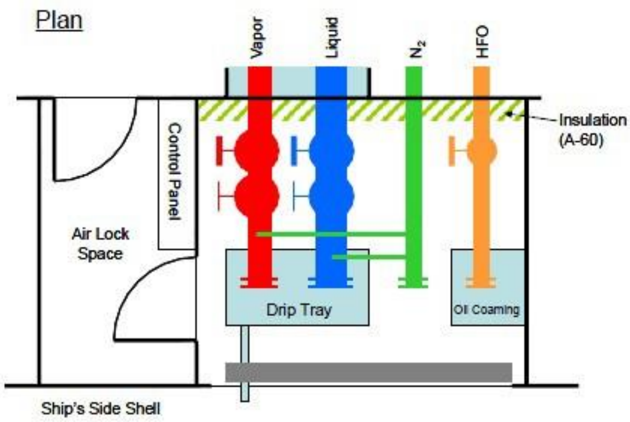


Figure 1-4 Bunker station plan view

The engine room arrangement of the vessel will be based on the conventional container ships. The major additional alterations from the conventional container ships are the following.

- Main engine type is changed from conventional oil fired two stroke diesel engine to dual fuel engine. Exhaust Gas Re-circulation (EGR) system for main engine is provided for meeting the requirements set in IMO Tier III in gas mode.

- Auxiliary engines are changed from conventional oil fired four stroke diesel engine to dual fuel engine. The generator engines need no NOx removal equipment for IMO NOx Tier III regulation in gas mode.

The arrangement of main engine is based dual fuel engine. Gas will be supplied to the engine inlet at a pressure between 150 bar – 300 bar.

In order to make the fore side space of the main engine larger, main engine is arranged on the aft side of engine room. Because the upside space of the shaft space (i.e. section between Fr.16 and Fr.64) is used as container space, main engine is arranged as near the Fr.64 as possible.

The EGR system is based on EGR system. In order to arrange EGR unit (scrubber & blower) near the exhaust gas manifold, space for EGR unit (scrubber & blower) is provided at the fore side of main engine on the 3rd deck. The other equipment (NaOH dosing system, water cleaning unit, etc.) of EGR is arranged on the lower floor.

The four generator engines of the DF type are arranged on the 3rd deck. Gas will be supplied to these engines at a pressure between 4 bar – 5 bar. Because it is impossible to arrange four gen. engines on one side due to the space limitation, two generator engines are arranged on the port side and the other two engines are arranged on the starboard side.

Except for the inside of Gas Valve Unit (GVU) room for generator engine, all gas supply piping in the engine room is to be double wall piping. Therefore, the engine room except for GVU rooms is regarded as gas safe machinery space. Because the engine room is gas safe machinery space, main engine and gen. engines are arranged in the same compartment.

1.3 Safety analysis results

The purpose of this risk analysis has been to determine the risk level for the vessel. Risk has been measured as the risk of loss of lives during normal operation, including intermediate phases, such as bunkering.

The total risk is estimated from summing up the contributions from each of the risks quantified in the previous chapters. This gives a FAR of 4.30 for the personnel onboard the vessel. Contributions to the personnel risk from the different types of accidents are given in Table 1-3.

Table 1-2 Total personnel risk

Accident type	**dual fuel 8,000 TEU container vessel**	
Occupational accidents	3.56	82.8 %
Ship Collision	0.28	6.5 %
Fire/explosion - leak in LNG fuel system	0.08	1.9 %
Fire/explosion not LNG initiated	0.06	1.4 %
Dropped objects	0.01	0.3 %
Grounding	0.02	0.4 %
Foundering	0.29	6.7 %
Total Fatal Accident Rate (FAR)	**4.30**	**100 %**

The main contributor to the increase in risk is ship collision with net additional FAR of 0.15. It was assessed that a high energy ship collision may penetrate the LNG fuel tank and cause a pool fire with heat radiation intensity around 220 kW/m^2. The threshold limit for fatalities is 12.5 kW/m^2 where exposed personnel will suffer extreme pain within 20s and fatality if escape is not possible. Thus, personnel not shielded by the accommodation unit or containers on deck within a 300 m distance are expected to be fatalities.

Considering the overall risk picture it should be noted that occupational accidents are the major risk contributor for the Vessel, contributing to 83 % of the total risk. The net risk increase of occupational accidents caused by asphyxiation (lack of oxygen) due to the presence of fuel gas piping and the LNG tank is assessed to FAR 0.02.

It is also recommended to work actively to promote a strong and sound safety culture. Involvement by all parties in the organization in the process of defining, prioritising and controlling risk along with a sense of shared purpose in safety, is important to the health and safety level onboard the vessel.

The risk for the dual fueled container vessel is compared to that of a diesel fueled container vessel. The focus of this report has been on risk of fatalities and the comparison is thus based on the personnel risk.

The gas fuel system and LNG tank has both positive and negative effects on the overall risk picture. The inherently safe engine space with double barrier piping and under-deck piping for high pressure pipes will have a risk reducing effect compared to a conventional diesel driven vessel. However, due to the hazards in terms of fire/explosion due to delayed ignition events (leak vented and ignited) and the consequences in case of a high energy collision with penetration of the LNG tank there will be a small overall increase in risk for the vessel compared to the reference ship. Table 1-4 shows the risk reduction and increase for the vessel compared to the diesel fueled container vessel.

Table 1-3 Risk level, dual fueled container vessel vs. diesel fueled container vessel

Accident type	Generic diesel fueled 8.000 TEU container vessel	Reduction in FAR	Increase in FAR	dual fuel 8,000 TEU container vessel
Occupational accidents	3.54	~	0.02	3.56
Ship Collision	0.13	~	0.15	0.28
Fire/explosion - leak in LNG fuel system	~	~	0.08	0.08
Fire/explosion not LNG initiated	0.18	-0.12	~	0.06
Dropped objects	~	~	0.01	0.01
Grounding	0.02	~	~	0.02
Foundering	0.29	~	~	0.29
Total Fatal Accident Rate (FAR)	**4.16**	**-0.12**	**0.26**	**4.30**

In total, the personnel risk for the vessel has been estimated to a FAR of 4.30. A similar conventional diesel fueled vessel will have an estimated personnel risk level of a FAR of 4.16. The net increase of FAR 0.14 corresponds to an increase in risk by 3.4% compared to a similar conventional diesel fueled container vessel.

The risk acceptance criterion applied for this risk assessment is based on the IMO Interim Guidelines for LNG fueled container vessels, defined in Chapter 2.5. As discussed above, the risk has increased with 3.4 % and overall the risk is considered to be on a similar level as for a diesel fueled container vessel. It is however important to emphasize that this conclusion is dependent on the assumptions related to the preliminary design of the Vessel.

Delayed ignition events and collision dominate the risks, which is primarily due to the limited immediate ignition probabilities (i.e. good ignition source controls) enabling a proportion of flammable clouds to become relatively large before igniting. As a result the main potential for risk reduction is the potential for personnel to escape. Key aspects of this will include:

- Ensuring that detection of releases is communicated to personnel onboard effectively.

- In terms of minimizing risks to personnel, and from delayed ignition events in particular, the most effective mitigation is to escape to a place of safety, which is either to accommodation or suitable shelter or to an area outside the flammable cloud envelope. The former is the most reliable, although the latter is likely to be practicable in most cases (noting however that the larger releases, e.g. due to collision or large leak during bunkering, will cover a significant proportion of the vessel).

- Training is fundamental in escape, although measures such as temporary shelters or ensuring that accommodation can be used as required are recommended.

- Ignition control is also essential to minimize delayed ignition events. Better control and understanding of hot work locations would assist further reductions in ignition potential.

Chapter 2 The Hazard Identification (HAZID) of LNG dual Fueled Ship

2.1 Introduction

Utilization of Liquefied Natural Gas (LNG) has rapidly grown and seen as a viable alternative to heavy fuel oils/marine diesel oil due to several factors such as the properties, economic and environment circumstances and its business is becoming a mature phase [6-11].

To cope with the demand of the LNG market with flexibility, this paper has newly and unique assessed and developed the Hazard Identification (HAZID) addresses all areas that need special consideration for the usage of the natural gas fuel- low flashpoint fuel to become a global fuel choice, it is essential that gaps and barriers on national and international regulations and standards are assessed and evaluated to promote safety and minimize the risk to the ship, it's crew and the environment and conformity in this new energy sector, ensuring that any risks, gaps and barriers arising from the use of natural gas-fueled engines affecting the integrity of the vessel's main safety functions are addressed. [12-19] [20].

The first version of the international Code of safety for ships using gases or other low-flashpoints (IGF Code) was adopted by resolution MSC.391(95), which entered into force on 1 January 2017. This first version of the IGF Code addresses only LNG (methane). Other low flashpoint fuels are being considered and amendments are made to the IGF Code as necessary.

The IMO has been tasked to develop the second version of the Code, addressing methyl/ethyl alcohol and other low-flashpoint fuels such as low-flashpoint diesel.

The IMO Interim Guidelines on safety for natural gas fueled engine installations in Ships MSC 285(86) (the Interim Guideline) and IGF code (the International Code of

Safety for Ships using Gases or other Low flashpoint Fuels) requires that a ship using an alternative fuel demonstrates by risk analysis that the safety level is equivalent to that of a conventional oil-fueled ship [8-10]. Therefore this study is to perform a HAZID in order to meet the requirements of the IMO Interim Guideline and IGF Code. The goal of these Interim Guidelines is to provide criteria for the arrangement and installation of machinery for propulsion and auxiliary purposes, using natural gas as fuel, which will have an equivalent level of integrity in terms of safety, reliability and dependability as that which can be achieved with a new and comparable conventional oil-fueled main and auxiliary machinery. it is assumed that the vessel will run on gas while performing on-loading and off-loading operations of containers.

This analysis is the concept the HAZID and based on by applying innovative thinking, maritime industrial experiences and the design concept of the vessel which is a typical container ship operating between Korean port/Busan and Iranian Port/Bandar Abbas [20-42] [43].

2.2 Analysis basis and methodology

The HAZID is a structured approach and exercises where documentation/drawings and a set of guidewords form basis for identifying hazards involved with an operation or the use of equipment and/or systems. HAZID's are commonly used throughout the maritime industry for all types of safety and risk assessments [13-18] [44] [45-50].

Figure 2-1 shows vessel's lifecycle. The focus for the HAZID assessment is the LNG fuel system and gas engines encompassing the following sequence of operations during the vessel's lifecycle:

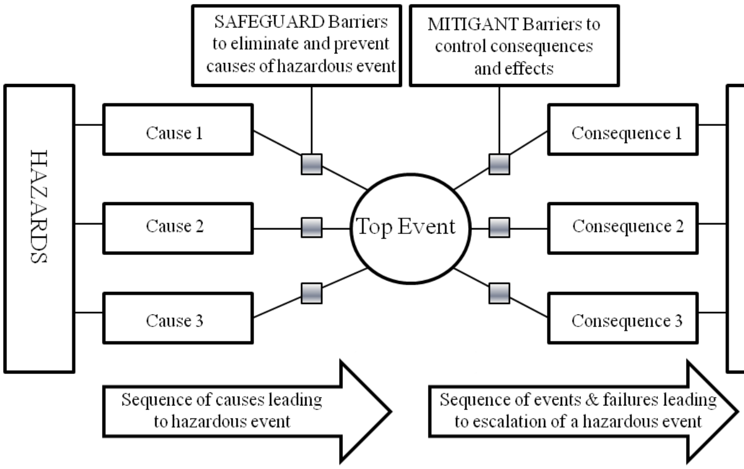


Figure 2-1 Bow tie hazard and effect model.

1. Construction/installation including testing and sea trials.
2. Operations (Loading/offloading of cargo, Voyage, Bunkering, Docking, Maintenance, Lay-up/Idle).
3. Decommissioning/Scrapping

Safety of ship propulsion during voyage and maneuvering to avoid black-out has been taken into account.

The following hazard guidewords used as a basis for the HAZID study [13-18] [43] [51]: Fire or explosion hazard, Fire/Explosion – LNG initiated, Fire/Explosion – not LNG initiated, Other hazards generated by materials and substances, Leakage of liquid LNG causing loss of structural integrity, Mechanical hazards, Electrical hazards, Thermal hazards, Hazards generated by malfunctions, collisions, dropped object, grounding, foundering, environmental hazards, pollution, occupational accidents, hazards generated by neglecting ergonomic principles, and hazards generated by erroneous human intervention. For each hazard causes/treats/initiating events, consequences, and controls (preventive and mitigating) are identified and recorded (i.e. HAZID findings and results), following Bow Tie Hazard and effect model in Figure 2-1 [52]. The diagram and model in Figure 2-1 is shaped like a bow-tie, creating a clear differentiation between proactive and reactive Hazards and Effects. The hazard and top event always appear together in the center of the bow-tie diagram.

A hazard is something with the potential to cause harm. If the hazard is kept under control then it is ‘safe’ and unwanted consequences will not arise. A cause is something that can start a sequence of events that, if unchecked, will lead to the top event. If a cause is present, and there are no barriers in place to intercept it, then the top event will occur. For example, over-pressurisation could be a cause of loss of containment/tank of a hydrocarbon carrying LNG/ Gas fuel. Causes appear on the left hand side of the bow-tie diagram. Causes should be independent of each other and should lead to the top event directly. Causes should not be failures of equipment as this is in fact a barrier failure.

A consequence is an unwanted, undesirable and potentially dangerous outcome of the top event occurring. A consequence results in loss or damage. It is common to think of consequences as impacting on people, the environment, assets, business and reputation. More Safeguards/barriers are put in place to try and stop the top event from developing into the consequences. Consequences appear on the right hand side of the bow-tie diagram. Barriers control the top event, by either preventing it occurring or preventing the consequences should it occur. Preventive barriers (also called Safeguards) appear on the left of the diagram and are designed to prevent the top event from taking place. They should be seen to completely prevent each cause from resulting in the top event occurring. Mitigation barriers appear on the right of the diagram. Given that control of the hazard has been lost they are designed to be able to prevent the consequences. Barriers should only ever appear on one side of the bow-tie diagram, and not on both sides. Barriers can, however, appear on a number of cause lines simultaneously.

2.3 Findings and results

The identified hazards have been summarized in Table 2-1. Figure 2-2 classified and ranked main hazards and consequences. Total 34 Hazards have been identified which ranked with respect to: Fire/explosion – LNG initiated (19), loss of propulsion power (3), dropped objects(3), collision(2), fire/explosion - not LNG initiated (1), other hazards generated by materials and substances (1), leakage of liquid LNG causing loss of structural integrity(1), grounding(1), foundering(1), hazards during installation(1) and hazards during scrapping(1).

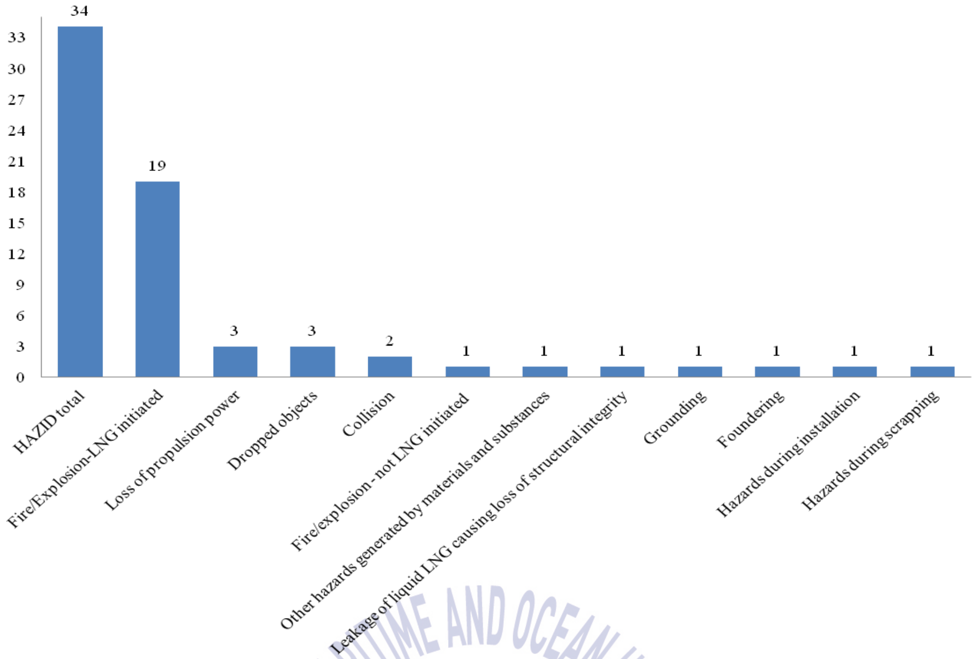


Figure 2-2 Classifying and ranking main hazards

Table 2-1 Hazard Identification (HAZID).

ID	Hazard	Cause	Consequence	Safeguards
1	Leak in bunkering manifold (flange connection) during ship-to-ship (STS) bunkering.	1. Human error 2. Design. 3. Wear and tear. 4. Smaller leaks may be difficult to detect. 5.Bigger scale (1000 m^3 per hour) and high pressure 6.Long filling time (7 hour), i.e. longer hazard exposure 7.Dropped objects 8.Mooring failure (ship drifting and breaking connection between shore	1. Outflow of LNG. 2. Flash fire/pool fire if ignition source present, (e.g. use of non-explosion equipment). 3. Injuries/fatalities to crew. 4. Large amount of liquid may be released due to rupture of hose or connection break. 5. Frost burns. 6. Potential escalation to dislodge neighboring equipment.	1. Design according to standard and regulations [8-9]. 2. Drip tray at bunker station (draining out to sea, avoiding brittle fracture for small leaks). 3. Bunkering procedures (tighten the flange is important). 4. This area is classified as a gas zone 1 and then will require explosion proof equipment. 5. Gas detection sensors. 6. Pressure measurement upstream and downstream of the manifold. 7. Personnel performance equipment(PPE) during bunkering. 8. The certified flexible hose by recognize

ID	Hazard	Cause	Consequence	Safeguards
		and Vessel, or between bunker ship and the receiving Vessel)		organization/certified body. 9. Emergency shutdown (ESD) system. 10. Procedures for mooring and ship-to-ship (STS) bunkering. 11. Weather restrictions. 12. Watchmen onboard the bunker ship and receiving vessel. 13. Installation and commissioning procedures including leak test. 14. Limited flange connection-all welded pipework/or Stud fitted flange. 15. Training of personnel. 16. Regular inspection and maintenance. 17. All piping located underneath dropped object protection. 18. Pipe stress analysis to be conducted considering cool down and heat up. 19. Emergency plan and procedure. 20. Dry chemical powder and water spray remotely controlled from fire control station in accommodation. 21. One fusible plug by vapor return valve automatically trigger ESD in event of fire.
2	Shutdown of gas supply from fuel tank to engines resulting in blackout.	Gas detection (two gas detectors)	Lack of power (blackout), may increase the severity in case of accident (e.g. fire), i.e. running of emergency fire pumps etc.	1. Dual fuel, the vessel may also run on diesel oil 2. For system configurations with inherently safe machinery spaces, there are two situations where automatic shutdown of gas supply to engine room is required, according to the requirements for gas supply system safety function [8-9]. 3. Also, automatic shutdown (ESD) should

ID	Hazard	Cause	Consequence	Safeguards
				only be given if there is gas detection in two detectors. Gas detection in one detector should give alarm.
3	Leak in bunkering pipes to LNG tank	leak in pipes, cracks etc.	Liquid leak	1. Double piping or pipe and ducting 2. Leak is vented to mast 3. The duct is monitored by the gas detectors.
4	Overpressure in tank (during bunkering)	1. BOG suction function on the bunker ship or land facility is failed. (Capacity of BOG compressor of the vessel is not considered to return the BOG at the bunkering operation) 2. Higher temperature of the LNG fuel tank or higher flow rate of bunkering.	1. Pressure will increase in the tank 2. May result in tank rupture and flash fire/pool fire/explosion	1. Vapour return system to shore or feeder ship during bunkering 2. Pressure monitoring of LNG fuel tank 3. Reduce flow rate or stop bunkering operation (ESD). 4. Safety valves (pressure relief), no damage is expected (gas will be vented through mast).
5	LNG leak in the tank containment system	1.Cracks due to fatigue 2.Corrosion, erosion 3.Operation exceeding maximum design condition (pressure, tempreture) 4.Ship collision and grounding 5.Human error 6.Lack of testing following construction 7.Failure of	1. Release of LNG in "Room for LNG tanks" 2. Both fire/explosion risk and frost burns to crew. 3. Gas released from vent system being ignited (Flash fire burning back to the vent mast where the gas will continue to burn as long as it is released. Consequences will depend on the vented gas rate and venting duration). 4. Cryogenic	1. Design according to standard and regulations 2. Drip trays for LNG tank designed to meet requirements 3. Two barriers for tank plus the "Room for LNG tank" as secondary/partial barrier 4. Tank Insulation 5. Ventilation to mast (evaporated LNG) 6. The annular space between the LNG fuel tank and the insulation will have continuous nitrogen supply and no venting to open deck 7. Design for fatigue life in the tank structure

ID	Hazard	Cause	Consequence	Safeguards
		tank bulkhead (e.g. welding defect, material defect, and sloshing)	vapor inside inerted hold space 5. Overpressure of hold space 6. Damage to hold space bulkhead	
6	LNG tank located below accommodation	Fire/Explosion in the LNG tank (below accommodation)	1.Fire/Explosion in accommodation area 2.Consequence high for crew	Design according to standard and regulations
7	LNG leak in pump room (HP/LP Vaporizer, Gas heater, Connections, Compressor)	1.Malfunction/failure of equipment 2.failure in the vaporizer 3.High pressure piping (for main engine) 4.more crew present for maintenance in pump room, in general there is expected some activity in this space.	1.Liquid/gas leak inside the pump room while crew is present with a following ignition due to use of non-explosion equipment or other types of ignition sources. 2.Flash Fire/Jet fire/ explosion risk 3. Gas released from vent system being ignited (Flash fire burning back to the vent mast where the gas will continue to burn as long as it is released. Consequences will depend on the vented gas rate and venting duration).	1.This area is classified as a gas zone 1. 2.The pump room is also classified as machinery space category A according to IMO Interim Guideline and should thus have appurtenant fire protection/insulation. 3.Ventilation (30 air changes per hour) 4.Gas detection and shut down (ESD). 5.Materials of piping in pump room of stainless steel 6.Connections covered in order to prevent spray/splash if leak. 7.Dome top covered by stainless steel
8	Leak in piping leading to the GVU room (inside the pipe recess)	High pressure (250-300 bar) gas passing inside the pipe recess without double piping (only one pipe and ducting)	1.Rupture of the pipe and high pressure gas leak is possible (jet fire), not only leak from connections 2.Vented to mast (large gas cloud), dispersion and	1.Pipe and duct (pipe recess) for low pressure gas to aux. engines and high pressure gas to main engine. 2.Suitable materials seamless carbon manganese steel with cast steel valve bodies. 3.Protection of flanges from

ID	Hazard	Cause	Consequence	Safeguards
			gas cloud may be ignited (flash fire).	cold jets (gas leak) 4.ESD 5.Ventilation 6.Gas detection
9	Gas leak in GVU room from piping, connections, valves	any malfunction causing leak inside the GVU room	1.Gas cloud release, vented to GVU exhaust line. 2.Crew is normally not expected to be present in the GVU room, besides maintenance.	1.Gas detection 2.Ventilation 3.ESD 4.Zone one protection equipment
10	Gas leak in the engine room	1. Leaks in valves, pipe connections 2.Corrosion and erosion 3.Vibration 4.Dropped objects 5.Gas ingress to engine room from GVU room	1.Ignitable mixture of gas 2.Ignition of such a cloud (flash fire) due to possible sparks from non-explosion proof electrical equipment or faulty ex-equipment. 3.Multiple fatalty	1.Engine room is classified as inherently gas safe machinery space. 2.Ventilation system 3.Gas detection in double walled piping inside engine room 4.ESD 5.Installation and commissioning procedure 5.Positive air pressure maintained in the engine room 6.Negative air pressure maintained in the GVU room minimizing gas release to engine room from GVU room 7.Engine room ventilation
11	Ignition failure (start-up of engines)	Malfunction of engine	1.Gas leak to exhaust system 2.Flash fire/explosion	Interim Guidelines states in “Requirements dual fuel engines that start and normal stop should be on oil fuel only. Gas injection should not be possible without a corresponding pilot oil injection [9].
12	Gas in the exhaust system	1.A leak from the exhaust system during start-up of the gas engines. 2.Fail in ignition	Flash fire/explosion	1.It is required that exhaust receiver is equipped with explosion relief ventilation to prevent excessive explosion pressures or the exhaust system has

ID	Hazard	Cause	Consequence	Safeguards
		system		sufficient strength to contain the worst case explosion. 2.Ventilation system in exhaust systems for gas fueled engines.
13	Fire/explosion or uncontrolled release of gas from the bunker ship affecting the vessel.	Any fault or malfunctions on the feeder ship	1.Fire (if ignition source exists) resulting in personnel injuries and/or brittle fractures of materials 2.Gas may be vented to mast a may reach possible ignition sources on the Vessel (gas cloud escaping the safety zone)	1.Vent mast on bunker ship 2.Safety systems onboard the Vessel and bunker ship
14	Hazards to 3rd party (yard) due to venting gas during docking.	any hazardous situations leading to venting of gas during docking (opening of pressure-relief valves)	Gas may ignite when reaching the yard/dock	1.Tank freeing system to empty the LNG tank before docking (liquid discharge followed by heating), 2.No LNG in the tank (gas free ship) during docking, etc. thus no venting, 3.Possible to inert the supply system while doing liquid discharge.
15	Hazards to crew due to vessel in lay-up condition	Continuous boil-off gas (need to handle BOG)	Pressure increase in the tank	1.Ship should not be cold-ship during lay-up, continually running of generators. 2.Possibility to gas-free the ship before layup
16	Entering hazardous areas for maintenance (e.g. pump room or GVU room)	Inspections, maintenance	1. Ignition sources may be present during maintenance (welding etc.) 2. Flash fire/explosion risk	1. Isolate local systems and rooms by valves for maintenance 2. Drain and inert (gas-free) before entering the space 3. Gas detectors 4.Ventilation
17	Transfer of gas to vent head	1.Leakage 2.Mechanical damage,	Release of minor amounts of gas into non-	1.Vent piping of stainless steel 2.Routing and shielding of

ID	Hazard	Cause	Consequence	Safeguards
		fatigue	hazardous spaces	piping, protecting for mechanical damage
18	Blockage of vent mast	Materials or ice formation	Failure or reduce pressure relief, with subsequent pressure increase in tank.	This is normal standard for gas vessels.
19	Fire/explosion(switchboard rooms(both sides of ECR), Aux.boiler,lub oil system, Engine workshop, Cargo/containe r)	1.Explosion in the switchboard (short circuit, breaker fails etc.) 2.Human error 3.Malfunction and failure	1.Fire/explosion 2.The fire may escalate to the LNG fuel system	1.The switchboard will be located in a separate room 2.A60 fire protection 3.Fire detection and gas supply shut-down (ESD)
20	Fire on container deck impacting bunker areas	1.Fire in one of the containers 2.Human error	Escalation to bunker area during bunker operation	1.Stowing arrangement to prevent hazard material being stored in this area 2.Emergency plans and procedures 3.Dry chemical powder and water spray remotely controlled from fire control station in accommodation 4.Water curtain 5.LNG and vapor lines inerted when not in use 6.Ship-to shore and ship-to-vessel communication link to allow remote shutdown of LNG supply pump and valve.
21	1.Hazards from contact with or inhalation of harmful fluids, gases, mists, fumes and dusts 2.Asphyxiation	Entering gas dangerous spaces of zone one, e.g. bunker station, pump room or GVU room	Injury or fatality	See separate safeguards for bunker station (HAZID ID No.1), GVU room (HAZID ID No 9.) and pump room (HAZID ID No.7).
22	Brittle fracture of structures	LNG spill	Loss of structural integrity	1.Stainless steel drip trays below potential LNG leak sources (bunker station and

ID	Hazard	Cause	Consequence	Safeguards
				LNG tank) 2.Equipment of stainless steel
23	Damage to pipes/pipe recess (starboard or port side)	1.Low energy collision 2.Hit by other vessel 3.Navigation error of other ship	1.Gas leak up to accommodation 2.Some gas, but very limited amount	1.Adequate shutdown (ESD) to be provided to minimize gas volume to be released. 2.Pipe, duct and ventilation 3.Gas detection sensors
24	Damage to LNG tank	High energy collision or other type of impact	1.Outflow of LNG 2.Large pool fire on sea.	1.Design according to standard and regulations 2.B/5 from ships side 3.Diesel oil tanks (on both sides) will also functions as protection 4.Independent tanks
25	Failure of the HP pump for main engine	Malfunction/system failure	1.No gas supply to main engine 2.Loss of power for propulsion	Duel fuel system, may run on diesel oil
26	Black-out (major system failure)	Any system failure causing blackout, e.g. short circuit in switchboard.	1.Loss of power for vaporizers, gas heaters etc. 2.Trapped LNG/freezing equipment may cause these equipment to break/fail due to the lack of circulation	1.Stand-by generators will be started before using emergency generator. If no standby generator is started, emergency generator will be used. (It is the second or third back up). 3.LNG will evaporate 4.Safety valves (if high pressure)
27	Failure of glycol system (lack of re-circulation)	Any causes leading to brine/glycol system failure	1.Gas heater will not function and we cannot send gas to engine, will thus need to vent the gas. 2.Lack of circulation 3.Not very safety critical, more an environmental issue	One of the Brine pump supplies electric power from emergency generator.
28	Dropped object on bunkering hose	Container(s) falling on the bunkering hose(s)	1.Large leak 2.Ignition sources resulting in flash fire/pool fire	1.Containers will come from quay side (not on feeder ship side) 2.Loading procedures and Securing containers

ID	Hazard	Cause	Consequence	Safeguards
				according to industry guidelines
29	Dropped objects on Pump room (below cargo deck)	1.Any impact loads that could penetrate the deck and further damage LNG equipment in Pump room. 2.Falling containers 3.dropped objects from provision crane	1.Flash fire/Explosion 2.Crew injuries/fatalities	1.Deck structure (strength) 2.Sensors for pressure drop, will lead to shut-down
30	Dropped objects inside the pump room	Lifting activity inside the pump room	1.Cutting gas pipes 2.Damaging equipment 3.Fire/Explosion	
31	Grounding	Any failures causing vessel to ground	1.Water ingress/filling of LNG tank space 2.Damage to tank, but we should have no dangerous leak of LNG from the tank	1.Support in upper deck (protect from tank impact) 2.Independent tanks 3.Anti-floatation supports 4.Tank can be damaged or be buckle, but not collapse (primary members in the tank should take these loads)
32	Foundering	Any causes leading to foundering	1.If the vessel sinks or list, LNG will probably start to “leak” from the tank. 2.Natural BOG and maybe leak due to tank/piping damage.	Evacuation of crew in lifeboats and life rafts before the vessel sink.
33	Hazards during installation (at dock/yard).	First time in use	Leakage in LNG fuel system equipment	1.Supervision by LNG fuel system supplier 2.FAT testing for valves etc. standard test, including pressure testing for leaks etc. 3.First test with diesel fuel, then do the “gas trial” 4.Part of the gas trial to check for leakages 5.Using yard with experience in building LNG

ID	Hazard	Cause	Consequence	Safeguards
				carriers (known concept – LNG fuel system)
34	Hazards during scrapping of the vessel.	Vessel to be phased out, no more in service due to age and market situation	Scrapping	Gas free (same as for entering dry-dock)

2.4 Recommendations

Total 18 recommendations with comprehensive summary in term of design and operation proposed and made covering a wide-range of design and operation topics with the division in high prioritization for follow-up. Several important gaps beyond mandatory regulations, standards, guidelines or of relevant organizations have been identified requiring for action under the recommendations below.

a) The following design recommendations should be considered for the safe operation of gas fueled container ship based on HAZID findings and results:

1. Thermal shielding of ship structure by use of water curtain.

A water curtain system covering the bunker area and side shell to mitigate damages in case of LNG leakage should be considered. While the drip tray in the bunker station is intended for small leaks, the waterfall curtain will provide thermal shielding to protect and maintain the integrity of the ship's structure, including tanks and neighboring equipment in case of larger liquid leaks during bunkering.

2. Mechanical ventilation in bunker station.

Mechanical ventilation should be provided in the semi-enclosed bunker station to prevent any accumulation of gas. The bunker station is too enclosed to ensure efficient natural ventilation, thus mechanical ventilation should be added.

3. Avoiding blackout when automatic shutdown (ESD) is activated.

A gas leakage with required shutdown (ESD) functions should not take out the whole propulsion and power generation system, thus causing blackout. For system configurations with inherently safe machinery spaces, there are two situations where automatic shutdown of gas supply to engine room is required according to the international requirements for gas supply system safety functions. also, automatic shutdown (ESD) should only be given if there is gas detection in two detectors. Gas detection in one detector should give alarm.

4. Full double pipe arrangement for high pressure piping.

Due to high pressure (300 bar) gas passing inside the pipe recess without double piping (only single pipe and ducting), full double pipe arrangement inside the pipe recess should be considered, concerning the crew safety and structural integrity. Protection of flanges only may not be sufficient. Rupture of the pipe, not only leak from connections, due to high pressure is possible. Alternatively, the pipe recess (ducting) should have sufficient constructive strength to maintain its structural integrity in case of pipe rupture, e.g. pressure testing etc., and installed and protected so as to minimize the risk of injury to personnel in case of rupture.

5. Airlock for access to the GVU room.

Direct access through doors, gastight or otherwise, are generally not be permitted from a gas- safe space to a gas-dangerous space according to the IMO Interim Guidelines.

non - hazardous spaces (Engine room) with opening to a hazardous area (GVU room) should be arranged with an air-lock and be maintained at overpressure relative to the external hazardous area. This to prevent any gas from the GVU room reaching the engine room, which contains non-EX rated equipment, i.e. may ignite the gas.

6. Redundant gas heating system for supply to generator engines.

Arrange for an additional heat exchanger for use as back-up for the one (1) gas heater currently proposed for supply of gas to generator engines. If the one gas heater does not function the Vessel need to vent the gas. This is not a safety critical issue, but an environmental concern.

7. Locations of double pipe ventilation air inlet and exhaust to be in safe position. in addition, the locations of vent mast to be especially considered to prevent ignition from funnel and ingress into any air inlet. ensuring also vent piping are routed in a way that external leakage do not result in hazardous

situation (e.g. release of gas to container spaces, accommodation).

8. High pressure components in the gas injection and system are to be designed in accordance to international standards.

b) The following operational recommendations should be considered for the safe operation of gas fueled container ship based on HAZID findings and results:

1. Attention to dropped objects, i.e. restrict/prohibit loading of containers near bunker station while bunkering.

It should be proposed to restrict/prohibit loading near the bunkering station while bunkering LNG in order to avoid containers tipping over the side (on water side/bunker ship side) or unintentionally being dropped on the bunkering hose or above the pump room. There should be constant monitoring of the entire bunkering operation, and use of watchmen. Company procedures should also be established for special concerns regarding internal lifting activity in the pump room and protection of LNG equipment.

2. Using checklist during bunkering.

Procedures/checklists should be established between ship owner and gas supplier for safe bunkering operation. The bunker station should have restricted access during bunkering operation, i.e. safety zone to be established. Make sure that the responsibilities during the LNG bunkering process are clearly defined for all foreseen LNG bunkering configurations and locations. The bunkering procedures are the preferred instrument to document the responsibilities during LNG bunkering.

3. Entering hazardous areas, e.g. pump room and GVU room.

Personal protective equipment shall be mandatory for entering the pump room due to cold piping and high pressure systems. In addition, training of personnel to operate the system should be given.

4. Harmonize the requirements for emergency repairs (including competence requirements of personnel performing these activities) of LNG fueled vessels in shipyards and develop initiatives to build competence and knowledge with regard to salvation of LNG fueled vessels.

5. The main potential for risk reduction is the potential for personnel to escape. Key aspects of that include, ensuring that detection of releases is communicated to personnel onboard effectively, and in terms of minimizing risks to personnel, and from delayed ignition events in particular, the most effective mitigation is to escape to a place of safety, which is either to accommodation or suitable shelter or to an area outside the flammable cloud envelope. The former is the most reliable, although the latter is likely to be practicable in most cases (noting however that the larger releases, e.g. due to collision or large leak during bunkering, will cover a significant proportion of the Vessel). Training is fundamental in escape, although measures such as temporary shelters or ensuring that accommodation can be used as required are recommended.

6. Fatalities during the actual evacuation by lifeboat or liferaft, e.g. due to malfunctioning of the evacuation means, or as a consequence of the attempted escape by sea may occur.

7. Continuously promote the developments on the effect of Methane Number over dual fuel engine operations. Operational guidelines need to be developed to reduce potential negative environmental impacts related to the possible release of methane. Establish a comprehensive approach for methane slip management, i.e. boil-off gas, vapour management and emergency venting.

8. It is also recommended to work actively to promote a strong and sound safety culture. Involvement by all parties in the organization in the process of defining, prioritizing and controlling risk and Hazards along with a sense of shared purpose in safety, is important to the health and safety level onboard the vessel.

9. The Busan port and Bandar Abbas port specific location for LNG Bunkering

by ship to ship (STS) or other means to be separately assesses to identify HAZID (if any) and mitigate and eliminate potential Hazard. The actual risk will depend on the location of operation, also taken in to account analysis of the following parameters such as:

- Operating environment (Service conditions between various ships may differ, and these might result in different leak frequencies for otherwise similar equipment. Comparisons of data sets from different ships are difficult because of inconsistent reporting, varying standards of safety management, different types of fluid and differences in environmental factors).

- Safety management (The quality of operation, inspection, maintenance etc. is a critical influence on leak frequencies. The leak frequencies for ships with lower standards may be higher).

- Materials (As different materials have different properties for corrosion, erosion, fatigue, etc., the materials used for the gas fuel system design is expected to affect the leak frequencies).

- Operating conditions (temperature/pressure) Equipment operating close to its design pressure may be more vulnerable to accidental overpressure. also, equipment operating above or below the normal temperature for its material of construction may be more vulnerable to material failure.

- Equipment age (in theory, new equipment is vulnerable to teething problems and old equipment to wear-out, producing a bath-tub curve of failure rate versus time. Equipment that is subject to corrosion or fatigue is normally designed with a finite life, and the probability of failure increases as it nears the end of that period).

- Process continuity (Many failures occur during shut-down or start-up. Failures are e.g. more likely in systems that experience many shut-downs).

- Manning levels (A high manning level is expected to increase the risk for process leaks as a large fraction of the registered leaks are related to some kind of human impacts/interventions. An increased activity level in vicinity of the gas fuel system may thus increase the potential for damaging equipment).

10. Arrangements for simultaneous bunkering and use of Accommodation ladder near to the bunker station are to be considered.

In summary, the proposed recommendations shall be taken into account and consideration as follows:

1. Work actively to promote a strong and sound safety culture, involvement by all parties in the organization in the process of defining, prioritizing and controlling risk and Hazards along with a sense of shared purpose in safety, is important to the health and safety level onboard the vessel.

2. The bunkering procedures are the preferred instrument to document the responsibilities during LNG bunkering.

3. The bunker station should have restricted access during bunkering operation, i.e. safety zone to be established.

4. Personal protective equipment shall be mandatory for entering the pump room due to cold piping and high pressure systems.

5. Training and competency of personnel to operate and do maintenance of the system should be given.

6. Escape and evacuations routes and means are to be always available, at least two widely separated escape routes and two evacuations means.

7. Operational guidelines need to be developed to reduce potential negative environmental impacts related to the possible release of methane. Establish a comprehensive approach for methane slip management to mitigate and eliminate both environment and Safety operation of Engines.

8. The parametres such as Operating environment, Safety management,

Materials specification/properties, Operating conditions, Process continuity and Manning levels for specific location of LNG Bunkering by ship to ship (STS) or other means to be assessed to identify HAZID and mitigate and eliminate potential Hazard (if any).

9. The separate HAZID study and investigation on-site shall be conducted in selecting an appropriate and feasible potential LNG bunkering methods and locations at Bandar-abbas port and Busan port considering the relevant hazards and risks at assumption locations. The focus of the selection bunkering methods (i.e. ship to ship, truck to ship transfer via flexible hose, intermediate tank to ship transfer and portable tank to ship bunkering methods) should also comply with relevant national regulatory requirements on usage of LNG as a marine fuel, and provision of bunkering services are to be also considered as part of the location selection and risk identification exercise.

The existing structures are to be evaluated whether capable of being accommodating such activities without upgrading and rebuilding the jetty (Technical feasibility and significant costs). The main selection criterion should be the potential technical & operational capabilities of handling LNG bunkering in these areas, without requiring prohibitive infrastructure development. In addition, all the locations are able to meet the requirement of suitably distant from on-site operations and populations. The HAZID study are to be aimed to answer the key question of whether LNG activities would be possible at the proposed locations, from the perspective of major risks, public safety or other activities in the direct vicinity, where specific major risks or public safety issues are identified, the study will advise on a set of possible mitigation measures.

The HAZID study for LNG bunkering at Bandar Abbas port and Busan port shall be included the following steps: Assumption of terminal layout, and fuel consumption of vessels, assessment of surrounding area of the location, including the potential presence of population, industrial areas, waterway traffic, nautical layout, etc., Identification of major hazards and high level assessments of credible events associated with the LNG bunkering operations, Hazard identification Study, Identification of significant consequences which could imply strong arguments to effect the continuation of the present efforts on the proposed project and the necessary mitigation measures to enable the continuation of the project, Risk ranking based on the consequence and likelihood.

The study should conclude, that it is technically feasible to locate an LNG bunkering facility at proposed locations/ jetties while meeting the requirements of local and international regulations and standards.

2.5 Conclusions

The overall, and the key results from the HAZID covering entire range of potential safety issues and the various types of Hazards that reached a good level of safety and no Safety and technical showstoppers identified. the HAZID results confirm that there are no major HSE showstoppers to carry out construction and conversion on vessels using dual fuel. The main selection criterion was the potential design, worst case scenario for location of LNG tank below accommodation, technical and operational capabilities in conducting such HAZID study and investigations.

The estimated HAZID increase is mainly due to the presence of the LNG tank and its effect on the risk from fire/explosions due to ship collision. A dropped container may potentially penetrate the main deck and damage gas piping and equipment in the pump room if dropped from large heights. However, a dropped container may only penetrate the main deck structure if no other containers are stored on the main deck. a dropped container may also damage/rupture the bunker line/hose if dropped and tipped over the ship side and onto the bunker ship/barge, causing fire/explosion.

Several important gaps in mandatory regulations, standards, guidelines or of relevant organizations beyond mandatory regulations have been identified requiring for action following the recommendations, however study can conclude, that it is technically feasible for the arrangement and installation of machinery for propulsion and auxiliary purposes, using natural gas as fuel, which will have an equivalent level of integrity in terms of safety, reliability and dependability as that which can be achieved with a new and comparable conventional oil-fueled main and auxiliary machinery, while meeting the requirements of local and international regulations and standards.

The study and investigation can conclude that there are no HSE (Health, Safety and Environment) show stoppers for construction/ conversion of conventional oil-fueled to dual fueled using LNG which HAZID can also be mitigated and eliminated with sufficient design, engineering and operational controls that meet the required standards.

Chapter 3 Fire and explosion for LNG fueled ship

3.1 Introduction

This section presents the concept risk analysis of LNG initiated accidents caused by the presence of the LNG fuel system. The hazards mainly relating to LNG leaks, either in liquid or gaseous phase, which may ignite if there is an ignition source present. Event Tree Analysis (ETA) has been used to track outcomes from the specified initiating event (i.e. LNG and/or gas leakage). Furthermore, the in- house software Phast has been used for dispersion calculations. The final risk figures have been quantified in terms of Fatal Accident Rates (FAR) for comparison to the diesel fueled reference ship.

The fire hazards related to the machinery spaces in general, as well as fire/explosions in other areas i.e. those not initiated by the LNG system, are added to the quantification of the total risk presented in this section.

3.2 Modelling principles

Since risk is the product of frequency and consequence, estimating the frequency with which events occur is as important as accurately predicting the consequences to the overall risk. High consequence events which occur infrequently may contribute as much to the overall risk as frequent events which have smaller consequences.

A flowchart showing the principles for modelling the fire/explosion risk for LNG initiated events is shown in Figure 3-2. The initiating event is LNG and/gas leak and the analysis further differentiate between the probability of immediate ignition and delayed ignition. The end event is either a fire (flash, jet or pool) or vapour cloud dispersion with no ignition

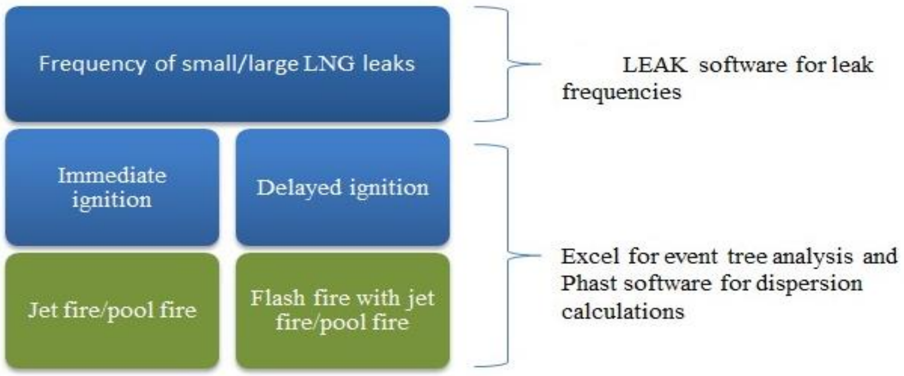


Figure 3-1 Modelling principle of LNG leaks

The LEAK software has been used for predicting leak frequencies, ETAs were used for tracking outcomes from the original leak event and Phast software has been used for gas dispersion modelling. The fire/explosion risks not related to the gas fuel system has been assed based on data from the IHS Fairplay Casualty Database [53]).

3.3 Fire and explosion due to leak in LNG fuel system

This main chapter provides the fire/explosion risk assessment of LNG initiated events, i.e. accidents caused by the presence of the gas fuel system. Based on the findings in the HAZID the main safety concern is LNG leaks, either in liquid or gaseous phase, which may ignite if there is an ignition source present. The present safeguards at the various hazardous spaces, e. g. bunker station, pump room and GVU room, with the objective to reduce the frequency of leaks and its consequences are described in Analysis Basis. Double failure, e.g. failure in both inner and outer pipe at the same time, is extremely rare events and is not considered in this assessment.

3.3.1 Initial events – LNG leaks

The LNG leak events are based on the findings of the Hazard Identification (HAZID). The leaks are considered and assessed in eight (8) different initial events, as illustrated below

- Initial event 1: Liquid leak by the bunker station during bunkering
- Initial event 2: Gas leak by the bunker station during bunkering
- Initial event 3: Liquid leak from LNG fuel tank
- Initial event 4: Liquid leak in pump room
- Initial event 5: Gas leak in pump room
- Initial event 6: Gas leak in pipe recess (inner piping)
- Initial event 7: Gas leak in GVU room
- Initial event 8: Gas leak in Engine Room (inner piping)

Leaks from the following spaces containing gas fuel piping or liquid storage have been applied in the analysis:

- **Bunkering station**

Liquid leak at the connection point of the liquid filling line (Initial event 1) or gas leak of the vapour return line (Initial event 2) could occur during LNG ship-to-ship (STS) bunkering operations due to design errors, poor maintenance or incautious handling of the bunkering equipment (human error).

Leaks and fire/explosion events on the bunker vessel are not part of scope of work for this risk analysis.

- **Room for LNG tank**

The LNG is carried in a cryogenic storage tank at temperatures down to -162˚C located within the “Room for LNG tank”. Leaks due to corrosion is considered negligible because of aluminium alloy tank material. However, vibrations, temperature fluctuations, material fatigue or other mechanisms may lead to cracks or ruptures resulting in leaks (Initial event 3).

- **Pump room**

The pump room (i.e. the “Tank Connection Space” defined by IMO) surrounds all connections to the LNG fuel tank and contains several potential leaks sources, e.g. single walled piping, high pressure pumps, vaporizers, gas heaters and compressors for gas supply system to main engine and generator engines. Joints, valves and fittings are common origins of leakage due to features such as loos bolts, ruptured gaskets or failed instrument connections. Maintenance work also gives rise to leaks, usually caused by failure to ensure isolation of the equipment or failure in re-connecting back to original state. The leaks may be released in either liquid (Initial event 4) or gaseous phase (Initial event 5) depending on whether the leak occurs before or after the vaporizers.

- **Pipe recess**

Two pipe recesses for gas supply system are provided below the under-deck passage on each side of the vessel between the engine room and pump room. Due to the single walled piping and high pressure (between 150 bar–300 bar for gas supply to main engine and 4 bar-5 bar for gas to generator engines) this increases the probability of leaks (Initial event 6) in the pipe recess. Pipe connections in the pipe recess are welded joints.

- **Gas regulation (GVU) rooms**

The objective of the gas valve units is to measure and regulate the gas flow to the generator engines. Possible leak (Initial event 7) sources are valves, flanges and single walled piping. Causes are very much the same as those described for the equipment in the pump room (previous page).

- **Engine room**

All gas supply piping in the engine room is to be double walled and some pipes are also located under-deck. Leaks in the inner piping (Initial event 8) may occur due to vibrations, temperature fluctuations, material fatigue or other mechanisms that may lead to cracks or ruptures resulting in leaks.

Furthermore, the initial events have been assessed and linked to three (3) main categories of possible consequences:

1. **Leaks during bunkering** .

Liquid- and gas leak during bunkering operation (initial event 1-2)

2. **Immediate ignition during normal operation, excl. bunkering operations**

Immediate gas ignition occurring within the space of the leak source during normal operation (initial event 3, 4, 5, 7)

3. **Delayed ignition during normal operation, excl. bunkering operations**

Leak vented and reaching potential ignition source during normal operation (initial event 4-8), excluding bunkering operations.

3.3.2 Leak size

The leaks are categorised based on leak sizes as follows:

Small leaks: Hole size range 1 mm-10 mm, representative hole size 10 mm.

Large leaks: Hole size range 10 mm – equipment diameter, representative hole size equal to equipment diameter.

3.3.3 Frequency assessment

In order to estimate the frequency of leaks the LEAK software has been used. The software tool establishes leak frequencies for sets of equipment, segments, areas and installations from a set of base element data. For this analysis the LNG equipment data is based on gas fuel supply system. The software then links the equipment data with a large Hydrocarbon Release Database (HCRD) of historical failure frequencies of equipment gathered from offshore installations in the North Sea and from onshore industry, and multiply these frequencies by the inventory of our gas fuel system. Accordingly, frequencies are adjusted with regards to number of equipment, pressure in pipes, and with regards to the assumed length of gas pipelines.

Other failure data sets exist that attempt to provide failure rates for cryogenic pipework, or for LNG- specific operating experience in general. Currently, such data sets are not considered to be sufficiently robust to justify any modification to or verification of the generic data derived from the HCRD (or other established sources). Thus, the HCRD database is recommended as the basis for the process and pipework failure data.

Most of the equipment for the gas fuel system may be made of stainless steel and specifically designed for cryogenic temperatures. The applied leak frequencies are thus considered to give a conservative total leak frequency. However, in the absence of alternative data sources it is proposed that this is used directly, rather than estimating any modification factor, with the intention of providing a “conservative best-estimate‟ base release frequency. The estimated leak frequencies, shown in Figure 3-3, are applied in this analysis.

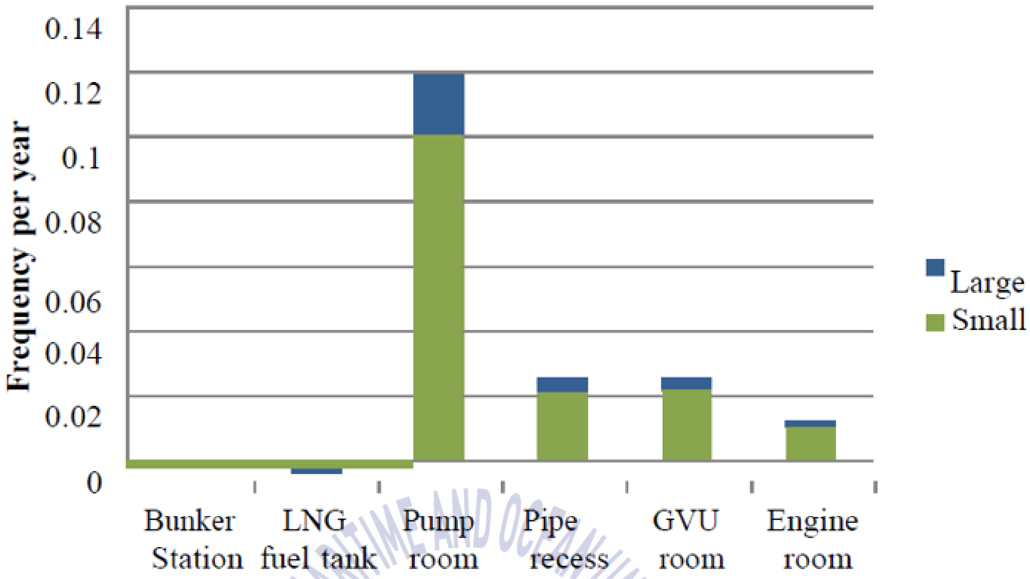


Figure 3-2 LNG leak frequency distribution by location

All piping in engine room is double walled according to the inherently safe machinery space philosophy. Leaks in the inner pipes within the engine room will thus be vented out by under pressure to outlets on deck aft of the accommodation unit. Hence, no gas will be emitted in the engine space. Accordingly, the origin of the leak and not necessarily where the gas disperses. Gas dispersion and its consequences will be described in the following chapters.

Furthermore, small leaks, such as those from pumps, valves and flanges, are quite probable, while larger leaks are less likely to occur. Due to the quantity of equipment in the pump room this space will have the highest frequency of gas/liquid leaks. The leak frequency at the bunker stations are low compared to the other locations due to the limited bunkering time. LNG bunkering only occurs 2% of the total operating time per year according to the assumed operational profile.

3.3.4 Consequence assessment

The following sections assess the consequences for the different initial events. Event trees have been used to track outcomes from the specified initiating event (i.e. gas leakage). The event tree starts with the specified initiating event and branch outward often based on binominal choices of possible outcomes (e.g. ignition? yes/no). Each branch follows the standard convention of yes upside and no downside, and the event tree shows the probability determined.

The software Phast (Process Hazard Analysis Software Tool) has been used to examine the progress of the leak to its far-field effects. Based on the initial discharge, as the gas expands from its storage condition to atmosphere, through dispersion, radiation profiles and contours from a range of fire scenarios including pool fires, flash fires, jet fires and fire balls are assessed, with distances to lower flammability limit (LFL) and heat radiation (kW/m^2). The Unified Dispersion Model (UDM) used in Phast has been extensively verified and has been validated against a large number of field experiments. Phast does however not take geometry into account, but the input parameters have been selected to take into account these effects.

Consequence modelling in Phast for each initial event involves the following main steps:

<u>Release rate and duration calculations</u>

The initial operating conditions for the bunker lines, as outlined in Analysis Basis, are used in the assessments. However, to correctly represent the large releases, which are likely to rapidly decay with time as the pressure within the pipe decreases, the release rates used further in the consequence assessments are taken as the average release rate over the first 60 seconds of the release.

<u>Gas dispersion modelling</u>

When released to atmospheric conditions, the gas is expected to cause a vapour cloud/plume. The size of the ignitable gas cloud, i.e. the distances to LFL, is important with respect to the potential for reaching ignition sources onboard the vessel, bunker ship/barge or nearby harbour facilities.

Dispersion is greatly affected by local atmospheric conditions; primarily wind speed, atmospheric stability and ground roughness. Obstructions and terrain like the Vessel's hull and placement of the bunker vessel can also be important. In order to take into account the Vessel's side and placement of the bunker vessel the wind speed (m/s) is set very low.

Stability is a measure of atmospheric turbulence. Pasquill and Gifford defined several classes of atmospheric stability; most commonly from A to F. Unstable conditions are categories A-C, the normal neutral conditions is D, while E-F are stable conditions with little turbulence. Weather roses typically show a high proportion of D stability and smaller portions of A-C and E-F stability. Thus, stability D has been used for this analysis.

A combination of calm wind and stable atmospheric conditions will make the gas cloud travel for a greater distance in contrast to more wind and turbulent stability which will cause the cloud to loop and dilute quit fast. Thus, low wind speeds and neutral stability will be worst- case scenarios for the risk calculation.

The values for upper flammability limit (UFL) and lower flammability limit (LFL) are 15% (1.5E5ppm) and 5% (5.0E4ppm). Phast somewhat under-predicts the flammable hazard zone distances when compared with field experimental data. It was thus recommended that 0.5 LFL (rather than LFL) should be used for LNG dispersion in a humid climate (i.e. coastal areas, at sea, etc.). However, for this analysis we have used LFL in order to not being too conservative. A conservative assumption has already been made regarding the release duration (shutdown time). PHAST includes the half-LFL in the contour plots, therefore the 0.5 LFL is shown in the results.

Fire modelling and radiation

The effect of thermal radiation from any fire is measured in terms of thermal radiation intensity and exposure duration. Intensity is the radiation flux (in kW/m^2). As a reference point, solar radiation on a clear day is about 1.0 kW/m^2.

The critical thermal radiation levels applied in the analysis is based on the OGP Risk Assessment Data directory, and summarized below:

Thermal Radiation (kW/m^2)	Effect
35	Immediate fatality (100% lethality)
20	Incapacitation, leading to fatality unless rescue is effected quickly
12.5	Extreme pain within 20 s; movement to shelter is instinctive; fatality if escape is not possible.
6	Impairment of escape routes
4	Impairment of lifeboat embarkation areas

12.5 kW/m^2 is the threshold limit in which personnel are likely to be killed due to excessive thermal radiation if escape is not possible, while at around 5 kW/m^2 designated safety functions (such as escape ways, muster areas, lifeboats, etc.) are impaired.

3.3.5 Leaks during bunkering (initial event 1-2)

Bunkering will be carried out in a semi-enclosed bunker station. Thus, the probability of explosion overpressure in case of an ignited leak is considered negligible. This consideration presupposes that mechanical ventilation is provided. The analysis differentiate between liquid leaks at the connection point of the liquid filling line and vapour return line, respectively, initial event 1 and initial event 2.

The bunker station is defined as "Hazardous zone 1" according to the Interim Guidelines. Immediate ignition due the presence of ignitions sources within the bunker station is thus assumed negligible.

An event tree model is established to evaluate the risk level associated with leaks during the STS bunkering. The event tree structure used in this part of the analysis is presented in Figure 3-4.

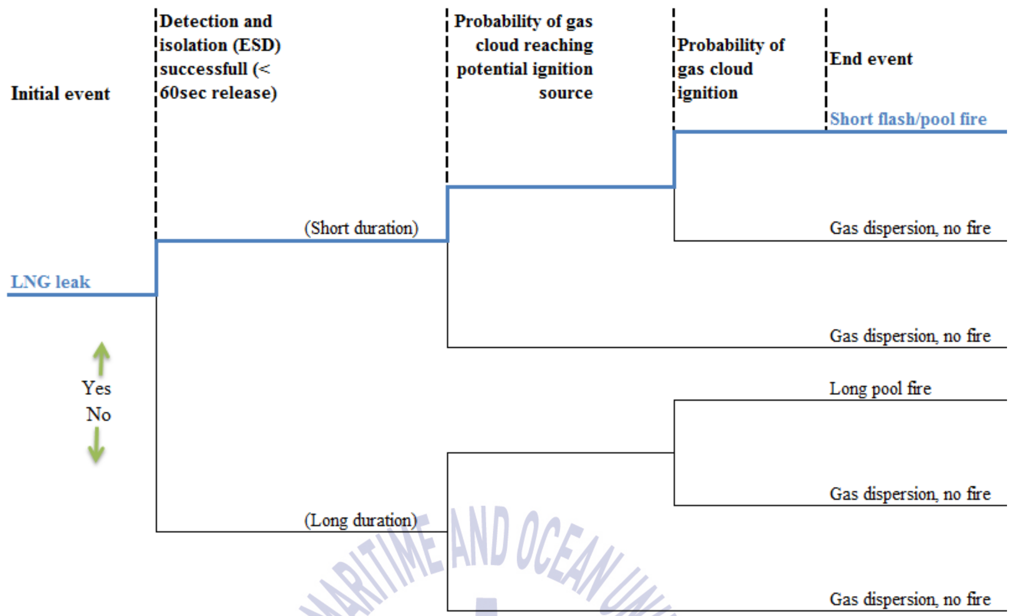


Figure 3-3 Event tree for leakage during LNG bunkering

The number of branches has been kept at a minimum in order to keep the event tree as simple as possible, whilst at the same time making sure that the most relevant accident scenarios are adequately represented. The following branches are included in the event tree:

- Probability of detection and isolation
- Probability of gas cloud reaching potential ignition source
- Probability of gas cloud ignition

The branch probabilities are determined based on the results of the consequence calculations in Phast, assessments of the safety systems, the geometry of the vessel and historical data. The end events from the trees have been grouped into the following fire and explosion consequence categories:

- Ignition, short flash/pool fire (isolation successful)

- Ignition, long flash/pool fire (no isolation)

- Gas dispersion, no ignition

A short flash fire (when the flame propagates back to the leak source) with a consecutive pool fire is thus assumed to be the worst case “fire/explosion event” for the bunkering operation accounted for in the risk assessment. This event sequence is stipulated with the blue line in Figure 3-4.

It is further differentiated between small leaks (10 mm) and large leaks (full bore rupture). The piping for the liquid filling line is assumed 150 mm and the piping for vapour return line is 100 mm, according to the assumptions in Analysis Basis.

3.3.5.1 Small leaks

The dispersion calculation in Phast, for small leaks, has been executed with the following input parameters:

- 10 mm hole diameter with 90 seconds ESD closing time
- The LNG (methane) is released in liquid state (-162°C) at atmospheric pressure
- The LNG is spilled onto water with no boundary
- Wind speed of 1.50 m/s
- Pasquill Stability class: D (neutral condition)
- Gas dispersion with free-field modelling and no obstacles

Release rate and duration

Smaller leaks are not easily detectable by the watchman on the bunker station. The cold LNG will make the pipes to freeze with some natural formation of white clouds which evidently will have the same colour as the “methane vapours” from accidental LNG leaks. For smaller leaks there will also be difficulty to detect any loss of pressure along the transfer hose compared to larger leakages. Thus, for small leaks the release duration is unlikely to be less than 90 seconds even with a comprehensive gas detection system and use of watchman with executive action. It has been assumed 60 seconds to detect and 30 seconds for the ESD valves on the bunker ship to be closed.

Results from Phast shows that the release rate of liquid LNG from a small leak would be 0.28 kg/s.

Gas dispersion modelling

The results from the gas dispersion calculations are shown for the horizontal release in Figure 6. The release is modelled from the bunker station and a generic bunker vessel of 100m in length is illustrated in the figure. The distance to LFL (5.0E4 ppm), indicated by the green contour line, is approximately 22 m from the origin of the leak. The area covered by the LFL level is used to determine the potential for ignition sources. The gas cloud will reach the bunker station and parts of the bunker ship containing several ignition sources. Thus, a 100% probability of the gas cloud reaching a potential ignition source has been applied. The 50% probability of ignition given gas cloud reaching potential ignition sources is generic and based on the RIVM, 2009 study.

The graph shows that the spilled LNG will be diluted quite fast with the gas cloud at its maximum concentration after 19 seconds.

It should be noted that the calculations are based on an average release rate the first 60 seconds of the leak. An average wind speed of 1.5 m/s is used in the calculations. The modelling does further assume unobstructed dispersion in a uniform wind field.

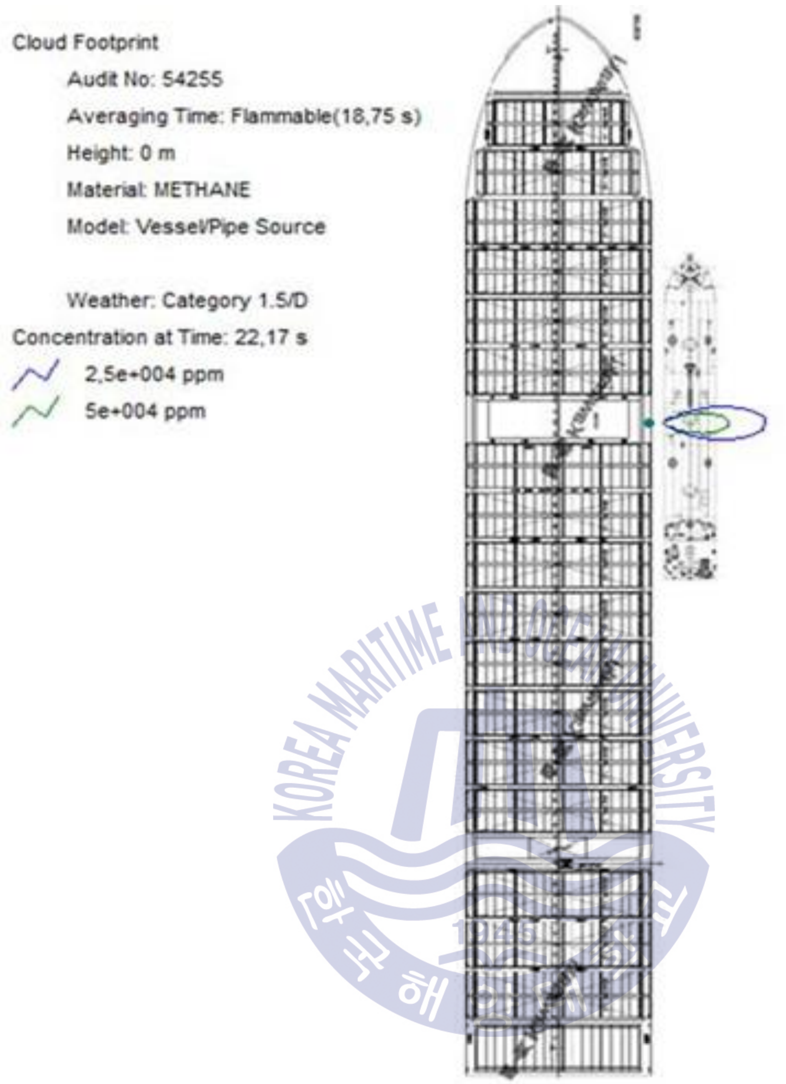


Figure 3-4 Minimum distances to LFL and UFL for small leak during bunkering (cloud at maximum concentration after 19 seconds)

Fire modelling and radiation

In the event of ignition of an LNG pool, the rate of burning is determined by the rate of evaporation. This is both from the substrate below the pool and from the flame above the pool. As the evaporation rate of LNG on water is greater than that on land, the burning rate is higher, generally by a factor of approximately 2. This increase in burning rate (of LNG on water compared with land) also gives a greater flame length (again by a factor of approximately 2).

The results from Phast gives two fire phenomena for ignited small leaks, *flash fire* and *pool fire.*

A *flash fire* is occurring when the cloud ignites and the flame propagates back to the leak source. The duration of a flash fire is very short. Personnel exposed within the flash fire are conservatively expected to be fatalities. The flash fire envelope for ignited small leaks is presented in Figure 3-6. The LFL in green (5.0E4 ppm/5% volume of methane) is expected to reach a downwind distance of approximately 22 m, as also illustrated in Figure 3-6. The blue contour radius indicates the 0.5 LFL threshold value.

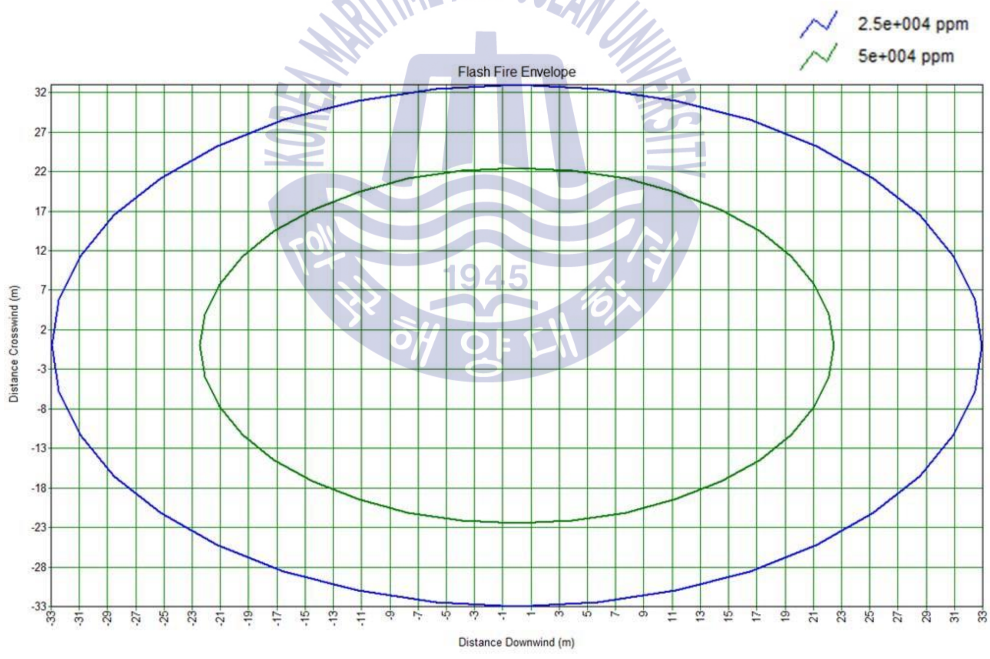


Figure 3-5 Flash fire envelope - distance crosswind vs. distance downwind (small leak)

Pool fires are burning pools of liquid that has collected on a horizontal surface. All ignited large leaks will form pool fires on the sea surface close to the bunker station. The thermal radiation resulting from a pool fire due to ignited small leaks is presented in

Figure 8. The graph shows that the heat radiation will have peak at around 3 m-4 m with 35.0 kW/m^2. The threshold limit for fatalities is 12.5 kW/m^2 where exposed personnel will suffer extreme pain within 20s and fatality if escape is not possible. Thus, personnel within the 12.5 kW/m^2 distance are expected to be fatalities

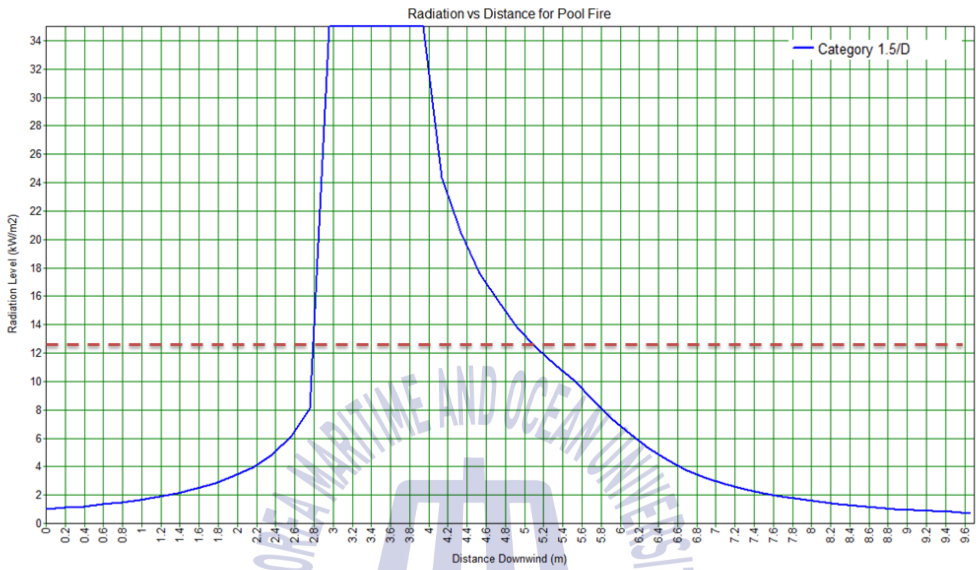


Figure 3-6 Radiation level vs. distance downwind for pool fire (small leak)

3.3.5.2 Large leaks

The dispersion calculation in Phast has been executed with the following input parameters:

150 mm hole diameter (full bore rupture/leak) and 60s ESD closing time

The LNG (methane) is released in liquid state (-162°C) at atmospheric pressure.

The LNG is spilled onto water with no boundary

Wind speed of 1.5 m/s

Pasquill Stability class: D (neutral)

Gas dispersion with free-field modelling and no obstacles

Release rate and duration

For large leaks the release duration is unlikely to be less than 60s even with a comprehensive gas detection system and use of watchman with executive action. It has been assumed 30 seconds to detect and 30 seconds for the ESD valves on the bunker ship to close.

Results from Phast shows that the release rate of liquid LNG for large leaks/full bore rupture would be 63.1 kg/s.

Gas dispersion modelling

The results from the gas dispersion calculations are shown for the horizontal release in Figure 3-8. Due to the large temperature difference between the LNG liquid and the water the boiling is expected to be very violent and unstable. The gas cloud is expected to cover the whole bunker ship and the distance to LFL (5.0E4ppm), indicated by the green contour line, is nearly 190 m from the origin of the leak. The area covered by the LFL level is used to determine the potential for ignition sources. As we see in Figure 9 the cloud can stretch downwind, almost the entire Vessel's length, or find an ignition source on the bunker ship, also within the LFL. Thus, a 100% probability of the gas cloud reaching a potential ignition source has thus been used. The probability of ignition given gas cloud reaching potential ignition sources is 50%, based on RIVM [54].

It should be noted that the calculations are based on an average release rate the first 60 seconds of the leak. An average wind speed of 1.5 m/s is used in the calculations. The modelling does further assume unobstructed dispersion in a uniform wind field.

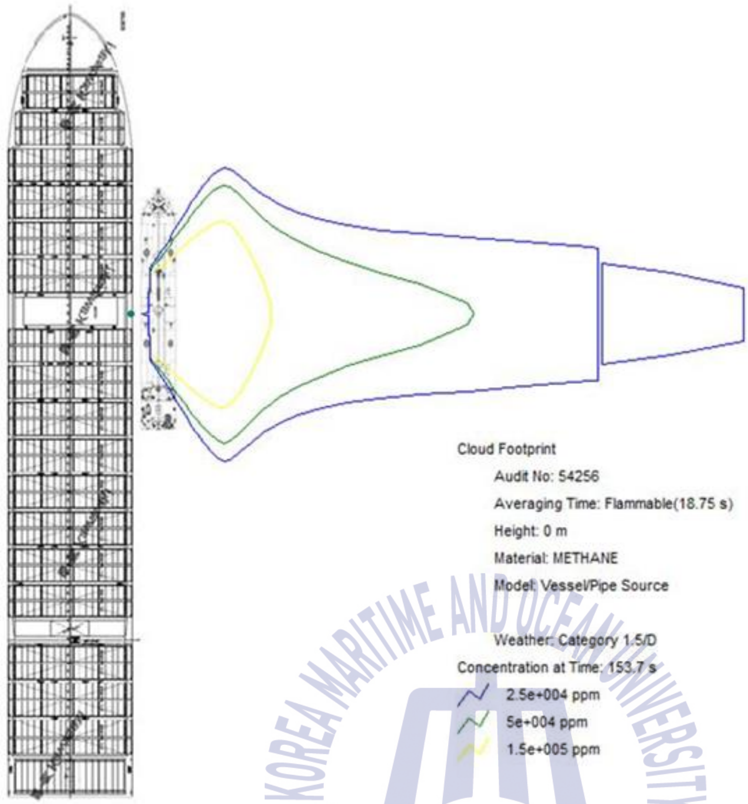


Figure 3-7 Minimum distances to LFL and UFL for large leak during bunkering (cloud at maximum concentration after 2 minutes and 51 seconds)

Fire modelling and radiation

The following fire types are considered for ignited large leaks:

- Flash fire
- Pool fire

A flash fire is occurring when the cloud ignites and the flame propagates back to the leak source. The duration of a flash fire is very short. Personnel exposed within the flash fire are conservatively expected to be fatalities. The flash fire envelope for ignited large leaks is presented in Figure 3-9. The LFL (green line/5.0E4ppm) is expected to reach a downwind distance of nearly 190 m, as also illustrated in Figure 3-8.

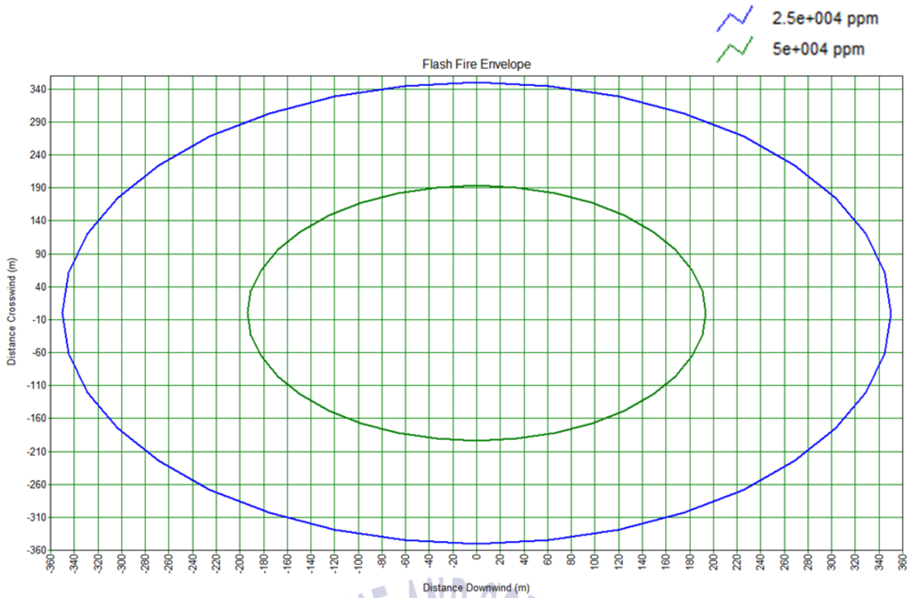


Figure 3-8 Flash fire envelope, distance crosswind vs. distance downwind (large leak)

Pool fires are burning pools of liquid that has collected on a horizontal surface. All ignited large leaks will form pool fires on the sea surface close to the bunker station. The thermal radiation resulting from a pool fire due to ignited large leaks is presented in Figure 3-10.

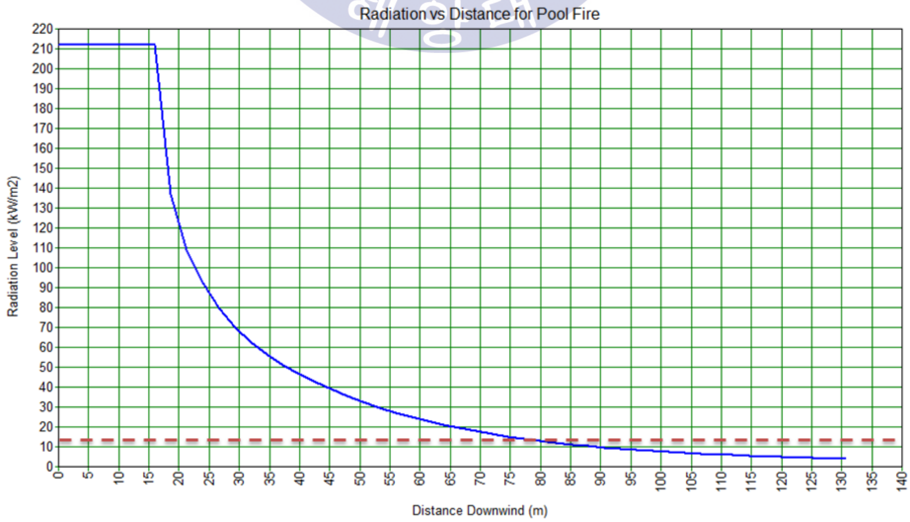


Figure 3-9 Radiation level vs. distance downwind for pool fire (large leak)

From the graph it is seen that the radiation level reaches the threshold limit level of 12.5 kW/m^2 within a distance of nearly 80 m. Personnel exposed within this area are likely to be killed due to the intensity of the thermal radiation.

3.3.5.3 Personnel risk

The final risk figures have been quantified in terms of Fatal Accident Rates (FAR) for comparison to the reference ship.

The calculated radiation contours have been used to evaluate immediate and escape fatalities due to radiation and impairment of main safety functions due to radiation. The expected number of fatalities associated with a leak are categorized as immediate-, escape- and evacuation fatalities.

Immediate fatalities

Immediate fatalities may be caused by exposure to excessive heat loads from the initial fire. Based on the heat radiation contours presented, it is assessed that ignition due to large leaks will cause immediate fatalities (100%), while delayed ignition due to small leaks will cause one fatality (50%). It is assumed two (2) crew members at/close to the bunker stations and that there will be next to nothing/little shielding to the intense heat radiation.

Small and large leaks in the vapour return line is not modelled in Phast due to the uncertainty in gas quantity within the pipe. It is conservatively assumed that only 0.1 of small leaks and 0.5 of large leaks in the vapour return line will reach a potential ignition source. The probability of gas cloud ignition remains the same at 50%, as well as the immediate fatality probability.

Escape fatalities

In case of small leaks personnel within accommodation or machinery spaces surviving the initial fire are expected to escape via gangway to shore. The breath of the Vessel (48m) and obstacles like the accommodation unit and containers are likely to protect from the heat intensity. Personnel may also have time to put on protective clothing and emergency escape breathing devices (EEBD). Thus, it is not assumed any escape fatalities. However, the escape ways for the Vessel is not provided at the time of the concept risk analysis and the base assumptions may change in the design/construction risk analysis.

In case of a large LNG leak during bunkering the pool fire will give significantly more heat intensity compared to small leak. The free-field modelling in Phast indicates an intensity peak of 210kW/m^2 within a 20 m distance of the spill location. Personnel within the accommodation unit and other paces will most probably wait inside the unit due to the heat radiation and escape when the fire is over. However, in order to account for that some personnel probably will have panic and not act rational according to given emergency procedures, and in order to apply the conservative assumption approach, a 5% fatality rate for escape has been applied in the analysis.

Evacuation fatalities

Fatalities during the actual evacuation, either due to malfunctioning of the evacuation means, or as a consequence of extreme weather conditions may occur. For this scenario the escape is via the gangway. Thus, fatalities due to malfunction of the gangway is assumed negligible.

Summary of personnel risk

Smaller leaks are the main contributor to the total risk picture for ignited leaks in the bunker station, mainly due to the higher frequency. Gas leak in the vapour return line has less impact on the risk mainly due to the small amounts of gas being released. The total Fatal Accident Rate (FAR) is 0.01.

3.3.6 Internal ignition - within the space of the leak source (initial event 3, 4, 5 and 7)

Immediate gas ignition within the space of the leak source during normal operation may occur in the following spaces:

Gas leak in “Room for LNG Tank” due to liquid leak from tank (*Initial event 3*)

Liquid leak in Pump room and connected piping system (*Initial event 4*)

Gas leak in Pump room and connected piping system (*Initial event 5*)

Gas leak in GVU room (*Initial event 7*)

The gas fuel system is designed with a gas safe machinery space with double piping gas lines to the dual fuel engines. In case of leak in the inner piping the outer piping will act as a second barrier and providing venting of the gas. The possibility of fire/explosion in the engine room initiated by a gas leak is therefore assessed to be negligible and thus not included in the list above. The same argument is valid for leaks in the pipe recess with single piping and ducting.

The pump room, Room for LNG Tank and the GVU room are, by definition, an area in which an explosive or flammable gas atmosphere is likely to occur in normal operation. EX-equipment is thus required to be installed and minimizing the number of ignition sources within the space is of great importance. An immediate ignition in these spaces due to leakage is thus assessed as unlikely. However, there will be regular activity in the concerned spaces and the personnel will from time to time contribute to potential ignitions sources being present.

An event tree as denoted in Figure 3-11 has been applied for the risk calculations for leaks and immediate ignition in the Room for LNG tank, pump room and GVU room.

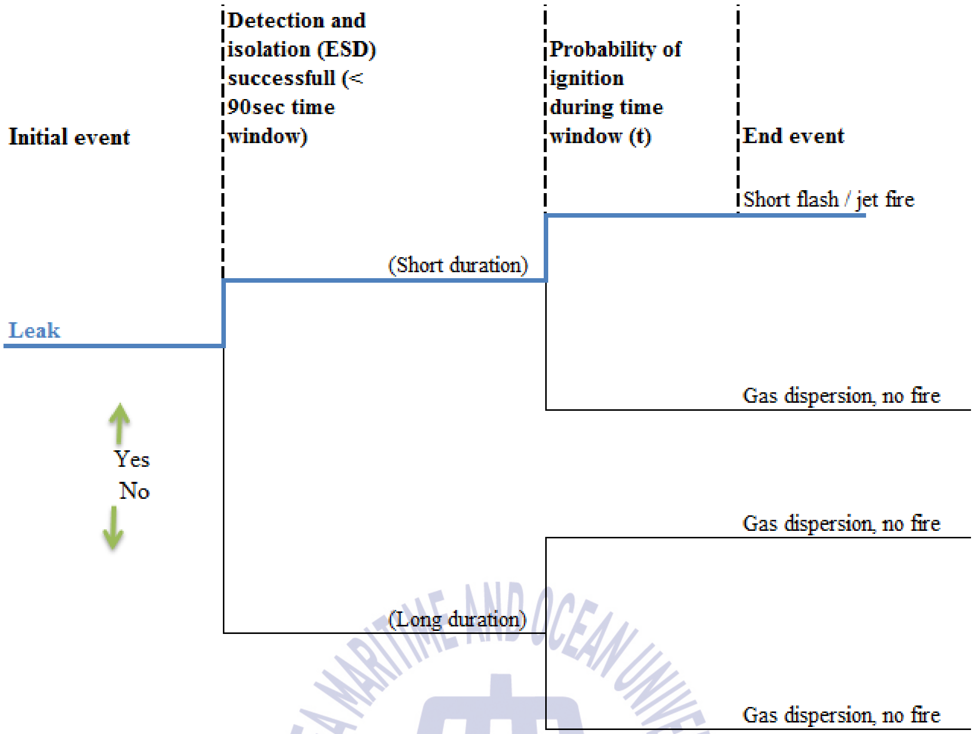


Figure 3-10 Event tree for immediate ignition of leaks in room for LNG tank, pump room and GVU room

RIVM (2009) has proposed the following formula for calculating the probability of an ignition during the time window t,

$$P(t) = P_{present} \times (1 - e^{-\omega t})$$

Where;

- P (t) is the probability of ignition during the time window t.
- P (present) is the probability that the ignition source is present when the cloud occurs.
- W is the effectiveness of the ignition (s-1).
- T is the time (s).

The effectiveness of one person is 0.168E-3 /s and the probability that the crew is inside the concerned space was assessed in the personnel distribution provided. The time (s) includes the detection time, isolation time and the time the gas will remain in the space after shutdown (dispersion time). The shutdown times that have been applied in the analysis, for small- and large leaks respectively are presented in Table 3-2.

Table 3-1 Shutdown times for small and large leaks in hazardous zone 1 spaces

Time	Small leak	Large leak
Detection time (s)	60	30
Isolation time (s)	30	30
Dispersion time (s)	10	30
Total time (s)	**100**	**90**

In case of a leak several process instruments may indicate abnormal conditions and one or more of the gas detectors will detect the leak. The failure rate of a conventional gas detector is typically 5.5E-6 per hour, and because there will be multiple gas detectors total failure of gas detection system is assumed negligible in this analysis and thus not included in the analysis.

The fatality rate is conservatively assumed 100% in case of personnel being present in the space, with no additional protective clothing, at the time of the ignition.

The final risk figures for immediate gas ignition within the space of the leak source during normal operation, the total FAR for this LNG leak event is 0.01.

A delayed ignition within these spaces may result in an explosion. However, there will be provided for mechanical ventilation with 50% redundancy, and delayed ignitions are therefore considered negligible.

3.3.7 External ignition - leak vented and ignited (initial event 4-8)

In case of detection of gas leak in the “Room for LNG tank”, the pump room or the GVU room the corresponding LNG/gas system will be shut down. However, due to the shutdown time some gas will be vented to the outlets on deck aft of accommodation until the shutdown valves have been fully closed assuming that ventilation not will be shut down in case of gas detection.

In case the wind is blowing in an unfavourable direction it may lead the gas against the accommodation or being entrapped between container stacks and eventually being ignited (delayed ignition). However, the accumulation of gas in the accommodation will be relatively slow and thus also the increase of gas concentration. Provided that the air inlets are closed and the ventilation system is stopped, the probability of ignition inside the accommodation is considered negligible. The prime sources for ignition in the vicinity of the vent outlets on deck are thus:

Hot-work
Electrical equipment
Rotating machinery
Static build-up

Other potential ignition sources valid for larger leaks may usually be the exhaust and intake systems of the power generators etc. However, the exhaust funnel is placed in a good distance from the vent outlets from hazardous spaces and it is thus very unlikely that the gas will reach the funnel due to wind turbulence and the number of containers aft of the accommodation unit.

Personnel will from time be involved with activities on deck during voyage close to the vent outlets for repairs (welding), inspections, securing (lashing of) containers after departure and checking temperatures of reef containers at least twice a day.

10% probability of the gas cloud reaching potential ignitions sources has been applied in the assessment based on engineering judgements.

In case of ignition in close vicinity of the vent outlets due to the presence of the possible ignition sources as listed above, 50% of the personnel present on the deck close to the accommodation unit are conservatively expected to be fatalities due to the burning gas. The personnel within this is assumed based on the average personnel on deck (in average 0.4 crew members) multiplied by the probability of being close to the vent outlets and accommodation unit (50%), hence the personnel exposure is 0.2. The flash fire will last for a relatively short time. In case the gas flow is not stopped, the fire may continue. However, the probability of ESD failure is considered negligible for this analysis. Due to the short time no evacuation is assumed necessary, thus evacuation fatalities is not modelled for this scenario.

The final risk figures for vented leaks reaching potential ignition source on deck during normal operation, the total FAR for this LNG leak event is 0.05.

3.3.8 Risk summary – Leak in LNG fuel system

The risk results are presented in Table 3-3 showing the risk per LNG accident scenario, denoted as Fatal Accident Rate (FAR).

The results show that the main risk contributor is large leaks from the pump room, “Room for LNG Tank” or the GVU room ventilated as a gas through the ventilation outlets. In case the wind is blowing in an unfavourable direction wind may lead the gas to reach ignition sources on deck and apparent to the accommodation unit.

The total risk contribution from LNG initiated fire and explosion events is assessed to a FAR of 0.08. The assumptions made in the analysis regarding gas cloud ignition probabilities and fatality rates are conservative, meaning that a preference for erring on the side of overstating has been used as opposed to understating risk under conditions of uncertainty.

Table 3-2 Risk results for LNG initiated events

Event type	**FAR**	**%**
Initial event 1-2: Liquid or gas leak during bunkering	0.012	14
Initial event 3, 4, 5 and 7: Internal ignition - Immediate gas leak ignition during	0.014	18
Initial event 4-8: External ignition - Leak vented and reaching ignition source during normal operation	0.054	67
Sum	**0.08**	**100**

The LNG initiated fire/explosion risk of the dual fuel container vessel is compared with a generic diesel fueled vessel of equal type in Figure 3-12. The additional risk for the Vessel in terms of FAR will be 0.08 due to that the comparison vessel will not have any LNG onboard, i.e. diesel only.

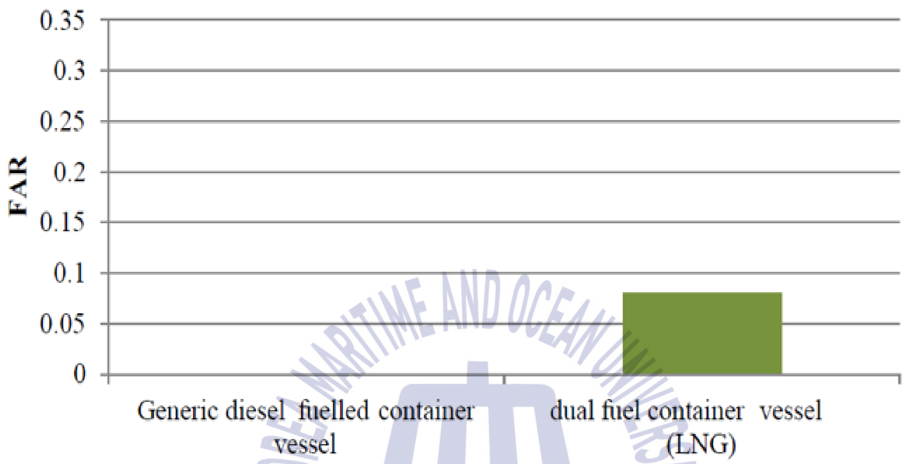


Figure 3-11 LNG initiated fire/explosion risk

3.4 Fire and explosion in other areas- not LNG initiated

In this chapter the risk of a fire/explosion initiated due to other causes than LNG system failures, have been considered. The potential consequences may become worse for the Vessel, if the fire/explosion is escalating to the LNG system. Thus, the risk due to escalation effects is included.

The risk is presented in terms of Fatal Accident Rate (FAR). According to hazard identification, fire and explosions initiated outside the LNG system may occur at the following locations:

- In the Engine Room
- In the cargo area (containers) and accommodation
- In the diesel fuel tank besides the LNG fuel Tank

Generic frequency for fire/explosion is estimated based on the IHS Fairplay Casualty Database with casualty data from 2004 to 2014. A total of 36,907 exposed vessel years was recorded in the dataset [53]

FAR takes into account exposed work hours (i.e. number of crew members), thus the generic diesel driven vessel may have less or more crew than dual fueled vessel without that affecting the difference in risk between the two vessels. A crew size of 17.1 on the generic container vessel is applied based on the average number of crew for general cargo ships of IACS class ships built during ten years period from 2004 to 2014 [54].

The statistics, as presented in Figure 3-13, shows that fires in general represent more than a third of all fatalities and injuries due to accidents onboard container vessels (excl. occupational accidents). Engine room fires are a major contributor, closely followed by fires in cargo areas. It should be noted that occupational hazards are not included in these figures. Such accidents would dominate the picture if included.

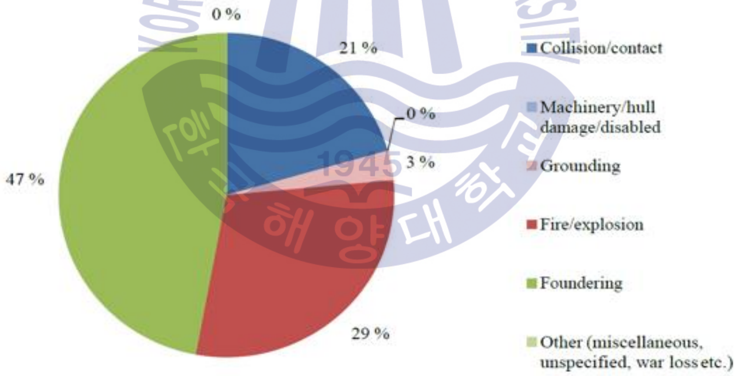


Figure 3-12 Accident statistics for container vessels - fatality distribution (excl. occupational accidents)

In average 70% of all fire/explosions origins from the engine room due to fuel leak etc. 20% are due to boiler explosion and other machinery related causes, while 10% is due to fire or explosions in the accommodation unit or the cargo hold.

3.4.1 Fire/explosion in machinery spaces/engine room

3.4.1.1 Not LNG initiated

In this chapter the risk for fire/explosion in the engine room due to other causes than LNG system failures, is considered. Relevant scenarios are e.g. ignited spills of diesel, lubricating oil or hydraulic oil, or fires that originate in an electrical failure. Statistics from IHS shows that the FAR for engine room fires not initiated by the LNG system is 0.14. However, due to the fact that the Vessel will primarily run on natural gas the fire/explosion risk has been reduced. it is assumed that the Vessel will run in average 95% of its operating time on LNG. The FAR has thus been reduced accordingly by the reduction in the frequency of engine room fires due to fuel (oil) leak. The frequency of fire/explosion in engine room due to boiler failure is assumed equal to a diesel driven container vessel. The risk due to engine room fires not initiated by the LNG system for the Vessel is thus FAR 0.024.

3.4.1.2 Escalation to the LNG fuel system

The Vessel will be built according to current rules and regulations regarding fire protection, e.g. requiring the engine room to be designed with A60 fire protection towards rooms for LNG tanks, A0 towards GVU rooms, cargo pump room and bow thruster room etc. The A-60 protection ensures enough time to evacuate the vessel before a potential fire will escalate to the areas containing LNG or gas. Gas piping in the engine room is also to be double piping and some piping for high pressure will also be routed under-deck to the gas engines. Fire/explosion, within or close to the engine room, other than those caused by the LNG fuel system, escalating to the LNG fuel system is assessed to make a negligible contribution to the overall risk due to the protective systems as detailed above.

3.4.2 Fire/explosion in cargo area and accommodation

3.4.2.1 Not LNG initiated

Cargo (container)

Several potentially hazardous mediums may be transported in the containers as Dangerous Goods. Dangerous goods comprise 5% to 10% of all transported cargo, depending on the route. In general, containerised poisonous, corrosive, and flammable gases are restricted to on-deck only stowage due to the greater risk of explosion, poisoning or suffocation given that gases, especially those being heavier than air, could accumulate inside a cargo hold [56]. Causes of container faults could be poorly manufactured containers, valve or vent problems, container that previously have sustained damage etc. [56].

The consequences due to leaks in dangerous goods containers are typically dependant on the fluid/gas medium, location of the leak (if the release is apparent to the crew) and weather the leak can be controlled. Some leaks are even not detected until after the container had been unloaded. Statistics show that for 3 of the 10 releases discovered at sea, the crew was able to control the leak without sustaining injuries [56].

A modern container carrier will be provided with a fire extinguishing system for enclosed cargo holds. This is usually a CO^2 gas system which may operate satisfactory if the hold in question remains sealed in a fire situation. Reaching the origin of the fire inside the container can however be a problem when applying CO_2 or any other fire extinguishing systems. Open decks are according to SOLAS to be protected by fire hoses. The philosophy is manually fighting of the fire with fire hoses or to jettison affected containers over board. Compliance with Dangerous Goods (DG) regulations will reduce the risk, primarily for the holds. However, open deck cargo remains relatively unprotected even when the DG code is met.

Accommodation

The accommodation spaces are located in the midship unit of the vessel, above the

LNG fuel tank. Typical risks for fires in the accommodation spaces are related to all technical rooms such as wheelhouse, mechanical workshop, control room, galley, laundry room, instrument room, sauna etc. In addition, smoking in day rooms and cabins contribute to the risk. Fires in such areas have so far only rarely had fatal consequences [53].

Consequently, and supported from the IHS Fairplay statistics, the risk to personnel from accommodation and bridge/control/instrument room fires is assessed to be small, provided that appropriate procedures are laid down and enforced for such events. The total risk contribution is found to be: FAR = 0.04. However, this will be the same as for diesel fueled vessels and regarded not additional for the LNG fueled vessel.

3.4.2.2 Escalation to the LNG fuel system

Cargo (container)

Fire and explosions in the cargo area may escalate to the LNG fuel system (e.g. pump room, pipe recess etc.). However, immediate fatalities due to the escalation and breach of piping/containment of gas fuel systems are unlikely, mainly because such chain of events would take a considerable amount of time and no personnel is thus assumed close to gas fuel systems during the extinguishing of a burning container. There may be escape and evacuation fatalities due to the process of evacuating the Vessel. However, taking into consideration the low frequency of containerised dangerous goods leaks (release frequency of gas from container in hold, open top, is typically 6.3E-4 per year [56], the low probability of escalation with breach of LNG piping/containment, as well as the low fatality rates for escape and evacuation, the risk for this scenario is considered negligible.

Accommodation

The accommodation is assumed to be constructed according to current legislation which, among other, means that only non-combustible materials will be used and smoke detectors are installed in all common areas. In addition, both active and passive fire protection are used to:

- Prevent a fire in the accommodation from spreading to other parts of the vessel (within pre- defined time limits).

- Prevent a fire in any other part of the Vessel from spreading to the accommodation

Most fires in accommodation areas are not likely to escalate beyond the immediate vicinity of the fire starting location - due to fire detection/protection and use of non-combustible materials. Furthermore, most accidents in accommodation areas are expected to be small fires that are quickly extinguished. The likelihood of fires will be influenced by maintenance standards of electrical equipment, safe systems for hot work and elementary precautions concerning smoking of cigarettes.

Accommodation fires resulting in major damage to living quarters [53] is found to have a negligible effect on the total risk picture for fire/explosion events. The pump room below the accommodation unit is also classified as a Machinery space of category “A” regarding fire protection. Escalation of fire/explosion from the accommodation to the pump room is thus assumed negligible.

3.4.3 Fire/explosion in diesel fuel tanks besides the LNG fuel Tank

The frequency of a fire caused by a leak from the diesel oil tanks besides the LNG fuel tank is found to be negligible [53]. The LNG tank room will have A60 fire protection. Considering the potential consequences with respect to loss of lives, due to fire/explosion escalating to the LNG fuel tank, the risk is assessed to be negligible. There is also a negligible risk that a diesel oil leak may develop into an explosion; thus this is not evaluated further.

3.4.4 Risk summary – Fire/explosion not LNG initiated

The total FAR for fire/explosion not initiated by the gas fuel system is the sum of FAR for engine room fires, cargo area fires and accommodation fires. Consequently, and supported from the IHS Fairplay statistics, the risk to personnel from such scenarios is

0.18 for a generic diesel fueled container ship of equal type.

Table 3-3 FAR for fire/explosion on a generic diesel fueled container ship of equal type

Location of fire/explosion	
Engine room (fuel diesel)	0.13
Engine room (boiler)	0.02
Other locations (accommodation and cargo hold)	0.04
Total fire/explosion risk (diesel only)	**0.18**

The FAR for dual fueled Vessel concerning fire/explosion not initiated by the gas fuel system is 0.06. The FAR is reduced due to the fact that the Vessel will operate on gas and the engine room fires due to fuel oil leakage is thus reduced by the operating time on LNG, according to the operating profile in Analysis basis.

Table 3-4 FAR for fire/explosion (not initiated by the LNG fuel system)

Location of fire/explosion	
Engine room (fuel diesel)	0.006
Engine room (boiler)	0.02
Other locations (accommodation and cargo hold)	0.04
Total fire/explosion risk	**0.06**

Figure 3-14 compares the FAR for the dual fuel Vessel with the diesel fueled reference ship. Note that fire/explosion due to LNG initiated events are not included in this comparison of FAR.

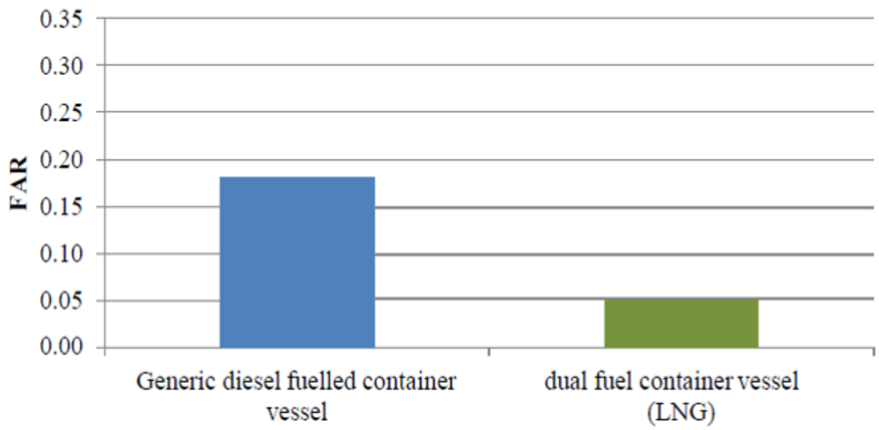


Figure 3-13 Comparison in FAR for dual fuel 8,000 TEU container vessel vs. diesel driven of equal type (fire/explosion not initiated by the LNG system)

3.5 Findings and results

Risk results for fire and explosion assessments are summarized in this section for the following events:

- Fire and explosion due to leak in LNG fuel supply system
- Fire and explosion not LNG initiated and Fire/Explosion escalating to the LNG fuel system

The total risk contribution from fire and explosion events given as FAR is provided in Table 3-1. Regarding the acceptance criteria, the risk contribution from fires and explosions for a generic diesel fueled container vessel of equal type is included for comparison and presented in Figure 3-1.

The results from the fire and explosion assessment show that the dual fueled vessel will have 33% reduction in FAR compared to a generic diesel-only fueled vessel of equal type. The total FAR for fire and explosion events is 0.14 for the vessel and 0.18 for the diesel fueled version.

Table 3-5 Additional risk for fire and explosion given as Fatal Accident Rate (FAR) per location of initial event

Fire and explosion event	Location	FAR	
		dual fuel container vessel (LNG)	Diesel fueled container vessel
Fire and explosion due to leak in LNG fuel system	Bunkering station	0.01	N/A
	Room for LNG tank	0.0002	N/A
	Pump room	0.06	N/A
	Pipe recess	0.01	N/A
	GVU room	0.001	N/A
	Engine Room	0.004	N/A
Fire and Explosion in other areas – escalating to the LNG system	Adjacent to the pump room, the room for LNG tank, the engine rooms and GVU rooms	Negligible	N/A
Fire and explosion in other areas - not LNG initiated	Engine room	0.02	0.14
	Other locations (accommodation, bridge, ECR, cargo hold etc.)	0.04	0.04
Total		**0.14**	**0.18**

The reason for the reduction in risk is mainly due to that 95% of all fire/explosions initiating from diesel fuel oil leakage in the engine room is excluded. The Vessel will run on gas with double piping within the engine room according to current rules for "inherently gas safe machinery spaces" with under deck-piping for parts of the high pressure system. Fire/explosion in other areas, not initiated by the gas fuel system, will be similar to the diesel fueled vessel.

Fire and explosion due to LNG initiated events contributes with FAR 0.08 with leaks in the pump room and GVU room vented to the area aft of the accommodation unit driving the total risk. It was calculated, by using software Phast (Process Hazard Analysis Software Tool), that a large leak/full bore rupture during the bunkering operation may have severe consequences (heat radiation peaking 200 kW/m^2), both in terms of immediate fatalities, as well as escape and evacuation fatalities. However, due to the low frequency of such events (bunkering only 2% of total operating time each year), the risk associated with bunkering will only have a minor influence on the total risk picture. Such events are often referred to as "low frequency, high consequence events” and should have the same attention as events with higher frequencies.

Fire and explosions in the cargo area may escalate to the LNG fuel system (e.g. pump room, pipe recess etc.). However, immediate fatalities due to the escalation and breach of piping/containment of gas fuel systems are unlikely, mainly because such chain of events would take a considerable amount of time and no personnel is thus assumed close to gas fuel systems during the extinguishing of a burning container. There may be escape and evacuation fatalities due to the process of evacuating the Vessel. However, taking into consideration the low frequency of containerised dangerous goods leaks (release frequency of gas from container in hold, open top, is typically 6.3E-4 per year [56]), the low probability of escalation with breach of LNG piping/containment, as well as the low fatality rates for escape and evacuation, the risk for this scenario is considered negligible.

Most fires in accommodation areas are not likely to escalate beyond the immediate vicinity of the fire location - due to fire detection/protection and use of non-combustible materials. Furthermore, most accidents in accommodation areas are expected to be small fires that are quickly extinguished. Thus, the risk for fire in accommodation is similar to the generic diesel fueled container vessel.

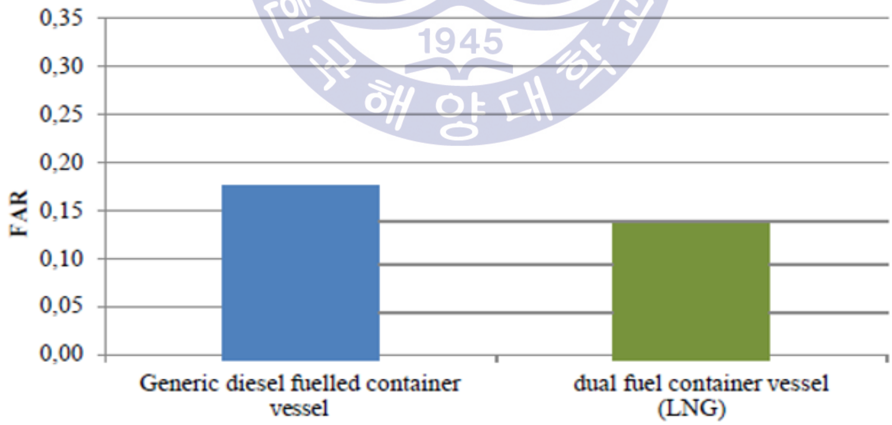


Figure 3-14 Fire and explosion - comparison in FAR for dual fuel vessel (LNG) vs. diesel driven of equal type

3.6 Conclusions

The result from the fire and explosion assessment shows that dual (LNG/ gas) fueled vessel will have 33% reduction in FAR compared to a generic diesel-only fueled vessel of equal type. The total FAR for fire and explosion events is 0.14 for the vessel and 0.18 for its diesel fueled twin.

The reason for the reduction in risk is mainly due to that all fire/explosions initiating from diesel fuel oil leakage in the engine room is excluded. The Vessel will run on gas with double piping within the engine room according to current rules for "inherently gas safe machinery spaces" with under deck- piping for parts of the high pressure system. Fire/explosion in other areas, not initiated by the gas fuel system, will be similar to the diesel fueled vessel.

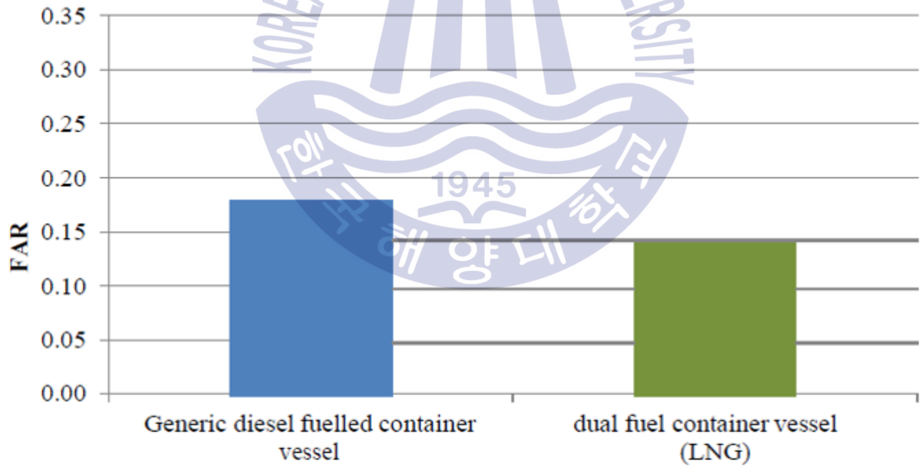


Figure 3-15 Comparison in FAR for dual fuel 8,000 TEU container vessel vs. diesel driven of equal type

Chapter 4 Safety simulations, modelling and analysis of LNG dual fuel in machinery space for internal gas combustion engines

4.1 Introduction

An LNG carrier is being developed where LNG gas is used as fuel in internal combustion engines (modified diesels). In this concept to investigate possible consequences of a gas leak in the feeding pipe to the engines. Depending on the size of the leak and the time of ignition, different developments of the accident can occur. Two main developments are foreseen; early ignition and late ignition. If the gas is ignited early, there will be a jet fire and no explosion. If the gas is ignited after most of the gas is released, there may be an explosion. The possibility for a strong explosion is dependent of the gas concentration and size of the gas cloud.

4.1.1 Objective

The main objective is to find the fire and explosion loads caused by a "rupture of high pressure double wall pipe in engine room".

4.1.2 Scope

The present study includes the following activities

3.6.1 **Geometry modelling.** the entire room is modelled with most details in the area where the leak will start. The geometry is modelled in FLACS v10 so that the geometry model can be applied for ventilation, dispersion, fire and explosion simulations.

3.6.2 **Ventilation and dispersion simulations**. The leak is modelled as a transient leak. The worst case leak size is estimated based on knowledge of the size of the room, ventilation conditions, etc. Two different leak rates in two different leak scenarios are performed. The ventilation in the room is simulated and used as start conditions when the leak starts.

3.6.3 **Explosion simulations.** Explosions are simulated in FLACS and explosion pressures on engine room walls are obtained. Total of six simulations are performed with different cloud size, locations and two ignition locations.

- **Fire simulations.** The leak is modelled as a jet fire assuming it is ignited from the start of the leak. The jet fire is simulated in KAMELEON FIREEX (KFX). Radiation flux on the structure is obtained during the fire. three simulations with different constant leak rates are performed. The extent of the fire when a steady state situation is established is presented. One worst case jet direction is performed based on other fire simulations. Note that the geometry model from FLACS will be converted to KFX.

- **Analysis.** The obtained explosion and fire loads are compared with typical collapse loads for similar structures. This evaluation is qualitative, and does not include rigorous calculation of structure strength. If the loads are above typical acceptable loads, simulations of the structure strength will be suggested. Possible mitigating measures will also be recommended. Typical mitigating measures are a good gas detection system, start of deluge on gas detection (this may reduce possible explosion pressures), Passive fire Protection (PFP) on critical structure and piping, automatic blow down of fuel pipe system on gas detection, improved air ventilation, reduced ignition sources, etc.

- **Reporting.** A technical report is produced together with animations showing the transient development of gas cloud dispersion and pressure waves from gas leak and explosion simulations, respectively. The stationary fire is shown with temperature plots in critical views.

The scope is extended to consider frequency assessment, and full bore rupture calculation. The effect of a smaller ESD segment and shorter ESD closure time are also considered.

4.2 Basis for analysis

4.2.1 Approach

Ventilation, dispersion and explosion are simulated with the CFD program FLACS. Fire simulations are performed with the CFD tool KFX.

FLACS v10 is an advanced tool for the modelling of ventilation, gas dispersion, vapour cloud explosions and blast in complex process areas. FLACS is used for the quantification and management of explosion risks in the offshore petroleum industry and onshore chemical industries.

KAMELEON FIREEX (KFX) is three dimensional transient numerical simulator for laminar and turbulent flow and combustion. KFX is used to enhance the safety in oil and gas industry on and off shore, land based industrial and public services. The simulator shall be applicable to practical problems with special emphasis on fire.

LEALPRO is an Excel/Visual basic program developed for calculation of leak rate profiles.

The conditions and models used in the analysis are further described in Table 4-1.

Table 4-1 Models and conditions applied for the three CFD analyses.

Analysis		**Dispersion**	**Explosion**	**Fire**
CFD Program		**FLACS from Gexcon**	**FLACS from Gexcon**	**KFX Beta KameleonFireEx from Computit**
Models	Turbulence	Standard k-ε model	Standard k-ε model	Standard k-ε model
	Combustion	N/A	Burning velocity model	EDC with 3 infinite fast reactions, including fuel, O_2, CO, CO_2, H_2 and H_2O.
	Radiation	N/A	Property to Gexcon	Discrete Transfer Model with 100 rays per wall point
Initial conditions	Velocities	Normal ventilation conditions	0 m/s	Normal ventilation conditions
	Temperature	25^{0C}	25^{0C}	20^{0C}
	Pressure	1 atm	1 atm	1 atm
	Turbulence intensity	Calculated in vent calcs.	1%-5%	Calculated in vent calcs.
Boundary conditions	Inlet	Jet release given composition, area and massflow vs time	No Inlet	Jet release given composition, area and massflow
	Outlet	Euler, constant pressure	Euler, constant pressure	Constant pressure with special cell data structure (SCD)
	Walls	No slip with log law at neighbour cells. Zero wall roughness.	No slip with log law at neighbour cells. Zero wall roughness.	No slip with log law at neighbour cells. Zero wall roughness.
Numerical method	Solver	SIMPLE	SIMPLE	SIMPLEC QTDMA STONE
	Equations solved	Compressible RANS	Compressible RANS	Incompressible RANS
	Spatial discretization	Second order	Second order	Upwind scheme, (90 % 2. order, 10% 1. order)
	Temporal discretization	Semi Implicit, first order	Semi Implicit, first order	Semi Implicit, first order
Time step (varies)		~ 0.0035 s	~ 0.0005 s	~ 0.005 s
Geometry		Distributed Porosity Concept. Sub-grid turbulence factors are calculated.	Distributed Porosity Concept. Sub-grid turbulence factors are calculated.	Distributed Porosity Concept.

4.2.2 Geometry

The basic geometry dimensions are shown in Figure 4-1, (side view) and Figure 4-2 (top view). Only PS machine room is modelled because one machine room is considered one closed room, and there will not be any exchange between the two machine rooms. Conclusions made for the Port Side (PS) room will also be valid for the Starboard room, due to symmetry. The engine, equipment, storage tanks, etc. are modelled in detail. General piping and structure are modelled based on engineering judgement and design of machine rooms. The final geometry model is shown in Figure 4-3 to Figure 4-5. Here the outer walls and some other objects (see picture text) are taken out so that the geometry can be seen. The gradual reduction of the aft part is also seen.

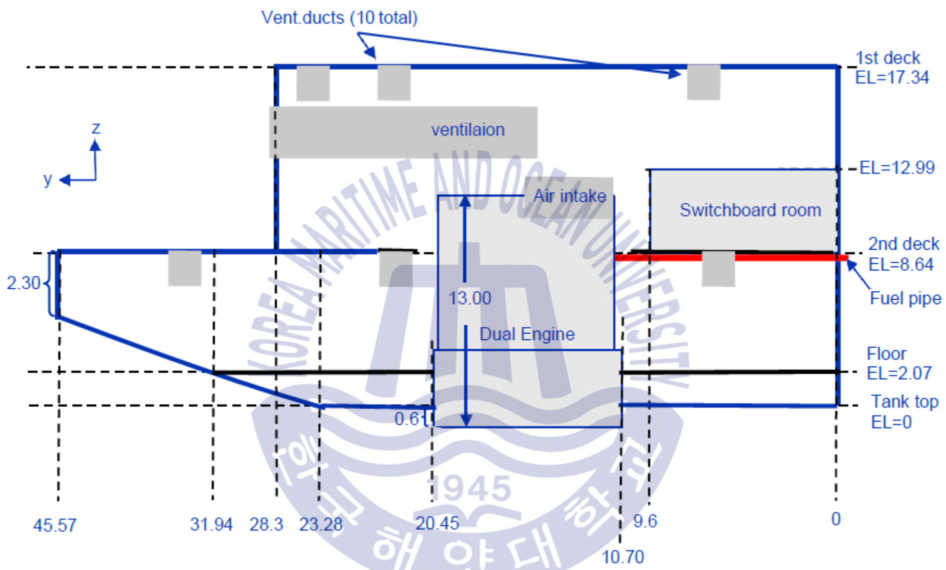


Figure 4-1 Basic geometry as modelled for the engine room (side view). There are 5 ventilation ducts underneath 1st deck and 5 ventilation ducts underneath 2nd deck.

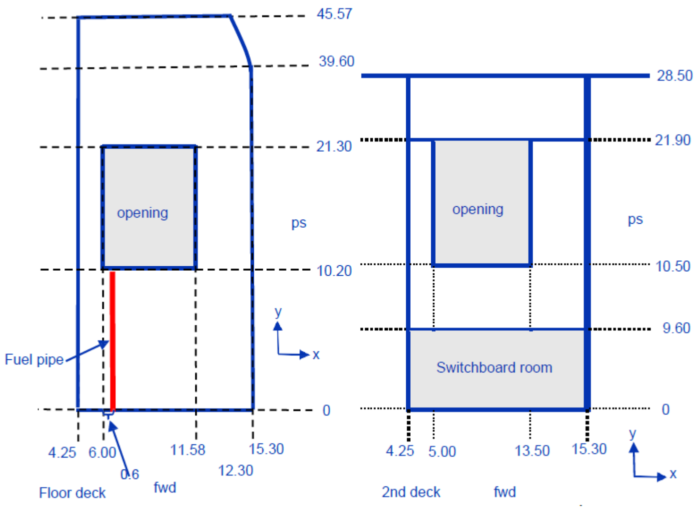


Figure 4-2 Basic geometry as modelled showing floor deck (right) and 2nd deck (left).

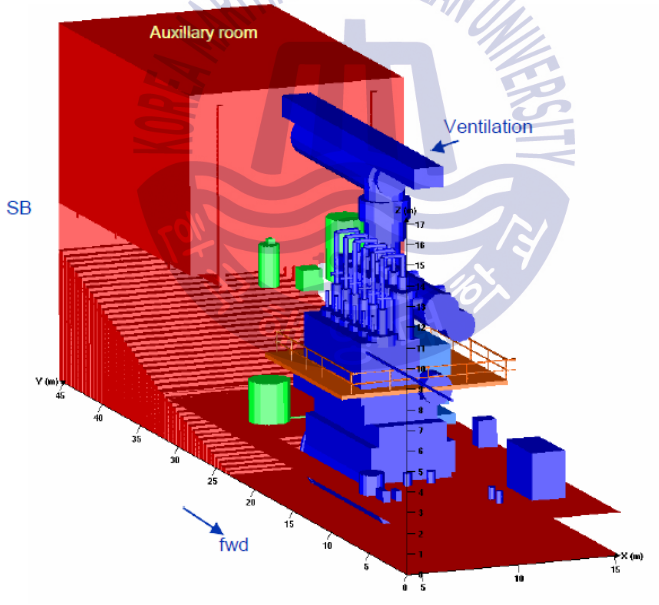


Figure 4-3 Machine room as modelled in FLACS (seen from fwd). The switchboard room, the walls, the 1st deck, the 2nd deck, and general piping and structure are made invisible in this figure in order to show the model. The colours are just for visual purposes.

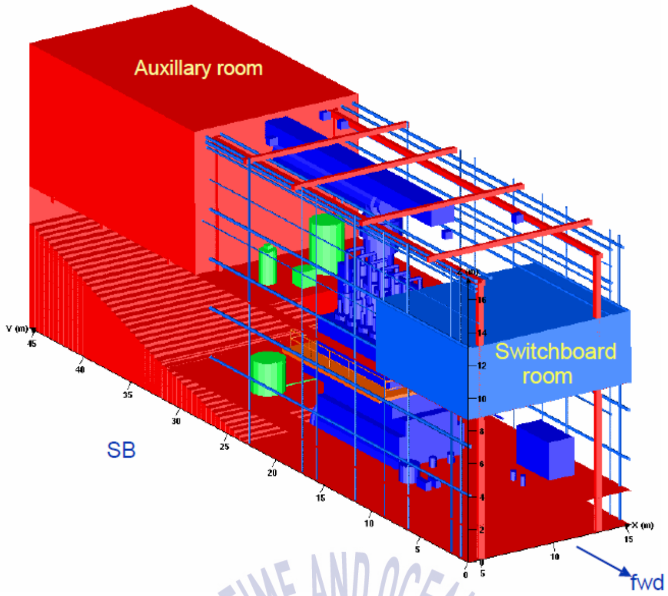


Figure 4-4 Machine room as modelled in FLACS (seen from SB). The walls are made invisible in order to get a view into the room. The colours are just for visual purposes.

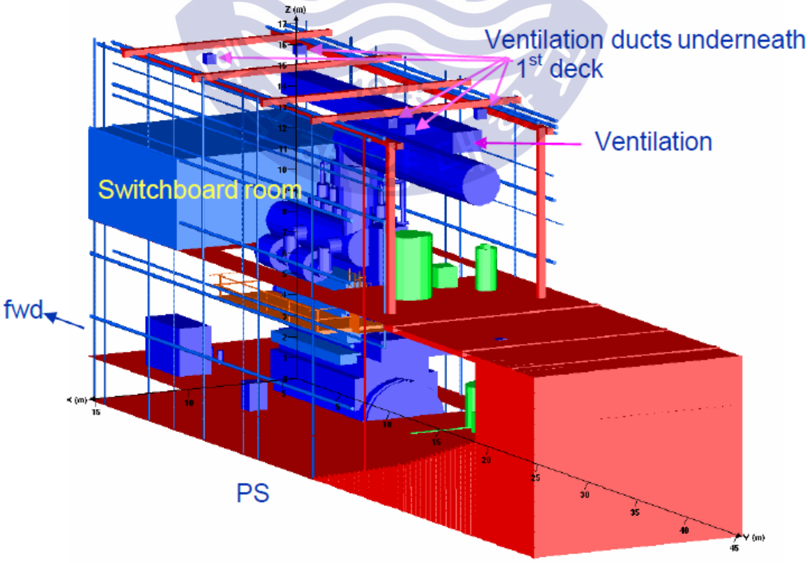


Figure 4-5 Machine room as modelled in FLACS (seen from aft, PS). The walls and the auxiliary room are made invisible in order to get a view into the room. The colours are just for visual purpose.

4.3 Leak scenarios

The feeding pipe has an outer pipe with ventilation air and an inner pipe with high pressure fuel gas (250 bar-300 bar). A possible fuel gas leakage in the engine room occurs when there is rupture in the outer pipe and a rupture or a smaller leak in the inner. When the leak starts, it takes some time before the gas reaches the detectors in the outer pipe. The gas detection system in the outer pipe of the dual pipe system will cause a shutdown and close the ESD valves to the fuel pipe segment. Gas detection at the first detector above 30% LEL gives an alarm, and gas detection at the second detector above 60% LEL leads to automatic shutdown of gas supply to the engine room. There are also pressure sensors in the fuel gas system which will give shutdown in case of a sudden pressure drop. The fuel gas pipe will be depressurized after ESD valves are closed. The effect of depressurization is conservatively not included in the leak profile and dispersion calculations. It is also mentioned that the engines switches to run on HFO/MGO automatically when the gas supply is shut down.

For the leak scenarios in this analysis it is assumed that it takes 20 and 5 seconds from the leak starts to the ESD valves are closed; 20 s in the two first scenarios and 5 s in the last. This time includes both time to gas leak detection, and time to close the ESD valves.

In the two first leak scenarios (010201 and 01202) in this analysis there is a full rupture in the outer pipe and a smaller hole in the inner pipe. It is conservatively applied that the compressor capacity is sufficient to maintain the high pressure in the fuel pipe until the ESD valves are closed. The leak rate is hence kept constant the first 20 seconds because the high pressure is maintained. It is assumed that the suction in the outer pipe will not affect the leakage. When the ESD valves are closed, the leakage is limited by 22 kg of gas in the fuel pipe segment. The pressure falls and the leak rate decrease with time after the ESD valves are closed.

Scenario 010203 is a full rupture in both inner and outer pipe; the initial leak rate becomes significantly larger than for the two first scenarios. In this case, the compressor capacity is assumed to maintain the high pressure in the fuel pipe the first 5 seconds before shut down, then leakage and blow down. The total duration of the leakage becomes shorter, so it is assessed not a worst case scenario for a possible fire. A very large leak rate may at first give a gas cloud which is too rich too explode, but after some time when the leak rate drops, the gas will be mixed with air and the gas cloud can be explosive. This is further discussed in the explosion and fire chapters.

The leak rate versus time for three leak scenarios with different initial leak rates is given in Figure 4-6, Figure 4-7 and Figure 4-8. These are calculated with the program LEAKPRO. The main leakage input parameters are given in Table 4-2 for the three dispersion simulation scenarios. The most conservative value of 300 bar is used for the fuel pipe pressure. The fuel composition used in the simulations is given in Table 4-3. This is considered as a conservative LNG composition due to higher explosion pressure with a larger part of heavy components. The initial temperature in the fuel pipe is set to 45 °C, the compressibility is calculated to 0.95, and the segment volume is calculated to 0.107 m^3 for scenario 010201 and scenario 010202. With these conditions, the total mass of gas in the segment is 22 kg. For the full bore rupture the volume of the two segments is 0.418 m^3 the first 5 seconds then after the valves closes, the volume of the last segment is 0.048 m^3. The total mass of gas in the two segments is 97.5 kg. The specific heat ratio applied (C_p/C_v) is 1.3. A gas temperature after the leak of -50 °C is conservatively applied in the dispersion simulations.

Table 4-2 Leakage input parameters

Dispersion Scenario no.	Hole diameter [mm]	Initial leakage rate [kg/s]
010201	8.5	2.5
010202	3.8	0.5
010203	39	53

Table 4-3 Fluid composition [57]

Component	Mole weight [kg/kmole]	Mole fraction [%]
Methane	16	0.930
Ethane	30	0.055
Propane	44	0.015
Total	17.2	1.000

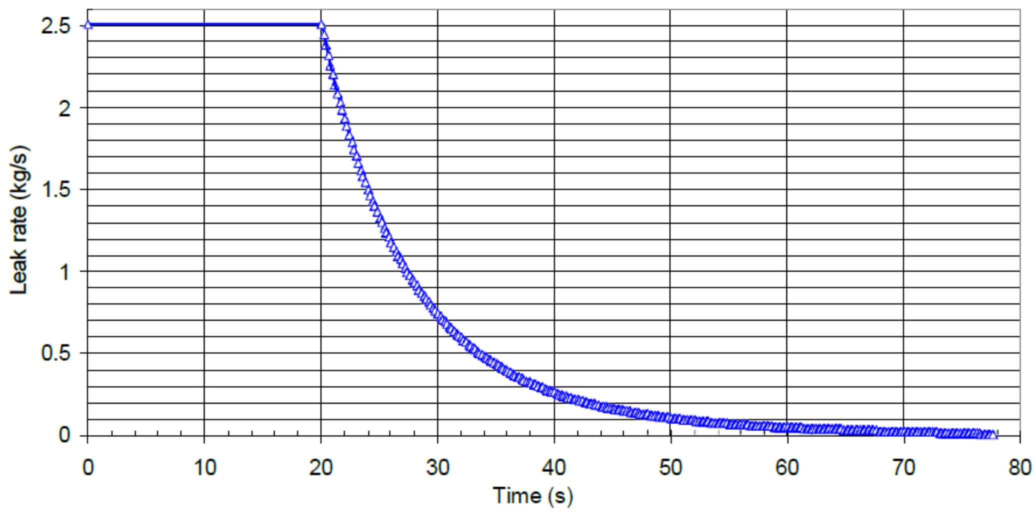


Figure 4-6 Leak profile of a leakage with an initial rate of 2.5 kg/s (scenario 010201)

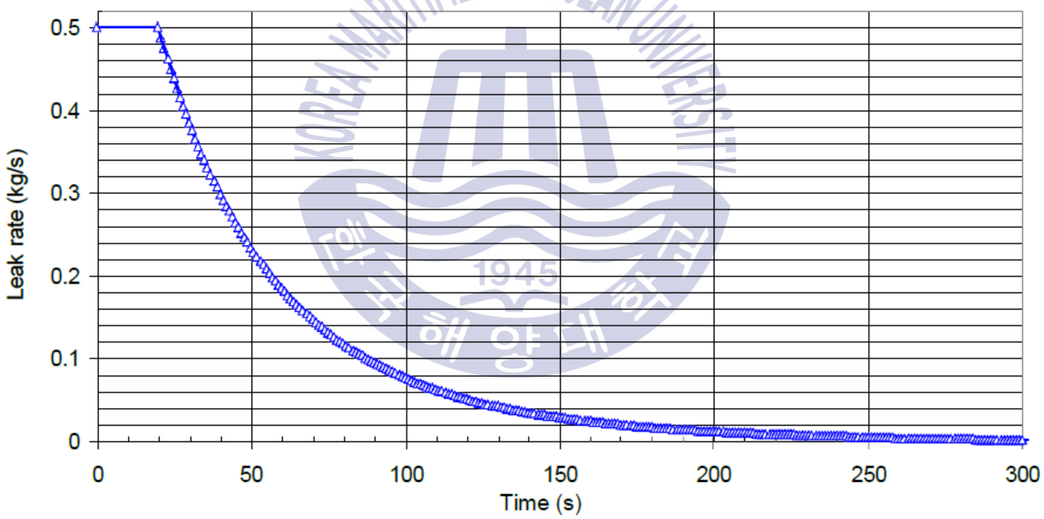


Figure 4-7 Leak profile of a leakage with an initial rate of 0.5 kg/s (scenario 010202)

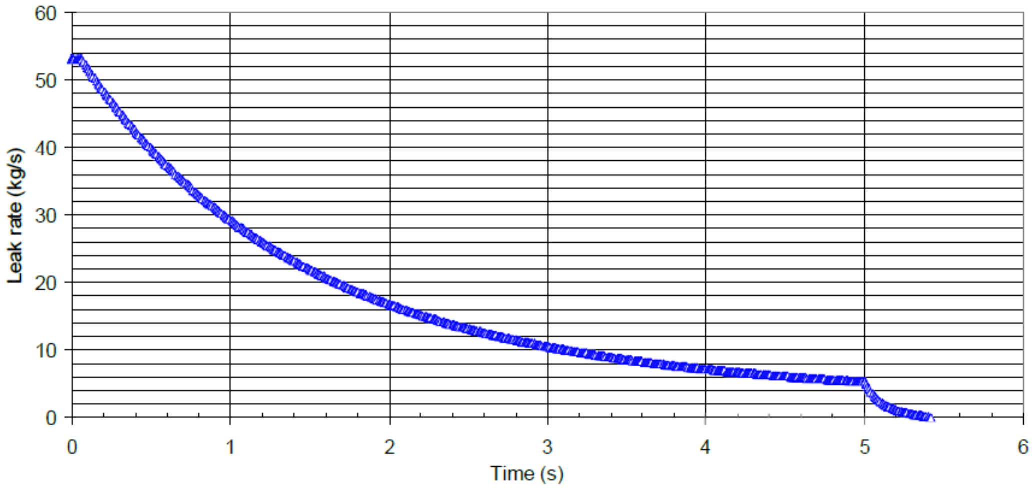


Figure 4-8 Leak profile of a leakage with an initial rate of 53 kg/s (scenario 010203)

4.4 Engine room ventilation

The ventilation conditions as modelled in FLACS are tabulated in Table 4-4. We have modeled several ventilation ducts under the decks which have different size and delivers different rate of air. The total ventilation rate for these ducts are summarized and divided into 10 equal ventilation ducts/boxes in the model for simplification purposes. five ducts are located under 1^{st} deck and 5 ducts under 2^{nd} deck. The modelled locations are around the engine, based on experience and engineering judgements. The ventilation duct above the engine supplies air to the engine, and the engine sucks in air from the room. The exhaust duct/hole in the 1^{st} deck is ventilation out of the room, and the ventilation rate is adjusted by FLACS. The ventilation is modelled to be constant before and during the dispersion and the explosion. The air supply is also conservatively maintained during the constant fire simulations. A discussion of the ventilation conditions during a fire is given in the fire chapter.

The initial air temperature is 26.4 in the whole room. The effect of the warm engine is not simulated, but the effect of the heat will cause more movement of the air in the engine room, especially above 2^{nd} deck. The warm engine will therefore not affect the ventilation condition near the leakage significantly.

Figure 4-9 shows the steady state ventilation condition before the leakage starts. The air has naturally highest activity around the top of the engine due to air intake and engine consume. The ventilation ducts underneath 1st and 2nd deck causes the air to circulate in the room.

Table 4-4 Ventilation condition during normal operation, as modelled.

Source or sink	Vent.rate [kg/s]	Vent. Velocity [m/s]	Vent Area each [m2]	Vent. Direction (in/out of room)	Comment
10 ventilation sources	2×10	8.2	0.203	Horizontal (in)	Ventilation underneath 1st deck and 2nd deck
Air supply for engine	53.3	8.0	5.55	Down (in)	Air distributed above the engine
Engine air intake	56.2	20.8	2.25	Down (out)	Air used by the engine
Ventilation out of engine room	17.1	2.28	6.25	Up (out)	Automatically adjusted by FLACS

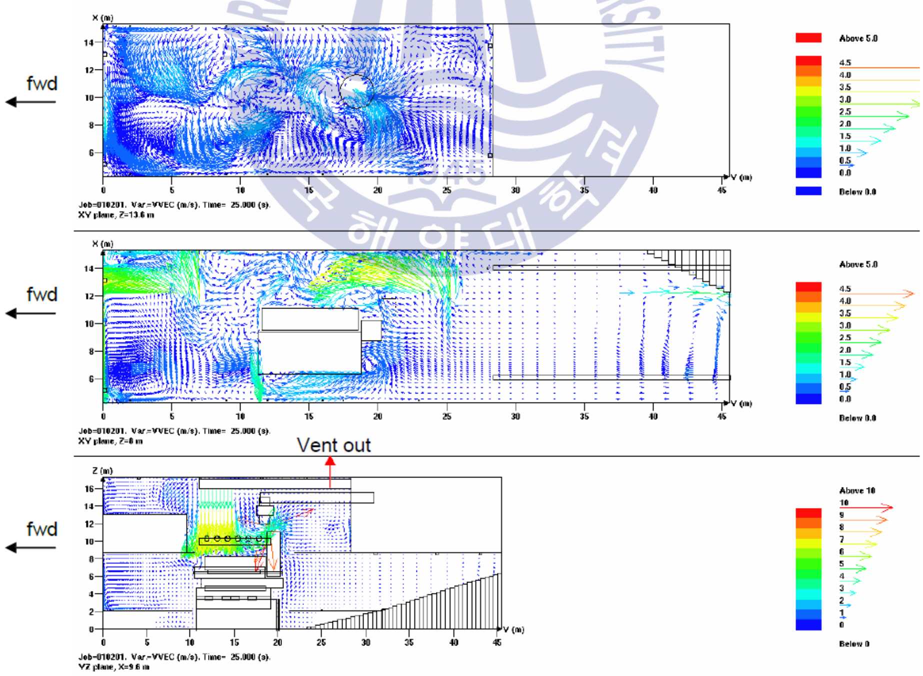


Figure 4-9 Steady state ventilation condition inside the machine room without no gas leak. Top view 2nd deck (top), top view floor (middle) and side view, from SB (bottom)

4.5 Dispersion analysis

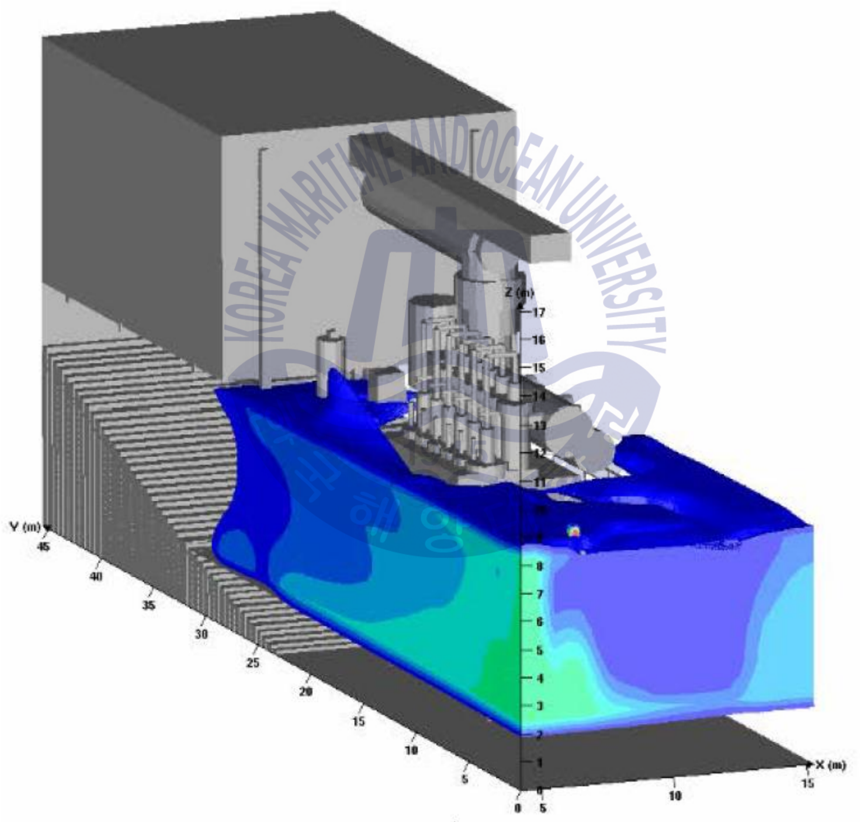
During the dispersion analysis it is assumed that the room ventilation is constant. First, the simulations are performed for 30 seconds without any leak in order to establish the air ventilation patterns (see Figure 4-10). The leak starts after 30 seconds with a fully established ventilation flow in the machine room. The leak is located in the floor deck, coming from the fuel pipe at the fwd end of the room, with the coordinates (x, y, z) = (6.6, 1, 8.19). The direction of the leak jet is downwards for both dispersion cases. The dispersion scenario definitions and main results are tabulated in Table 4-5. The mass of gas released is the sum of the gas released the first 20 seconds and the 22 kg gas released after the ESD valves are closed (see Figure 4-6 and Figure 4-7 for leak profiles used).

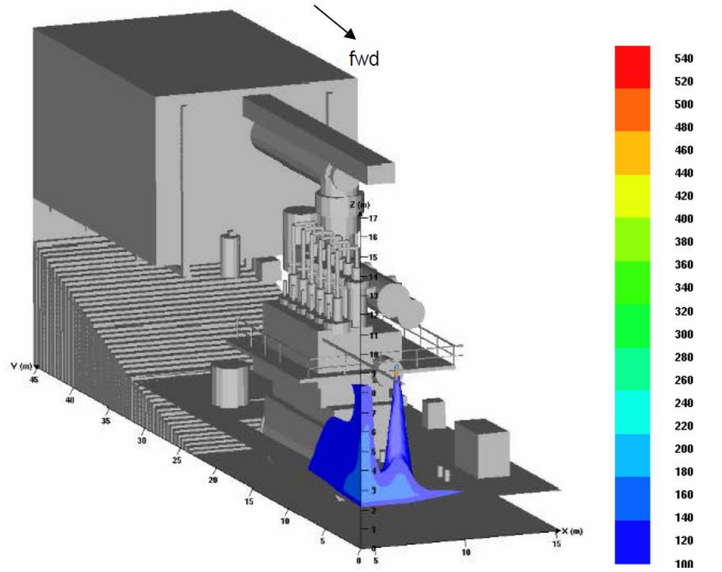
The results show that the maximum flammable gas cloud size occurs for the full bore rupture rate and that the cloud is located between floor and 2nd deck in the fwd direction (near the leak location, Figure 4-10). Following this report are also animation files which shows the transient development of the flammable clouds. Figure 4-10 shows the volume in the engine room at a snapshot when the flammable gas clouds are at maximum. The flammable gas cloud size which is integrated during the simulations, is defined as the size of a stoichiometric gas cloud which is equivalent to the real inhomogeneous cloud (i.e. has similar amount of flammable gas). Figure 4-11 shows the time development of the gas volume in the engine room for all scenarios where the maximum cloud size occurs 30 seconds after the leak has started for both scenarios.

The smallest leak rate of 0.5 kg/s gives an insignificant flammable gas cloud size. Most of the gas mixture is below LEL; only 0.5 kg of 32 kg released is inside the flammable gas cloud. The ventilation causes a good air circulation so that the fuel is diluted. Therefore, it is important to maintain the ventilation when gas leakage occurs. The second largest leak rate of 2.5 kg/s gives a gas cloud of 530 m^3, whereas less than half of the fuel released is inside the flammable gas cloud. If the ventilation in floor deck is lower than modelled, or the initial leak rate is larger, the flammable gas cloud can be larger due to a richer gas cloud. The full bore rupture with initially 53 kg/s release rate gives a gas cloud of 947 m^3.

Table 4-5 Dispersion scenarios and main results.

Case no.	Initial leak rate [kg/s]	Mass of fuel gas released [kg]	Maximum size of flammable cloud [m^3]	Mass of fuel gas [kg] in flammable cloud
010201	2.5	72	530	33.7
010202	0.5	32	8.3	0.5
010203	53	92	947	65.9





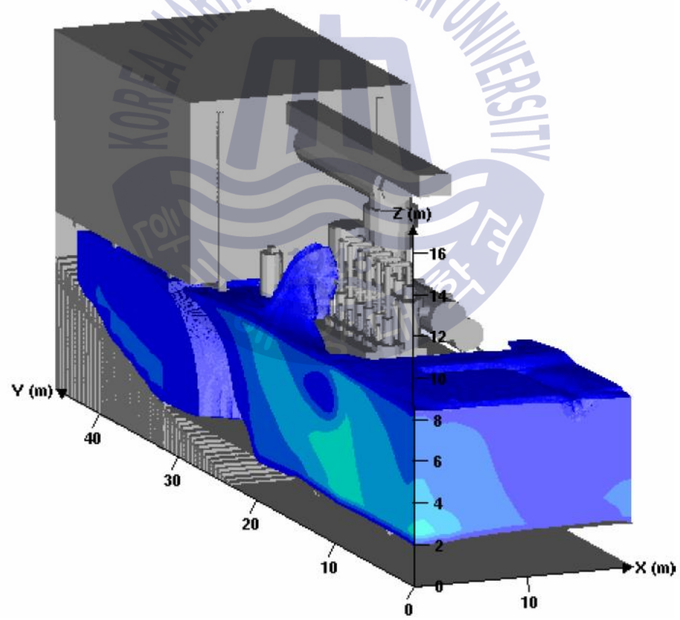


Figure 4-10 Gas dispersion scenario 010201 (top) and 010202 (middle) and 010203(bottom) – 30 seconds after leak started which is when maximum flammable gas cloud size is achieved. Only flammable gas is seen in the plot. The values in the colour scale are percentage of LEL. The simulations show that most of the gas is kept between floor and 2nd deck.

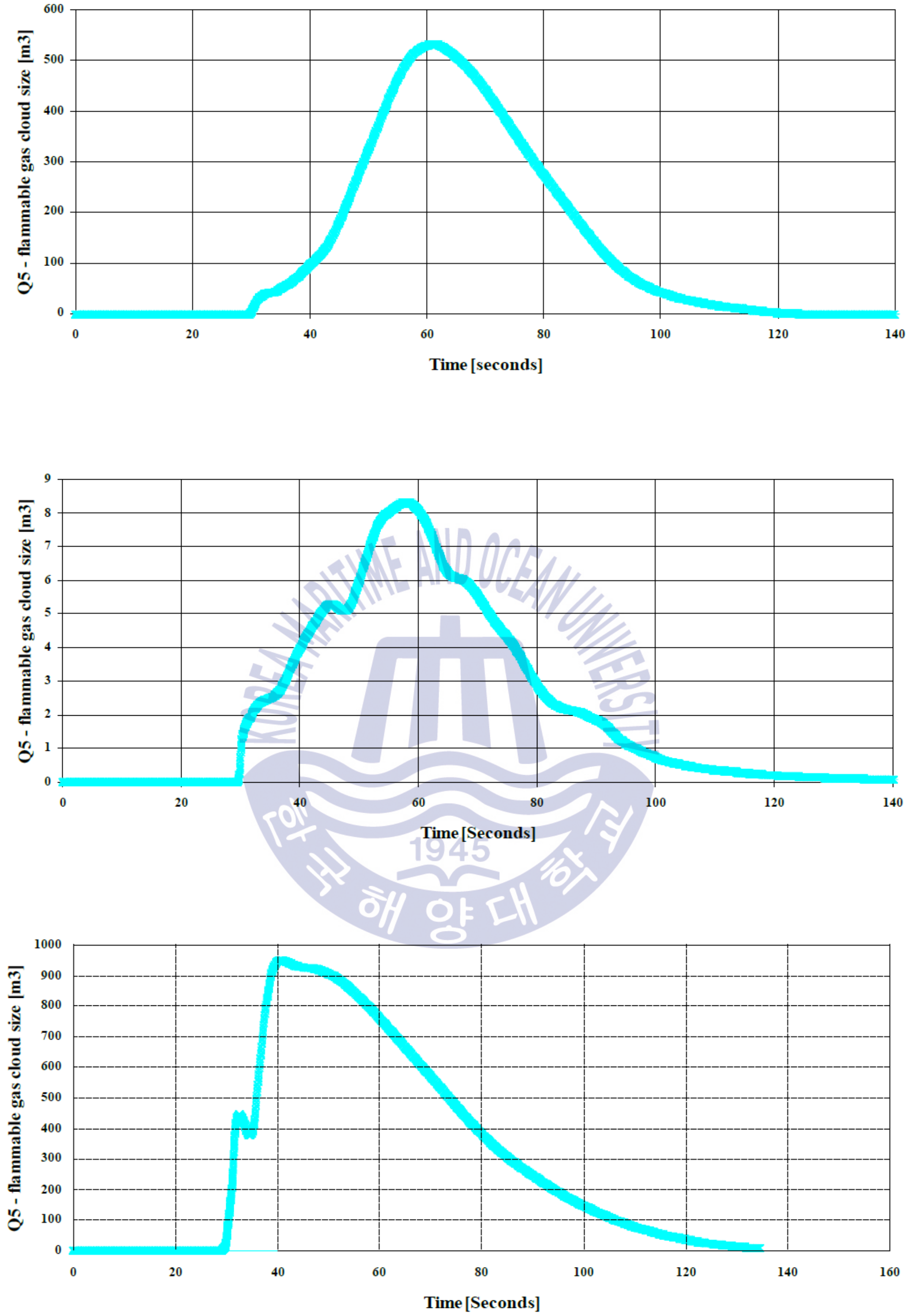


Figure 4-11 Flammable gas volume in the engine room as function of time for scenario 010201 (top) and scenario 010202 (bottom). The leakage profile is described in chapter 3.0

4.6 Explosion Analysis

4.6.1 Vapour cloud explosion simulations

In total 6 explosion scenarios have been simulated for the engine room for different gas cloud sizes, gas cloud locations and ignition locations. The explosion scenarios and main results are tabulated in Table 4-6. Here, the cloud volume is the actual volume of a stoichiometric cloud in open space. The maximum gas cloud size obtained from the dispersion analysis is 530 m^3 while up to 1,500 m^3 is applied in this explosion analysis. This is applied as a worst case cloud size. Factors which can make the gas cloud larger than the simulated gas cloud are; a larger initial leak rate than 2.5 kg/s, failure of ESD valve to close, lower ventilation rate in the floor deck, different leak direction or leak location, etc.

The worst case flammable gas cloud size is limited by the highest possible mass of released fuel. A cloud size of 1500 m^3 contains 95 kg fuel, i.e. at least 95 kg fuel has to be released to get this cloud size. (If 95 kg fuel is mixed stoichiometric with air, the gas cloud becomes 1,500 m^3). In case of a full rupture of the fuel pipe, the initial leak rate is calculated to 53 kg/s. With this initial leak rate, the fuel in the 22 kg fuel pipe is released in about 2 seconds (calculated with LEAKPRO). After a full bore rupture, the pressure drops instantly, and the gas compressor works at abnormal conditions until the ESD valves are closed. The released gas is then the gas in the total fuel piping system plus the gas delivered by the compressor with open ESD valves. If there is a possibility to release at least 95 kg fuel in this scenario, a flammable gas cloud of 1,500 m^3 can theoretically occur. Scenario 010203 indicates that the gas cloud is not ideally mixed to a stoichiometric cloud; hence the cloud size becomes 947 m^3.

If the ESD valves do not close, the compressors will continue delivering 2.5 kg/s, and this case can theoretically form a larger gas cloud. The volume of the gas cloud is limited by the volume of the floor deck itself, which is approximately 1500 m^3. Dispersion simulation results indicate that only small amounts of flammable gas goes above 2nd deck.

The explosion pressures are monitored with 91 pressure panels with equal size (0.8 m x 0.8 m) at decks, walls and roofs. The pressure is also monitored with 54 monitor points which are distributed around the engine room. The maximum monitored panel pressure are tabulated in Table 4-6 and shown in Figure 4-12 as a function of gas cloud size.

Figure 4-13 shows the pressure at pressure panels were highest pressure is achieved as function of time for scenario 030104. The time development is similar for the other scenarios. The maximum pressure is achieved after approximately 1.5 seconds. Note that the pressure build-up starts approximately 0.8 s after ignition. The duration of the high explosion pressure is of the order 2-3 seconds indicating that it is a relatively long lasting explosion compared to an outdoor explosion.

The pressure pulses are starting at the front of the engine room (fwd) and propagates backward in the room until it reach the maximum at the end of room between floor and 2nd deck. Figure 4-14 to Figure 4-16 shows typical pressure distributions at a snapshot close to the time of maximum pressures for the three different cloud sizes. Animations following this report show the pressure and temperature development in more detail. The temperature animations show where the temperature is higher than 2,250 K. The pressure difference within the room is small due to closed room. Similar pressures are obtained for the panels and monitor points in the room.

Table 4-6 of Explosion scenario definitions and main results. The maximum explosion over- pressure is monitored with pressure panels all over the engine room. Maximum overpressure is almost the same all over the room due to the closed room.

Case no.	Volume of gas in cloud [m3]	Gas cloud position	Size of gas cloud Δx	Δy	Δz	Ignition location	Max panel pressure [barg]
030101	500	Floor, front of engine	11.05	7.1	6.57	Center	0.47
030102	500	Floor, front of engine	11.05	7.1	6.57	Fwd, PS, upper corner	0.30
030103	1,000	Floor, front of and along engine	11.05	16.2	6.57	Center	0.80
030104	1,000	Floor, front of and along engine	11.05	16.2	6.57	Fwd, PS, upper corner	1.11
030105	1,500	Floor, front of and around engine	11.05	24.5	6.57	Center	1.07
030106	1,500	Floor, front of and around engine	11.05	24.5	6.57	Fwd, PS, upper	1.70

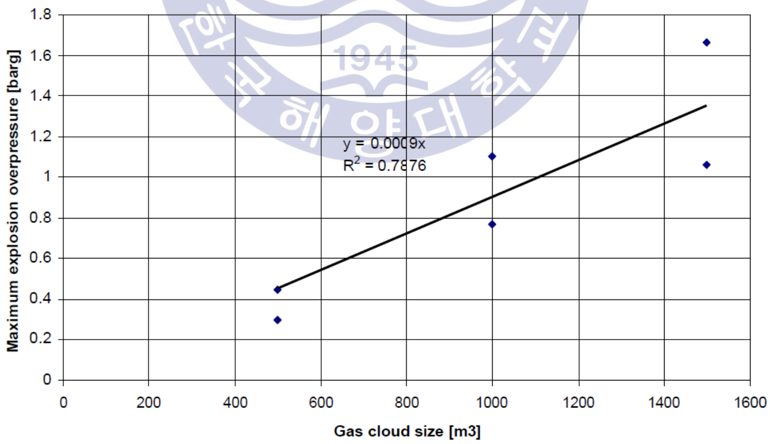


Figure 4-12 Relation between maximum explosion overpressure in the engine room and flammable gas cloud size.

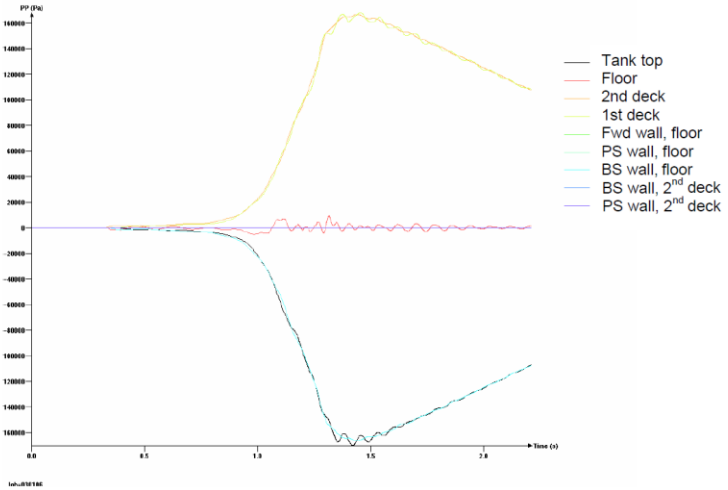


Figure 4-13 Pressure at pressure panels as function of time for scenario 030104. Only pressure panels were highest pressure is achieved at different decks and walls are plotted. The pressure pulse reaches its maximum 1.5 seconds after ignition. The pressure is plotted negative when pressure pulse acts in a negative space direction. Only absolute values should be read from this plot.

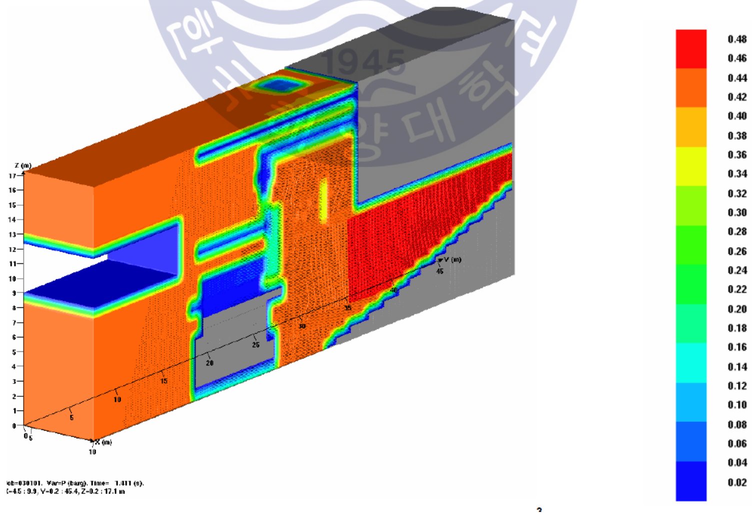


Figure 4-14 3D plot of pressure for scenario 030101 (500 m^3 gas cloud) at time when highest pressure is achieved in the engine room. For this snapshot, the maximum pressure is achieved at the end of the machine room. However, the maximum pressure can be regarded as uniform all over the room.

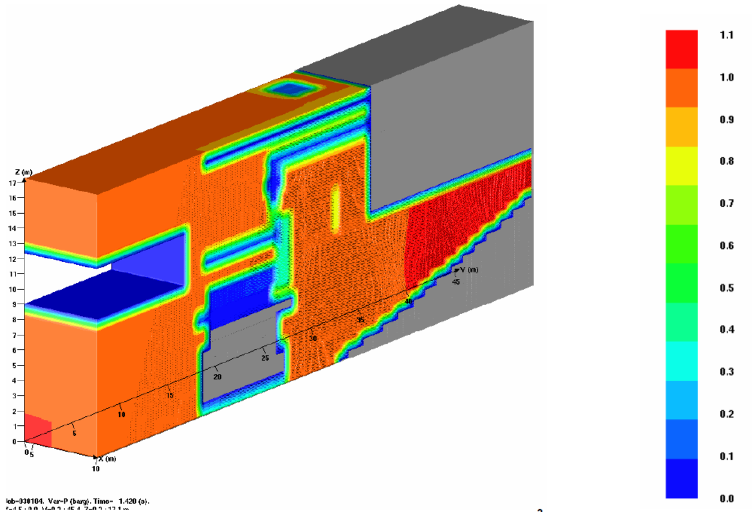


Figure 4-15 3D plot of pressure for scenario 030104 (1,000m^3 gas cloud) at time when highest pressure is achieved in the engine room. For this snapshot, the maximum pressure is achieved at the end of the machine room. However, the maximum pressure can be regarded as uniform all over the room.

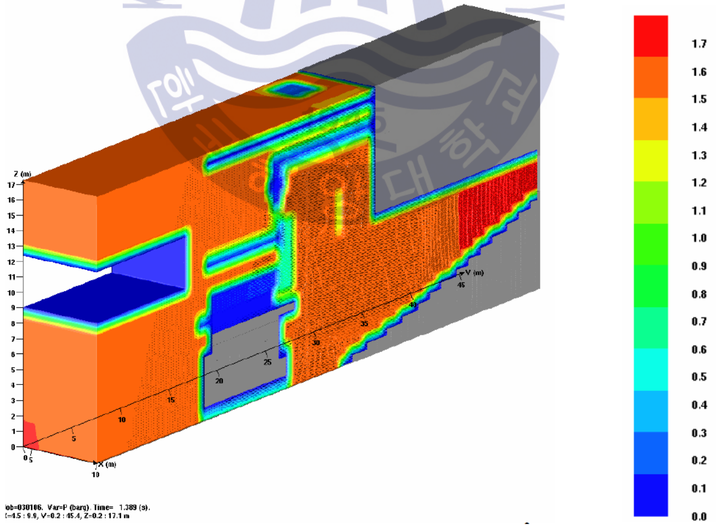


Figure 4-16 3D plot of pressure for scenario 030106 (1,500m^3 gas cloud) at time when highest pressure is achieved in the engine room. For this snapshot, the maximum pressure is achieved at the end of the machine room. However, the maximum pressure can be regarded as uniform all over the room.

4.6.2 Pressure impact on humans

The effects of overpressure on humans are mainly case by the following:

- injury to the body as a result of the pressure change
- injury as a result of fragments or debris produced by the overpressure impacting on the body

The human body is capable of adapting to pressure changes. However, organs can be damaged if the change is sudden. The lung is generally regarded as the most susceptible organ which is affected by overpressure and damage to it can lead to death. The ear is more sensitive but damage to it does not lead to fatality.

Related to explosion there is a different impact if the human is exposed transient or with solid background. The following table gives the fatal overpressure for transient and solid background exposure:

Table 4-7 Pressure impact on human.

Explosion exposure	Overpressure (bar)	Exposure time(s)
Transient exposure	0.1	0.2
	0.2	0.1
Solid background exposure	1	0.1

4.6.3 Summary of explosion analysis

Critical explosion pressures for structure are obtained for clouds larger than 1,500 m^3.

This cloud size may be obtained for full bore ruptures when the ESD closure time is 20 s and the ESD valve is on Main deck next to the compressors (segment is 22 kg).

When the segment size is reduced by moving the ESD valve to just outside the engine room wall, and 5 seconds closure time, the cloud size will not reach 1,500. The 1,500 m^3 cloud may then only be obtained for medium and full bore rupture and failure of ESD.

For humans, a cloud size of approximately 200 m^3 and larger is expected to be critical. This cloud size may be obtained for medium leaks when the ESD closure time is 20 s and the ESD valves are located on main deck next to the compressors (22 kg gas in the segment).

If the ESD closure is reduced to 5 seconds, and the ESD valve is moved to just outside the engine room, then the duration of the leak will be reduced significantly. In this case it is expected that the likelihood of obtaining critical explosion pressures on humans is reduced.

It is recommended to reduce the volume in the pipe segment by moving the ESD valve to just outside the engine room wall. It is also recommended to reduce the ESD closure time to 5 seconds by an efficient and reliable shutdown system

4.7 Fire analysis

4.7.1 Jet fire simulations

A jet fire can occur in the engine room if the gas ignites shortly after the leak has started. A probable location of a jet fire is under the switchboard room, where the fuel pipe is located (Figure 4-17). The leak location applied to all fire scenarios in this analysis is in the middle of the fuel pipe, with the coordinates (x, y, z) = (6.75, 5, 8.17). The fires are defined, and the main results are given in Table 4-8. The direction and the location of the jet fires are shown in Figure 4-17. The leak speed applied is 417 m/s (sonic). Other properties of the release are given in Chapter 3.0.

Table 4-8 Definitions of jet fire scenarios and main results.

Case no.	Leak rate (kg/s)	Leak jet direction (to platform angle)	Max radiation (kW/m^2) to the switchboard room	Max radiation (kW/m^2) to the fuel tank wall
Fire1	0.5	+x (against PS)	240	229
Fire2	0.1	+z (Upwards)	135	2
Fire3	0.15	+x (against PS)	102	44

Required safety actions at fire detection in the engine room are that the ventilation shall stop automatically and fire dampers shall close. In the analysis it is assumed that 20 seconds are needed from the leak starts to the fire detection system stops the ventilation and close the fire dampers. An important assumption is also that the engine continues running after fire detection. It is likely that the engine will suck air from somewhere providing air also to the fire. In the structure heat-up analysis both situations are considered; when the air supply is closed and when it is open. The same time (20 s) is applied for closure of the ESD valves in the fuel pipe. It is assumed that the pressure of 300 bar in the fuel pipe is maintained until the ESD valves close. A steady state simulation with constant room ventilation and a constant leak rate is simulated in order to represent the initial phases of the fire. The ventilation conditions are modelled as described in Chapter 5.0 with 5 air sources underneath the 2nd deck. In 1st deck, five ventilation sources and the main air outlet are modelled.

The worst consequence of a jet fire is a radiation of such a level so that the fuel tank wall collapses. If the fire burns a hole in the tank wall, the fire can escalate. Another consequence of a jet fire is a collapse of the 2nd deck plate under the switchboard room, leading to loss of control. The leak rate and the leak direction in the fire scenarios are chosen in order to get the worst case, i.e. a fire with a high radiation level and the longest possible duration at the tank wall and the switchboard room. The fuel pipe is close to the switchboard room, only 1/2 meter beneath. Only a small leak rate is needed to get the fire up to the switchboard room. Case “Fire 2” of 0.1 kg/s is sufficient to give high radiation below the switchboard room. The tank wall is 8.5 meters from the leak point. A leak rate of 0.5 kg/s is needed to get the intense jet flame as far as the tank wall.

The results from Fire1 and Fire3 are given in Figure 4-18 to Figure 4-21. These fires have the same location and direction; only the leak rate differs. The temperature plots show that the Fire1 scenario has a flame length long enough to reach the fuel tank wall. The temperature is over 1,600 K up to the tank wall, and the radiation level is high. This is about the worst leak rate for the tank wall. A larger leak rate has a shorter duration. A larger leak rate gives initially a flame which is longer than the distance to the tank wall. This leads to a richer gas mixture in the jet flow, and the fuel will burn after it hits the tank wall. Then it will stop quicker, after the ESD valves closes. It is also noted that depressurization will empty the fuel pipe within 30 s.

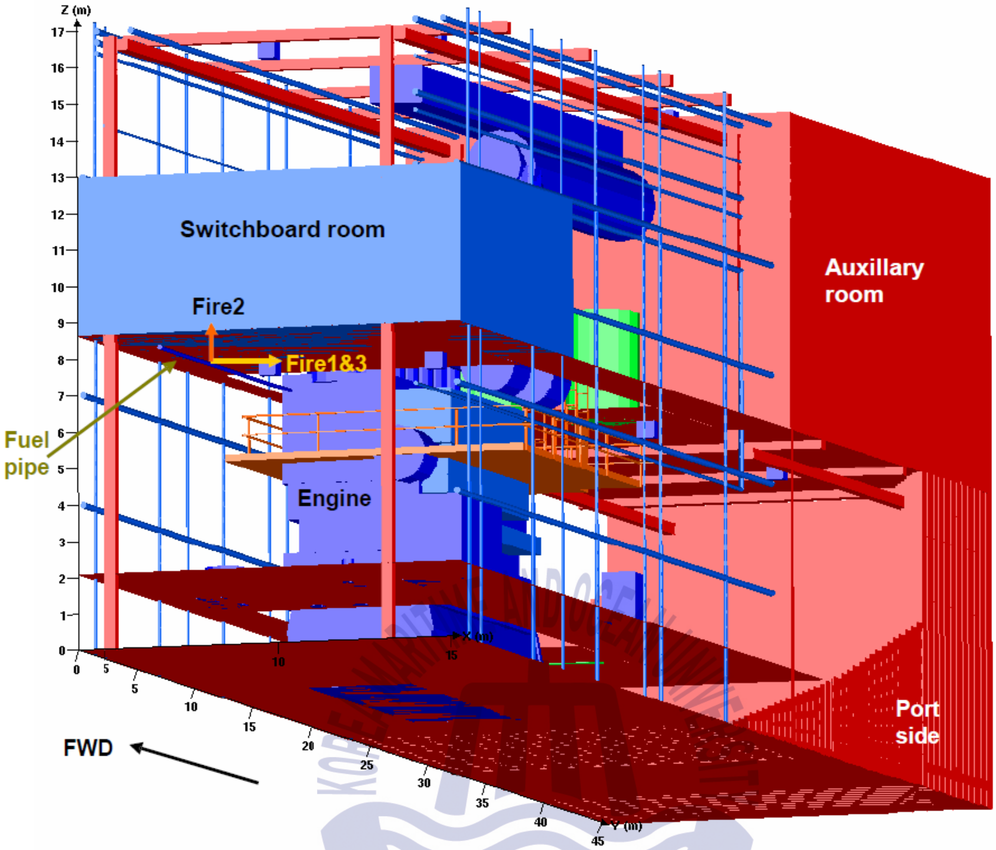


Figure 4-17 Location and direction of leaks selected for the jet fire scenarios. The leaks are from the fuel pipe and directed against the PS fuel tank and the above switchboard room. The fuel tank room is located at the port side of the engine room. The walls and the ceiling in the engine room are made invisible in this figure.

The temperature plots in Figure 4-18 to Figure 4-20 of the Fire3 scenario show that a lower leak rate gives a flame which is not long enough to reach the tank wall. Figure 4-21 show that the radiation on the tank wall is reduced from 229 kW/m^2 to 44 kW/m^2 when the leak rate is reduce from 0.5 kg/s to 0.15 kg/s. Hence, the duration of the fire which can affect the fuel tank wall is limited by the amount of fuel in the fuel pipe after the ESD closes.

Since the distance from the jet fire to the switchboard room is shorter, the radiation on the switchboard room is higher in Fire3, as shown in Figure 4-22.

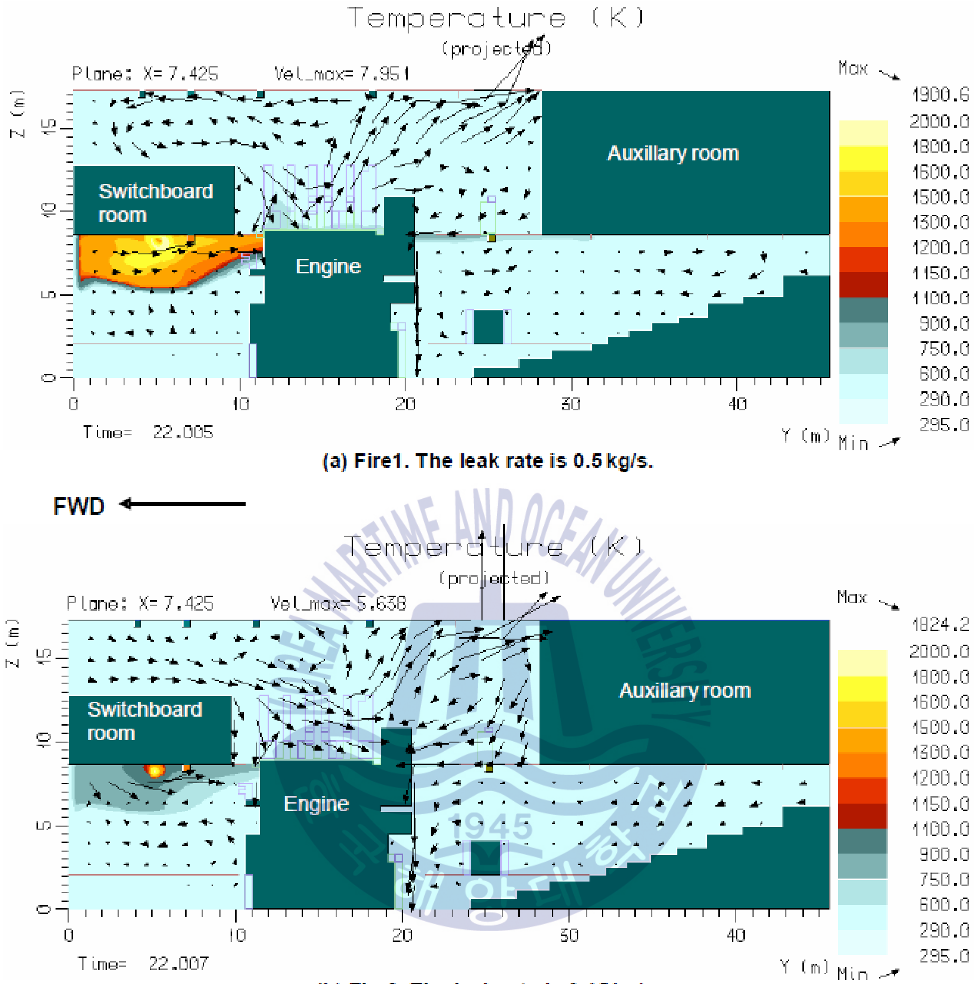
The results from Fire2 are given in Figure 4-23 to Figure 4-25. This jet fire is directed upwards against the switchboard room. It is a small jet fire with a longer duration. The jet hits the ceiling only after ½ meter, causing a lot of turbulence and a good mixing of fuel and air. This leads to a high peak temperature of 2,100 K as shown in the figures. The radiation level of Fire2 (shown in Figure 4-25) is lower than the radiation of Fire1 (in Figure 4-22) because the flame is smaller. However, the Fire2 scenario has a longer duration than the Fire1 scenario.

Because the fires are simulated with venting, the results are primarily applicable for the first period of the fire. After gas and fire detection, the ventilation stops, and the leakage is limited by the 22 kg segment mass. Then the leak rate decrease as the pressure in the segment decrease (as shown in Chapter 3.0). The 22 kg of fuel gas requires 376 kg air in a stoichiometric combustion. The mass of air in the modelled engine room is 6,218 kg, 18 times more than needed for the fire. The engine uses 56 kg/s of air, i.e. it consumes the available air in about 110 seconds, assuming it runs constant until it dies. That means that the steady state results are valid also some time after the first 20 seconds. Here it is also assumed that the engine suction will not cause opening of some air supply.

The Fire3 scenario can be used in two ways: It can be applied to a fire with an initial leak rate of 0.15 kg/s, or it can be considered as a snapshot of a fire with a higher initial leak rate, like 1.5 kg/s as in the Fire1 scenario. Considering the second application, Fire1 and the Fire3 scenarios can be considered as the same fire. The Fire1 scenario describes the fire the first 20 seconds, and the Fire3 scenario gives a snapshot of the fire after 68 seconds when the leak rate is reduced to 0.15 kg/s (Figure 4-6). At 68 seconds there is still excess air, and the results are applicable even though the simulation is performed with ventilation. This is a conservative assumption since the ventilation gives a better mixing of fuel and air, causing higher maximum temperature and radiation flux. In the structure heat-up analysis in the next section, this scenario is considered further.

In summary, the fire with an initial leak rate of 0.5 kg/s is limited by two factors at the same time. In approximately 2 minutes after the leak has started, the fire will extinguish because the fuel segment is almost empty and the air in the engine room is consumed. For smaller leak rates, the fire is limited to two minutes or somewhat more of air availability. For larger leak rates than 0.5 kg/s, the fire is limited by the leak profile

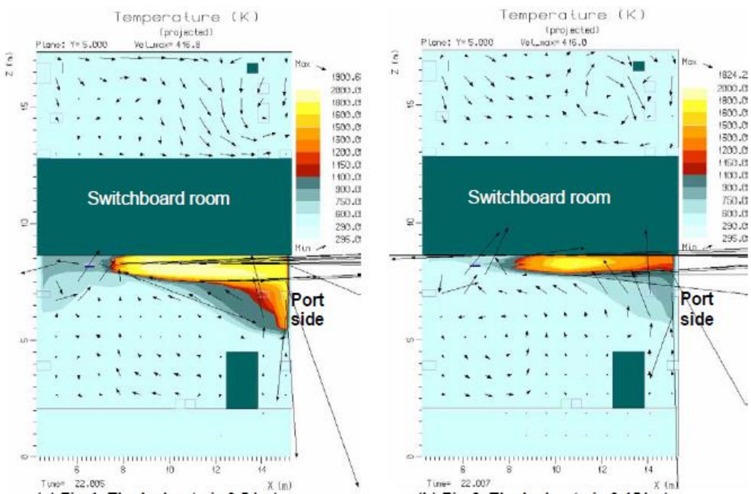
(50-60 seconds for 2.5 kg/s, see Figure 4-7).



(a) Fire1. The leak rate is 0.5 kg/s.

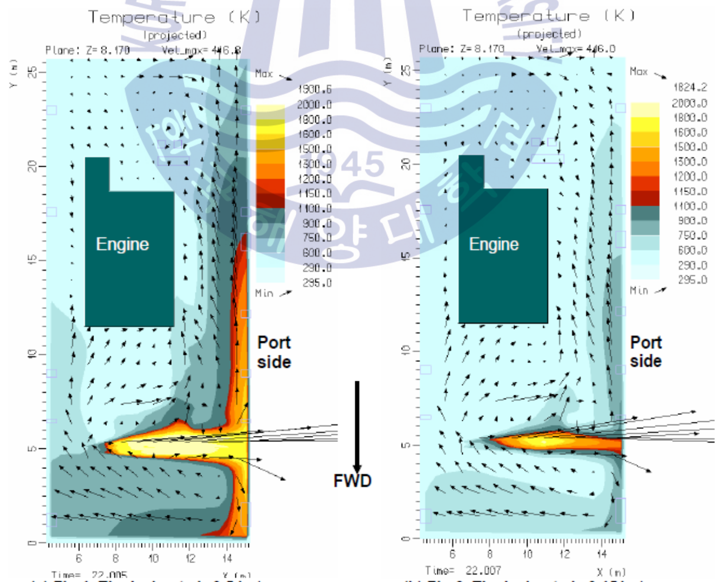
(b) Fire3. The leak rate is 0.15 kg/s.

Figure 4-18 Side view of Fire1 and Fire3, seen from port side. The maximum temperature (K) is projected into the y-z plane. The velocity vectors illustrate that air/smoke flows through the vent opening.



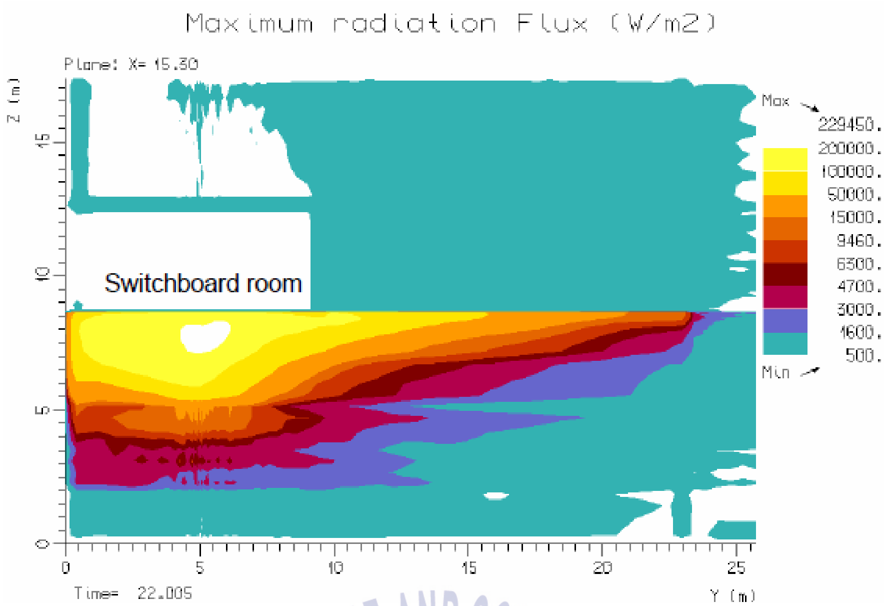
(a) Fire1. The leak rate is 0.5 kg/s. (b) Fire3. The leak rate is 0.15 kg/s.

Figure 4-19 Side view of Fire1 and Fire3, seen from FWD. The maximum temperature (K) is projected into the xz-plane. The velocity vectors show the flow field in the xz-plane where the jet fire is.



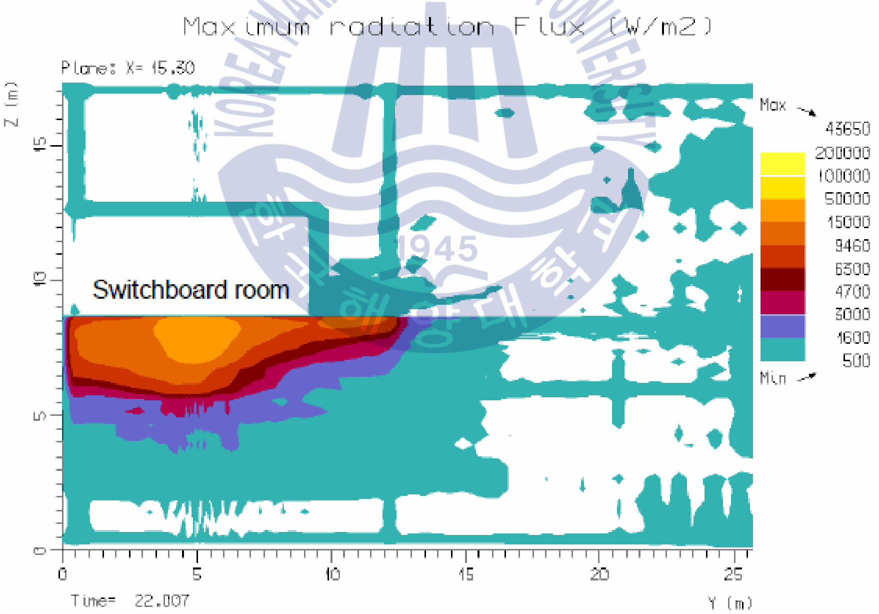
(a) Fire1. The leak rate is 0.5 kg/s. (b) Fire3. The leak rate is 0.15 kg/s.

Figure 4-20 Top view of Fire1 and Fire3. The maximum temperature (K) is projected into the xy- plane. The velocity vectors show the flow field in the xy-plane where the jet fire is.



(a) Fire1. The leak rate is 0.5 kg/s.

FWD



(b) Fire3. The leak rate is 0.15 kg/s.

Figure 4-21 Side view of Fire1 and Fire3, seen from port side. The radiation flux (W/m^2) is displayed in the yz-plane at the port side fuel tank wall. The maximum values of 229 kW/m^2 and 44 kW/m^2 for the current leak rates are the radiation levels exposed to the fuel tank wall.

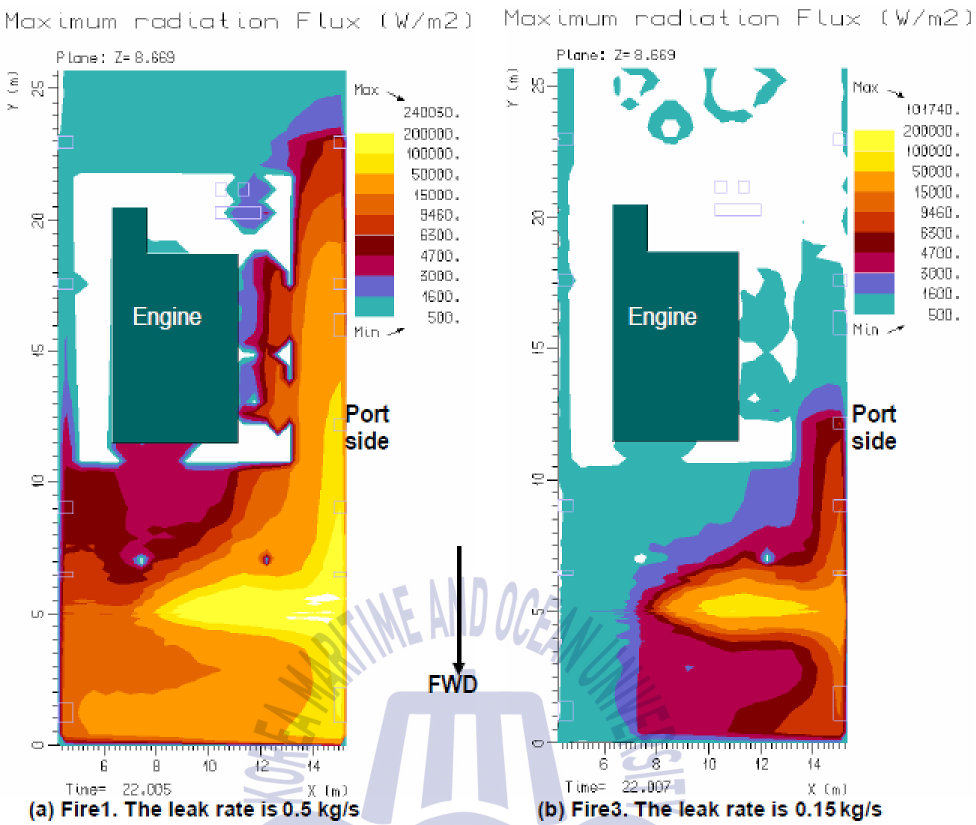


Figure 4-22 Top view of Fire1 and Fire3. The radiation flux (W/m^2) is displayed in the xy-plane up under the 2nd deck plate. The maximum values of 240 kW/m^2 and 102 kW/m^2 for the current leak rates are the radiation levels exposed to the switchboard room.

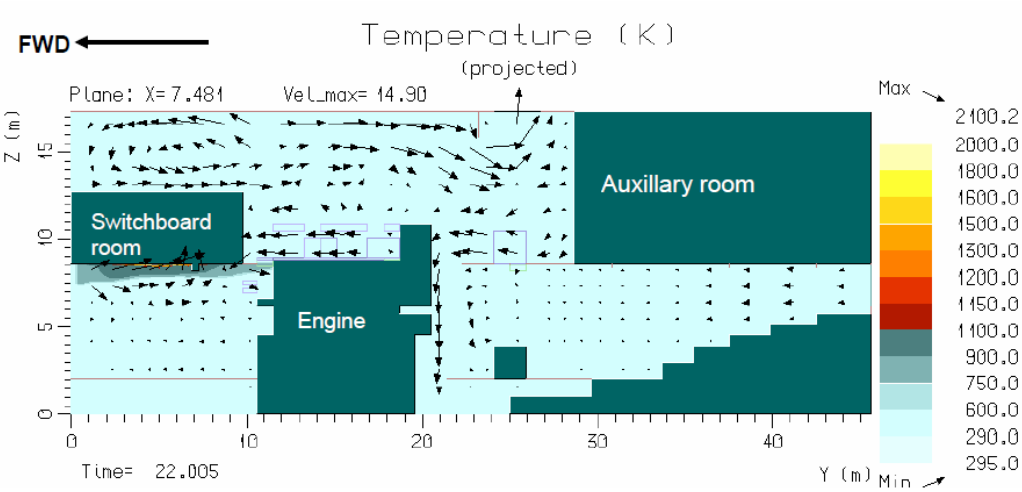


Figure 4-23 Side view of Fire2 (0.1 kg/s), seen from port side. The maximum temperature (K) is projected into the y-z plane. The velocity vectors illustrate that air/smoke flows through the vent opening.

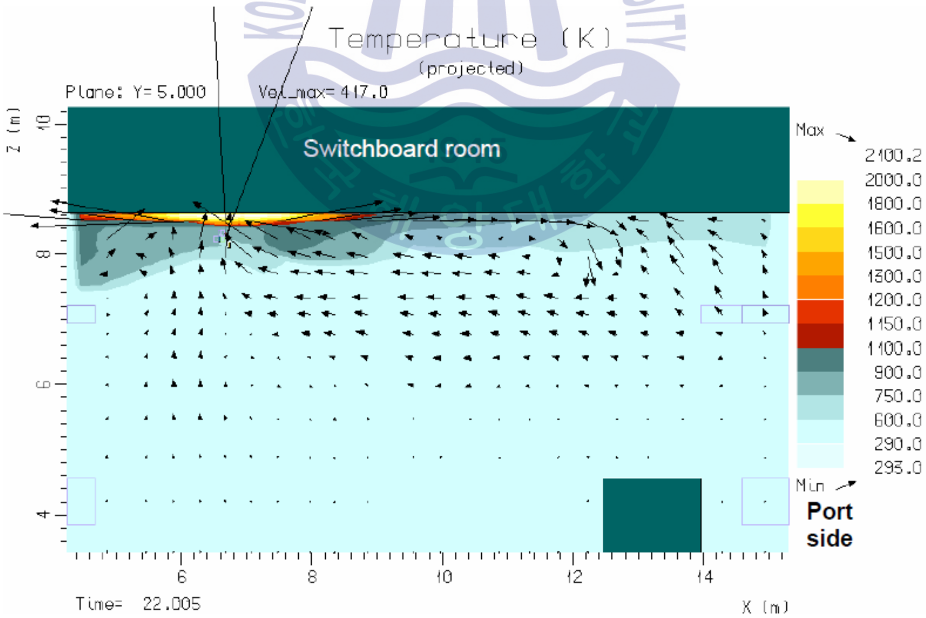


Figure 4-24 Side view of Fire2 (0.1 kg/s), seen from FWD. The maximum temperature (K) is projected into the xz-plane. The velocity vectors show the flow field in the xz-plane where the jet fire is.

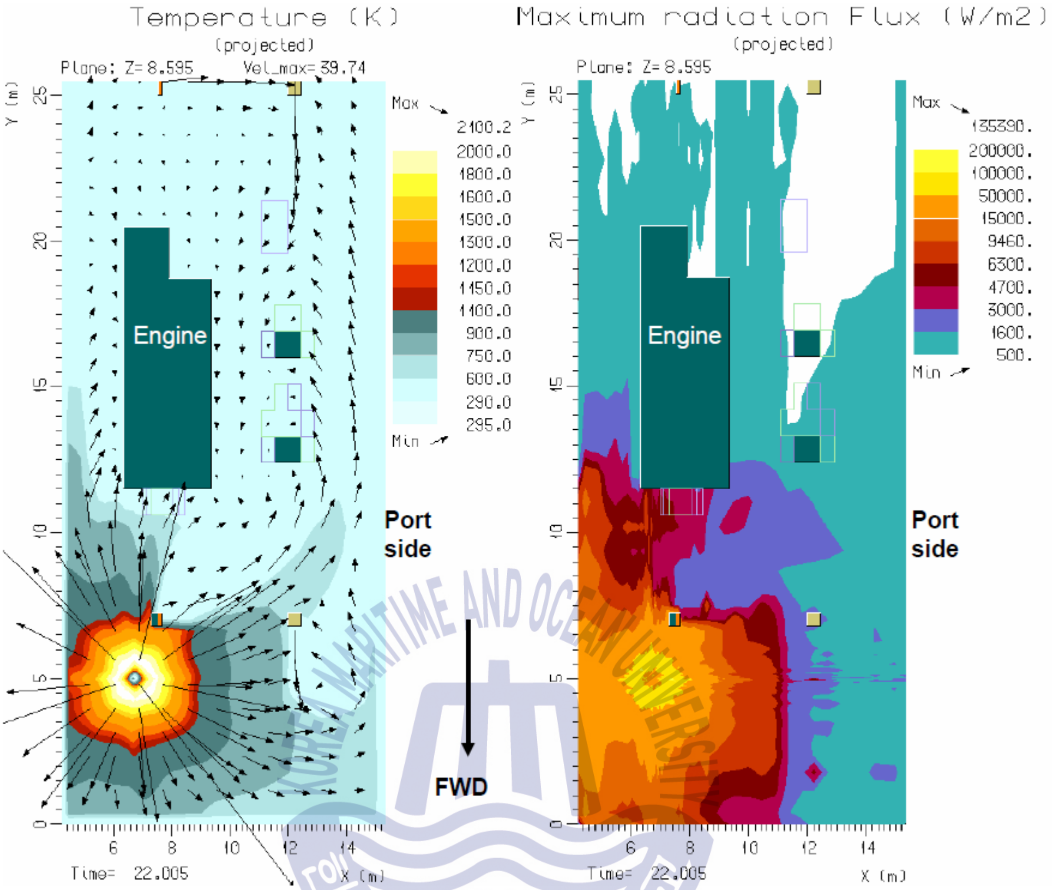


Figure 4-25 Top view of Fire2 (0.1 kg/s). To the left, the maximum temperature (K) is projected into the xy-plane. The velocity vectors show the flow field in the xy-plane up under the 2nd deck plate. To the right, the radiation flux (W/m^2) is displayed in the xy-plane up under the 2nd deck plate. The maximum value of 135 kW/m^2 is the radiation level exposed to the switchboard room.

4.7.2 Summary of fire analysis

The results from the structure heat-up analysis give relatively high temperatures in the switchboard room deck plate for small fires, both when the engine stops and when it continues running. In Table 4-9 are indicated the temperatures in the switchboard room for normal cases and for cases when the ESD is failing. In addition, the effect of ventilation stopping or not stopping is indicated. It is uncertain whether the air supply to the engine room will stop when the engine continues running. It is likely that the suction from the engine will ensure some air also when the ventilation system shuts down. The results in Table 4-9 are obtained with ESD valves located on Main deck next to the compressors (22 kg gas in the segment). Also, it is applied that the ESD valves close after 20 seconds from the fire starts.

If the ESD valves are moved just outside the wall of the engine room, the ESD closure time is reduced to 5 seconds, and the fuel pipe is depressurized; the fire duration will be reduced significantly. This will also cause reduced heat-up and temperatures in the switchboard room deck plate.

Table 4-9 Scenarios identified for a fire in the engine room. Results are given when main engines and ventilation either stops or continues running when a fire is detected in the engine room. The available gas and air is considered when determining the duration of the fire. Results are indicated in terms of temperature in the switchboard room deck plate just above the jet fire.

Engine action on fire detection	ESD	Ventilation in engine room	Leak size	Fire duration restricted by	Comments and temperature in Switch board room deck plate
Goes	No failure	Not relevant	Large	Fuel	Short duration gives low temp.
			Medium	Fuel	Short duration gives low temp.
		Stops	Small	Air (approx. 2 min)	Fire 2 gives 420 °C in SW.B. deck plate
		Does not stop	Small	Fuel	Longer duration gives 630 °C SW.B. deck plate
Stops	No failure	Not relevant	Large	Fuel	Short duration gives low temp
			Medium	Fuel	Short duration gives low temp
			Small	Fuel	Longer duration gives 630 °C SW.B. deck plate
Goes	Failure	Assumed that air is available due to engine running	Large*	No restrictions	Engine switched to liquid fuel due to gas supply is cut. Assumed that compressor don't stop gives high temperatures
			Medum*	No restrictions	Engine switched to liquid fuel due to gas supply is cut. Assumed that compressor don't stop gives high temperatures
			Small*	No restrictions	Steady state solution Fire 2 gives: 940 °C SW.B.
Stops	Failure	Not relevant	Large	96 kg fuel	Fuel supply assumed to stop when engine stops. Low temp.
			Medium	96 kg fuel	Fuel supply assumed to stop when engine stops. Low to medium temp.
			Small	96 kg fuel	Fuel supply assumed to stop High temperature assumed (max 940 °C SW.B.)

*Constant leak rate for leakages of 2.5 kg/s and less, large leaks limited by 2.5 kg/s delivered by the compressor.

4.8 Frequency assessment

4.8.1 Leak frequency

The concept leak frequencies are estimated for the dual fuel pipe in the engine room. Leak frequencies for inner and outer pipe is based.

The annual leak frequency is generated by means of Software LEAK.

By using LEAK, the release frequencies may be calculated for the entire installation, parts of installation and defined systems and equipment groups. LEAK utilizes a library of release frequencies for standard process components which is based on release recordings from such equipment in the UK offshore industry in the period 2002-2012, a total of some 2000 leak events. These equipment items comprise of valves, pressure and storage tanks, heat exchangers, pumps, compressors, filters, flanges and process pipes.

Leak frequencies are established for three defined leak rate categories of which the consequence outcomes are expected to differ. These are represented by the leak sizes given in Table 4-10.

Table 4-10 Process Leak Rate Categories

Leak category	Leak rate range [kg/s]
Small	0-1
Medium	1-10
Full bore	10-53

The equipment included in inner and outer pipe leak frequency is listed in Table 4-11. These parts counts are applied as input to the Leak program.

Table 4-11 Equipment included in leak frequency.

Part	Equipment	Diameter [mm]	Length [m]	Number
Inner pipeline	Pipe	39	20	1
	Pipe	17.5	1	6
	Flange	17.5		6
	Actuated valve	17.5		12
	Manual valve	17.5		6
Outer pipeline	Pipe	70.5	20	1
	Pipe	73	0.5	6
	Flange	73		6
	Protective hose	73		6
	Pipe	34	0.5	6
	Flange	34		6
	Protective hose	34		6

As explained earlier a realistic gas leakage scenarios are defined assuming a full breakage of the outer pipe and a full or smaller hole in the inner fuel pipe. A summary of the estimated leak frequencies for inner and outer pipe and the total leak frequency are presented in Table 4-12.

Table 4-12 Estimated Process Leak Frequencies

Leak category	Inner pipe [per year]	Outer pipe [per year]	Total dual fuel line [per year]
Small	1.84E-02	0	2.7E-04
Medium	4.02E-03	0	5.9E-05
Full bore	2.18E-03	1.46E-02	3.2E-05

The total dual fuel line is obtained by co-incident events, multiplying the frequency for inner pipe with frequencies for full bore in the outer. This is a conservative approach.

It should be noted that the established leak frequencies are a coarse estimate, and changes in process design parameters may affect the leak frequencies.

The following issues may have an influence on the estimation of leak frequency:

Operating environment

Service conditions between various installations may differ, and these might result in different leak frequencies for otherwise similar equipment. Comparisons of data sets from different installations are difficult because of inconsistent reporting, varying standards of safety management, different types of fluid and differences in environmental factors.

Safety management

The quality of operation, inspection, maintenance etc. is a critical influence on leak frequencies. The basic leak frequencies used in the calculations reflect safety management in UK offshore installations during 2002-2012, which is believed to be a good modern standard. The leak frequencies at plants with lesser standards may be higher. In order to reflect the standard of safety management at an individual plant, it is possible to quantify this using a safety management audit, and convert the audit score into an overall management factor (MF), by which all the generic failure frequencies can be multiplied. Due to lack of experience with this technique, the relationship between the audit scores and management factors is highly speculative.

Design codes

Pressure systems usually follow a design code, and hence design standards are usually considered uniform. The basic leak frequencies used in the calculations are based on a population that follows modern codes. Accidental failure to follow design codes is implicit in the failure frequencies. For example, in the HSE data design faults contributed to 16 % of leaks.

Materials

As different materials have different properties for corrosion, erosion, fatigue, etc. the materials used in process equipment design is expected to affect the leak frequencies.

Equipment content

Overall, the leak frequency may be largely independent of the fluid in the pipe. The fact that some fluids are more likely to promote corrosion should be compensated by extra inspection if the safety management standard is uniform.

Operating conditions (temperature/pressure)

Equipment operating close to its design pressure may be more vulnerable to accidental overpressure. This is a commonly modelled for cross-country pipelines, but is normally not included in a risk analysis of a process plant due to lack of a suitable model and the complexity that it would add to the analysis. Also, equipment operating above or below the normal temperature for its material of construction may be more vulnerable to material failure.

Seismic activity

Seismic activity is a potential cause of equipment failure for offshore installations, although it has not occurred in the HSE offshore data. The level of seismic activity can very widely between different areas.

Equipment age

In theory, new equipment is vulnerable to teething problems and old equipment to wear-out, producing a bath-tub curve of failure rate versus time. Equipment that is subject to corrosion or fatigue is normally designed with a finite life, and the probability of failure increases as it nears the end of that period.

Process continuity

Many failures occur during shut-down or start-up. For example, in the HSE data these accounted for 28 % of leaks [59]. Failures are more likely in plants that experience many shut-downs.

Passive fire protection and equipment insulation

Equipment with passive fire protected or insulated should be inspected more carefully to compensate for the difficulties introduced by the coating. The coating may introduce higher corrosion rates and thus increase the leak frequencies.

Manning levels

A high manning level is expected to increase the risk for process leaks as a large fraction of the registered leaks are related to some kind of human impacts/interventions. An increased activity level in the vicinity of the process equipment may thus increase the potential for damaging process equipment.

4.8.2 Ignition probability

The ignition probabilities can be approximated as follows. This approximation is based on offshore experience:

$$\begin{aligned} P_{\text{ignition probabilities}} &= 0.03 \times Q^{0.5} \text{ K } for \text{K} Q < 280 kg/s \\ \text{KKKKKK} &= 0.5 \text{KKKK} for \text{ K} Q > 280 kg/s \end{aligned} \quad \textbf{(1)}$$

where:

P = ignition probability
Q = release rate (kg/s)

The ignition probability calculated for the dual fuel pipe is listed in Table 4-13.

Table 4-13 Process Leak Rate Categories

Leak category	Representative Leak rate [kg/s]	Ignition Probability
Small	0.5	0.021
Medium	5	0.067
Full bore	25	0.15

4.8.3 Detection and isolation of fuel leaks from dual pipeline

The frequency of fires and explosions also depend on the probability of detection and probability of isolation of a fuel leak from the dual pipeline. In the consequence assessment, scenarios are considered where it is assumed that the detection and shutdown systems are working. Here a quantitative assessment of the frequency of failure of these systems is given.

4.8.3.1 Detection failure

The outer air-pipe is equipped with gas detection and flow measurement, and the inner pipe is equipped with pressure drop sensor. The flow in the air pipe will be disrupted if there is a breakage of the outer pipe. This is assumed to be the main method of detecting leaks. A reliable flow measurement is hence essential in order for this to be detected.

The pressure drop sensor in the inner pipe should be located as close as possible to the location it should detect the leaks. It is also noted that small leaks will have a too low pressure reduction to be detected. As an example, it is indicated that a leak of 1 kg/s will cause a pressure drop pf 80 bar in 5 seconds. a pressure sensor will not be able to detect smaller pressures than this. Hence, a smaller leak where the outer pipe is completely off must be detected by the reduction in flow in the flow sensors. The gas detector in the outer air pipe will not be exposed to gas in the scenarios where the outer pipe breaks.

There is no gas detection in the engine room.

It is assessed that full bore and medium leaks above 1 kg/s has a very small probability for not being detected. The smaller leaks rely only on one method of detection and have therefore a higher probability of not being detected. If gas detectors are installed in the engine room, the probability of detection of small leaks will be considerably higher.

Another hazard to be addressed is related to the under pressure in the machine room. This pressure difference may cause air to enter the outer pipeline even if there is a leak. This event is conservatively assessed to give a failure probability of detection of 20% for small leaks. For medium and full bore leaks, the pressure drop sensor is assumed to detect the leaks.

4.8.3.2 Isolation failure

There are two independent emergency shutdown (ESD) valves on each end of each segment on the inner pipe. A separate system of blow down of the fuel line is also installed. The blowdown will open 30 sec. after isolation.

ESD is automatically initiated upon 60% LEL confirmed gas detection, and is assumed to be effective within 30 sec from a detected leak/fire.

The objective of installing the ESD valves is to limit the inventory that has the potential of feeding the release and thus reduce the release duration. When isolation is complete, manual blow down of the segments may be initiated. Both ESD valves are “fail close” hence it is assumed that if the ESD control system fails, the valves will close automatically. For this reason no common mode failure is assumed whereby all the ESD valves fail to close.

The demand failure probabilities for ESD valves used in this analysis are based on OREDA data and are given in Table 4-14 for the various valve sizes and types.

Table 4-14 Valve Failure Probabilities

Valve size (inch)	On demand failure probability [-]
2" – 4"	0.0055
4" – 8"	0.014
8" - 16"	0.019
16" – 36"	0.045

In addition, the ESD logic may fail. The on demand failure probability for the ESD logic is assumed to be 0.001. With dimensions of the valves and number of ESD valves in each segment known, the "on-demand" isolation failure probability can be estimated

The "on-demand" failure probabilities calculated for the representative failure cases are shown in Table 4-15. The numbers are derived from the following formula (example calculation for machine room):

$$P_{Isolation\ failure} = 1-(1-0.0055)^2 \times (1-0.001) = 0.012$$

The above formula indicates that isolation failure occurs whenever one or several ESD valves or ESD logics required to isolate the segment fails.

Table 4-15 On Demand Isolation (ESD/XV) Failure Probabilities

Case	No. of ESD valves					
Representative Segments	2" – 4"	4" – 8"	8" - 16"	16" – 36"	ESD logic	Isolation failure probability [-]
Machine room	2				1	0.012

The effect of isolation failure is reflected through the duration of the release and thus the duration of a potential fire which has an impact on the potential for escalation.

4.8.4 Summary of frequency assessment

The total frequency of fires and explosions are given in Table 4-16.

The fire frequency is the yearly frequency of obtaining an ignited leak. The explosion probability is the probability of obtaining the pressures above the human tolerable limit, 0.1-0.2 barg, given a leak and an ignition. The explosion frequency is the yearly frequency of obtaining human tolerable limit.

The main contribution to the detection/isolation failure probability is the failure of detection of small leaks, which is assumed to be 20%.

Table 4-16 Summary of frequency of fires and explosions.

Failure mode	Leak size	Leak frequency [per year]	Ignition probability [per year]	Fire frequency [per year]	Explosion probability [per year]	Explosion frequency [per year]
No failures	Full bore	3.20E-05	0.15	4.7E-06	1	4.7E-06
	Medium	5.90E-05	0.067	3.9E-06	0.5	2.0E-06
	Small	2.70E-04	0.021	4.5E-06	0	0.0E+00
Detection/ isolation failure	Full bore	3.20E-05	0.15	5.8E-08	1	5.8E-08
	Medium	5.90E-05	0.067	4.7E-08	0.5	2.4E-08
	Small	2.70E-04	0.021	1.1E-06	0.5	5.7E-07

4.9. Findings and results

Realistic gas leakage scenarios are defined assuming a full breakage of the outer pipe and a full or smaller hole in the inner fuel pipe. Actions from the closure of the ESD valves, the ventilation system and the ventilation conditions after detection are included in the analysis. The amount of gas in the fuel pipe and the manifold limits the duration of the leak. It is further applied that the leak ignites and causes an explosion or a fire. Calculations of the leak rate as a function of time, and the ventilation flow rates are performed and applied as input to the explosion and fire analyses. The conclusions of each of these analyses are given in the sections below.

4.9.1 Explosions

The main results from the explosion analysis are summarized in Table 4-17. The main conclusions are described as follow:

- The maximum explosion pressure obtained is 1.7 barg. This occurs with a cloud size of 1,500 m^3. The probability of this is small because it may only occur during a medium or a full bore rupture and failure of shut down of the fuel pipe. Note that this cloud size has not been obtained from CFD simulations, but it is limited by the volume of the deck level where the leak occurs.

- For a full bore rupture with shutdown working, the maximum pressure is 1.1 barg. This will not cause restrictions to the structure examined. This is valid only when the ESD valve is located just outside the engine room. With a larger ESD segment, obtained when the ESD valve is located on Main deck next to the compressors, the cloud size may reach 1500 m^3 and the pressure may reach 1.7 barg, also when the ESD is working.

- For a medium hole size of 8.5 mm the explosion pressure will not cause failure of the structure. For this hole size, a maximum cloud size of 500 m^3 is obtained from the simulations.

- For small leaks (holes less than 3.8 mm) the explosion pressure is negligible.

- Critical pressures on humans (above 0.1 barg) can be obtained for medium and large leaks, applying 22 kg gas segment and 20 seconds ESD closure time. For a smaller segment and faster ESD closure time, the likelihood of a critical pressure on humans is reduced.

- The explosion results are obtained applying normal air ventilation in the room. If the ventilation is reduced, even a small leakage may cause gas cloud build-up and explosive gas clouds. Depressurisation of the fuel pipe will reduce the chance for explosive gas clouds for small leaks.

Table 4-17 Main results from explosion analysis. ESD valve is located on Main deck (22 kg gas in the segment) and 20 seconds ESD closure time, except for full bore rupture case. Explosion frequency is the frequency of reaching pressures which can be intolerable to humans (0.1-0.2 barg).

Hole diameter [mm]	Size/ ESD failure mode	Initial leak rate [kg/s]	Gas cloud size [m³]	Max explosion pressure [barg]	Frequency of explosion (per year)	Comments
39 (full bore rupture)	Full bore/no failures	53	947**	1.1	4.7E-06	Max cloud size obtained from simulations. No failure of structure
8.5	Medium/no failures	2.5	500	0.47	2.0E-06	No failure of structure
3.8 and smaller	Small/no failures	0.5 and smaller	8 and smaller	Negligible	0	No failure of structure
39 (full bore rupture)	Full bore/failure of shut down	53	1000 to 1500*	1.1 to 1.7	5.8E-08	Can cause restrictions on girder
8.5	Medium/failure of shut down	2.5	1000 to 1500*	1.1 to 1.7	2.4E-08	Can cause restrictions on
3.8 and smaller	Small/failure of shut down	0.5 and smaller	500*	0.5	5.7E-07	No failure of structure

*Assumed

** Note that in this case only is applied ESD valve located just outside engine room and 5 seconds ESD closure time.

4.9.2 Fires

The main results from the jet fire analysis are summarized in Table 4-18, including detailed assessment of temperature in the switchboard room floor plate, and the liquid fuel tank wall. The main conclusions indicate that only the switchboard room floor plate is found to obtain critical steel temperatures for the cases with no failure of the shutdown:

- The highest steel temperature (630°C) is conservatively obtained in the switchboard room floor plate, caused by an upward directed jet fire, from the fuel pipe located ½ m below this deck plate. It is conservative because it is obtained when it is sufficient air to feed the fire. The air supply is likely to be reduced because the ventilation is shut down and the engine is continuing running.

- A critical steel temperature of 420°C is obtained in the switchboard room floor plate for the 0.1 kg/s fire when the air ventilation stops. The reason why this scenario gives a lower temperature is the duration of the fire. When the air ventilation stops, and the engine continues running, it is assumed that the fire is extinguished due to lack of oxygen.

- The maximum temperature obtained in the crude oil fuel tank wall steel plate is 278°C. This occurs only for medium size holes, 3.8 mm and larger, and a jet directed from the fuel pipe to the fuel tank wall. The reason for the low temperature is the distance from the fuel pipe to the fuel tank wall, and the short duration of a fire which is long enough to reach the tank wall. The fire duration caused by a 3.8 mm hole, and larger are limited by the (22 kg) amount of gas in the fuel pipe.

- If the ESD valve is moved just outside the wall of the engine room, the ESD closure time is reduced to 5 seconds, and the fuel pipe is depressurized; the fire duration will be reduced significantly. This will also cause reduced heat-up and temperatures in the switchboard room deck plate.

- In the unlikely event that the ESD valve fails to close, a longer duration fire may occur. If this fire is large enough to reach the fuel tank wall and the fuel tank wall is dry inside where the jet fire hits, it may lead to a rupture of the fuel tank.

- Failure frequency of the ESD is conservatively assessed to be relatively high. In 20% of small leaks it is assumed that the ESD will fail. The reason for the relatively high failure frequency is that detection is obtained by measuring change in air flow by flow measurement in the outer air pipe.

Table 4-18 Main results from fire analysis. ESD valve is located on Main deck (22 kg gas in the segment) and 20 seconds ESD closure time.

ESD Failure mode	Leak size	Fire duration [min]	Fuel tank wall		Switchboard room		Fire frequency (per year)
			Max (initial) radiation [kW/m2]	Max temper- ature* [^oC]	Max (initial) radiation [kW/m2]	Max temperature [^oC]	
No failures	Full bore	short	Not available	< 278	Not available	< 342	4.7E-06
	Medium	1 and shorter	Not available	< 278	Not available	< 342	3.9E-06
	Small	1.5 and longer	Max 229	278	240	630	4.5E-06
Failure of shut down	Full bore	Long	Not available	High	Not available	High	5.8E-08
	Medium	Long	Not available	High	240	High	4.7E-08
	Small	Long	229	High	135	940	1.1E-06

*Applying dry wall inside fuel tank.

4.10 Conclusions

Realistic gas leakage scenarios are defined assuming a full breakage of the outer pipe and a full or smaller hole in the inner fuel pipe. Actions from the closure of the ESD valves, the ventilation system and the ventilation conditions after detection are included in the analysis. The amount of gas in the fuel pipe and the manifold limits the duration of the leak. It is further applied that the leak ignites and causes an explosion or a fire. Calculations of the leak rate as a function of time, and the ventilation flow rates are performed and applied as input to the explosion and fire analyses. In order to reduce the fire impact of small fires and explosion pressures for large and medium fires, the ESD valve to move just outside the engine room, ensure a quick ESD valve closure time, and apply automatic depressurization of the fuel pipe on ESD. the reliability of detection by flow measurement in the outer air pipe to be considered. Gas detectors in the engine room are believed to give a more reliable detection including installing gas detectors which will shut down the fuel supply automatically. Air ventilation in the engine room is an important effect which causes the gas clouds to be small. Hence, it is recommended to keep a high availability on the air ventilation system. If the air ventilation system fails, it is recommended to shut down the gas supply.

Chapter 5 Conclusions

The overall, and the key results from this study covering entire range of potential safety issues and the various types of hazards that reached a good level of safety and no Safety and technical showstoppers identified.

The estimated risk increase is mainly due to the presence of the LNG tank and its effect on the risk from fire/explosions due to ship collision. A dropped container may potentially penetrate the main deck and damage gas piping and equipment in the pump room if dropped from large heights. However, a dropped container may only penetrate the main deck structure if no other containers are stored on the main deck. A dropped container may also damage/rupture the bunker line/hose if dropped and tipped over the ship side and onto the bunker ship/barge, causing fire/explosion.

Realistic gas leakage scenarios are defined assuming a full breakage of the outer pipe and a full or smaller hole in the inner fuel pipe. Actions from the closure of the ESD valves, the ventilation system and the ventilation conditions after detection are included in the analysis. The amount of gas in the fuel pipe and the manifold limits the duration of the leak. It is further applied that the leak ignites and causes an explosion or a fire. Calculations of the leak rate as a function of time, and the ventilation flow rates are performed and applied as input to the explosion and fire analyses. In order to reduce the fire impact of small fires and explosion pressures for large and medium fires, the ESD valve to move just outside the engine room, ensure a quick ESD valve closure time, and apply automatic depressurization of the fuel pipe on ESD. the reliability of detection by flow measurement in the outer air pipe to be considered. Gas detectors in the engine room are believed to give a more reliable detection including installing gas detectors which will shut down the fuel supply automatically. Air ventilation in the engine room is an important effect which causes the gas clouds to be small. Hence, it is recommended to keep a high availability on the air ventilation system. If the air ventilation system fails, it is recommended to shut down the gas supply.

Several important gaps in mandatory regulations, standards, guidelines or of relevant organizations beyond mandatory regulations have been identified requiring for action following the recommendations, however study can conclude, that it is technically feasible for the arrangement and installation of machinery for propulsion and auxiliary purposes, using natural gas as fuel, which will have an equivalent level of integrity in terms of safety, reliability and dependability as that which can be achieved with a new and comparable conventional oil fueled main and auxiliary machinery, while meeting the requirements of local and international regulations and standards.

The study and investigation can conclude that there are no HSE (Health, Safety and Environment) show stoppers for construction/ conversion of conventional oil fueled to dual fueled using LNG which risk analysis can also be mitigated and eliminated with sufficient design, engineering and operational controls that meet the required standards.

Reference

[1] S. H. Han, Y. S. Y, J. S. Kim, Y.C. Lee, "A study on the development of educational programs for LNG bunkering in consideration of the safety system," Journal of the Korean of Marine Environment & Safety, vol. 22, no. 3, pp. 268-277, May, 2016.

[2] IGF Code, International Code for the Construction of Gas Fueled Ships.

[3] "Interim Guidelines on Safety for Natural Gas Fueled Engine Installations in Ships" The IMO publication, IMO Resolution MSC 285 (86), 2009.

[4] International Maritime organisation (IMO)-SOLAS, "The International Convention for the Safety of Life at Sea", 2014.

[5] J. L. Woodward and R. M. Pitblado, LNG Risk based Safety – Modelling and consequence analysis, Wiley, 2015.

[6] LNG Overview - US Federal Energy Regulatory Commission, www.ferc.gov/for-citizens/citizen-guides.asp.

[7] BSI, "Installations and equipment for liquefied natural gas. General characteristics of liquefied natural gas," BS EN ISO 16903, June. 30, 2015.

[8] ISO, "Natural Gas – Calculation of calorific values, density, relative density and Wobbe index from composition," ISO 6976:2016, Aug. 15, 2016.

[9] SIGTTO, Liquefied Gas Carriers – Your Personal Safety Guide: Witherby

Seamanship International Ltd, 2012.

[10] ISO, “Natural Gas”, ISO 14532:2014, June. 15, 2014.

[11] MARPOL, International Convention for the Prevention of Pollution from Ships.

[12] SIGTTO, Liquefied Gas Fire Hazard Management: Witherby Seamanship, 2004.

[13] Directive 99/92/EC (also known as ‘ATEX 137’ or the ‘ATEX Workplace Directive’) is on minimum requirements for improving the health and safety protection of workers potentially at risk from explosive atmospheres.

[14] Directive 94/9/EC (also known as ‘ATEX 95’ or ‘the ATEX Equipment Directive’) is on the approximation of the laws of Members States concerning equipment and protective systems intended for use in potentially explosive atmospheres.

[15] BSI, “Explosive Atmospheres,” BS EN 60079, April. 30- 2009.

[16] BSI, “Explosive Atmospheres Gas detectors – Selection installation, use and maintenance of detectors for flammable gases and oxygen,” BS EN 60079-Part 29-2, 2007.

[17] SIGTTO, Contingency Planning and Crew Response Guide for Gas Carrier Damage at Sea and in Port Approaches: Witherby Seamanship, 1999.

[18] ISO, “Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries,” ISO/TC 67.

[19] 2014/94/EU of the European Parliament and of the Council, “Directive on deployment of alternative fuels infrastructure,” OCT. 22, 2014.

[20] J. de Wit, “EEMUA Recommendations for the design and construction of refrigerated liquefied gas storage tanks," Cryogenics, vol. 28, no. 12, pp 800-804, December 1988.

[21] BSI, “ Installation and equipment for liquefied natural gas – Design and testing of marine transfer systems – Part 1: Design and testing of transfer arm,” BS EN ISO 16903, June. 30, 2015.

[22] ISO, “Guidelines for Systems and Installations for Supply of LNG as Fuel to Ships,” ISO/TS 18683, Jan. 15, 2015.

[23] ISO, “Liquefied natural gas installations and equipment,” ISO/TC 67/SC 9, 2015.

[24] SIGTTO, The selection and testing of valves for LNG applications, http://www.sigtto.org/media/7205/ selection -and -testing -of- valves-for-lng.pdf, 2008.

[25] ISO, “Guidelines for Systems and Installations for Supply of LNG as Fuel to Ships,” ISO /TS 18683, Jan. 13. 2015.

[26] NMD, “Regulation of the Norwegian maritime directorate concerning the construction and operation of gas-fueled Passenger Ships,” Regulation No. 1218, Sep. 09, 2005.

[27] SIGTTO, ESD Arrangements and Linked Ship/Shore Systems for Liquefied Gas Carriers, http://www.sigtto. org/media/7201/esd-arrangements-and-linked-ship-shore-systems.pdf, 2009.

[28] ISO, “Petroleum and natural gas industries -- Design and testing of LNG marine transfer arms for conventional onshore terminals,” ISO 16904, ISO/TC 67/SC 9, Feb. 12, 2016.

[29] BSI, “Installation and Equipment for LNG – Design and testing of marine transfer systems – Part 2: Design and testing of transfer hoses,” BS EN 1474-2, March 13, 2009.

[30] SIGTTO, Manifold Recommendations for Liquefied Gas Carriers: Witherby Seamanship International Ltd, 2011.

[31] IEC TC/SC 18, Electrical Installations in Ships: Tankers - Special Features: IEC, IEC 60092-502, 1999.

[32] BSI, “Specification for Metallic Hose Assemblies for Liquid Petroleum Gases and Liquefied Natural Gases,” BS 4089, Dec. 15. 1999.

[33] NFPA, “Standard for the Production, Handling and Storage of Liquefied Natural Gas (LNG),” NFPA 59A – 2016.

[34] BSI, “ Installation and Equipment for LNG - Design of Onshore Installations,” BS EN 1473, May 31, 2016.

[35] Guidance on performing risk assessment in the design of onshore LNG installations including the ship/shore interface – ISO draft 116901.

[36] American Bureau of Shipping , Guide for Propulsion and Auxiliary Systems for Gas Fueled Ships, American Bureau of Shipping Publication, June 20, 2015.

[37] SIGTTO, A Risk Based Approach for the Provision of Firefighting Equipment on Liquefied Gas Jetties: Witherby Seamanship, 1999.

[38] Bureau Veritas, “Safety Rules for Gas-Fueled Engine Installations in Ships,” NR 529, May 2011.

[39] LNG Fire Protection and Emergency Response, Institution of Chemical Engineers,

2007.

[40] SIGTTO, Accident Prevention - The Use of Hoses and Hard-Arms at Marine Terminals Handling Liquefied Gas: Witherby Seamanship, 1996.

[41] SIGTTO, The Selection and Testing of Valves for LNG Applications, http://www.sigtto.org/media/7205/ selection-and-testing-of-valves-for-lng.pdf, 2008.

[42] BSI, "Installation and Equipment for LNG Design and testing of marine Transfer Systems - Offshore transfer systems," BS EN 1474-3, June 30, 2008.

[43] IACS, Formal Safety Assessment of general Cargo Ships Preparatorystep,http://www.iacs.org.uk /document/public/Publications/Other_technical/PDF/_FSA_General_Cargo_Ships_Preparatory_Step_pdf848.pd, 2008.

[44] SIGTTO, ESD Arrangements & linked ship/shore systems for liquefied gas carriers, http://www.sigtto.org/ media/7201/esd-arrangements-and-linked-ship-shore-systems.pdf, 2009.

[45] OGP, Risk Assessment Data Directory; Vulnerability of humans. Report No. 434-14-1. International Association of Oil and Gas Producers, March, 2010.

[46] SAFEDOR WP 4.2 FSA of RoPax ships, Design and Operation and Regulation for Safety, 2012.

[47] M. Hightower, L. Gritzo, A. Luketa-Hanlin, J. Covan, S. Tieszen, G. Wellman, M. Irwin, M. Kaneshige, B. Melof, C. Morrow and D. Ragland, Guidance on Risk Analysis and Safety Implications of a large Liquefied Natural Gas (LNG) spill over water, SAND2004-6258, Sandia Report, United States, 2004.

[48] J. L. Woodward, R. M. Pitblado, LNG Risk Based Safety, Modelling and Consequence Analysis, Wiley, 2010.

[49] J. G. “Quintiere, Smoke Measurements: An assessment of Correlations between Laboratory and Full-scale Experiments,” Fire and Materials, vol. 6, no. 3-4, pp. 145-160, 1982.

[50] NTS, Risk and emergency preparedness analysis, Rev 2, NORSOK Standard Z-013, 2001.

[51] SIGTTO, Guidance for the Prevention of Rollover in LNG Ships, July, 2012.

[52] ISO, “Risk Mangaement – Risk Assessment Techniques,” IEC/ ISO 31010, ISO/TC 262, Dec. 01, 2009.

[53] IHS Fairplay Casualty Database search through the DNV Maritime Advisory Portal in Vadis, modified 2015/12/15. Vessel type: Container ship (fully cellular) (A33A2CC).

[54] IACS Formal Safety Assessment of general Cargo Ships – Preparatory step, 2014-07-28.GP, Risk A

[55] IMO Interim Guidelines on Safety for Natural Gas-fueled Engine Installations in Ships. Resolutions MSC. 285 (86) adopted 1 June 2009.

[56] FSA – Dangerous Goods Transport with Open-Top container vessels. Submitted by Denmark. International Maritime Organization, Maritime Safety Committee, 87th session, Agenda item 18. MSC87/INF.2. 10. September 2014.

[57] Material Safety Data Sheet (MSDS) of Methane.

[58] RIVM (2009). Reference Manual BEVI Risk assessments version 3.1 – module B.

[59] HSE (2016) , Offshore hydrocarbon release statistics 2016, Offshore technology report OTO 2016 079

Lists of Publications and Lecturing

Lists of Publications and Journal Papers

[1] Hamid Etemad and Jae-Hyuk Choi, “The Hazard Identification (HAZID) of LNG-dual Fueled Ship operating between Korean Port/Busan and Iranian Port/Bandar Abbas”, Journal of the Korean Society of Marine Engineering, Vol. 41, No. 5, pp. 473~488, 2017 J. Korean Soc. of Marine Engineering (JKOSME).

[2] Hamid Etemad and Jae-Hyuk Choi, “Fire, Explosion and Safety Hazard Identification (HAZID) of the entire Methanol-dual Fueled System and Ship”, Journal of the Korean Society of Marine Environment and Safety (JKOSME), Vol., No., pp.000-000, 2017.

[3] Design and operation of Ethane Gas Fuel System on Ethane Carrier/ Ethan Gas fuel ships.

[4] Design and operation of Hydrogen fuel ships.

[5] LNG/Gas Pipe rupture analysis.

[6] Risk Assessment of LNG Bunker vessel.

[7] LNG Bunkering Facility.

[8] HAZID Small Scale LNG activities.

[9] LNG Bunkering Location selection and Risk Assessment in supply Facility.

[10] Location and placement of LNG Fuel tank.

[11] Risk Assessment/FMEA for Gas Fuels on Two-four stroke Engines and Boilers.

[12] Risk Assessment of Liquid Propane for Maritime Applications.

[13] LNG Bunkering outlook/ Forecast LNG bunker demand / Analyses development of LNG bunkering infrastructure globally/ LNG demand and setting the Price.

[14] LNG , GAS FUEL AND BUNKERING ASSESSMENT AND OUTLOOK.

[15] HAZID /Risk Assessment study on Small Scale LNG Bunkering/activities (STS, Shore to Ship, TTS, Location selection).

[16] Concept Risk Analysis for Dual Fuel ship's Type (Container, PSV, BC, Cruise, Barge, VLCC, Ro-Ro/Passenger, Tanker-medium).

Lecturing and Class Courses as associate Professor at KMOU

[1] LNG Bunkering, FSRU/LNG/Gas fuel/Low flash points fuels ships, System and Internal Combustion Engines Design, installations and operation.

[2] FSRU/ LNG/Gas fuel/Low flash points fuels Internal Combustion Engines and Systems.

[3] FSRU/LNGC/Gas fueled/ Low flash points Fueled ships and System Design, installations and operation.

[4] FSRU/ LNGC Gas Management and Operations.

[5] Relevant Risk assessment (HAZID, FMEA, FMECA) for LNG Bunkering, LNGC, FSRU, Gas fuel/Low flash points fuels Internal Combustion Engines and Systems, Gas fuel/Low flash points fuels Ships and system, and similar applications for other Alternative Gas/Low flash points Fuels (Methane, Methanol, Ethane, Ethanol, Hydrogen, LPG).

[6] International Maritime Laws on LNGC, FSRU, LNG Bunkering, Gas Fuel Ships and Gas carriers.