Article 1

Domino effect analysis of LNG cargo ships in harsh environments

Shibilson Ippenparambil, Division of Safety and Fire Engineering, School of Engineering, CUSAT, Kochi, Kerala, India.

V.R Renjith, Division of Safety and Fire Engineering, School of Engineering, CUSAT, Kochi, Kerala, India.

Key terms used:

Risk Assessment, Domino effect, Harsh environment, LNG cargo ships.

ABSTRACT

The integrity of a transportation facility can be ensured by understanding the hazards and estimating the risk and providing steps to minimize it to an acceptable level. Even though methods for performing risk assessment are well established, the quality of data used for the risk assessment is often debatable. When a facility has to be operated in harsh environmental conditions safety barriers may become unavailable and operators feel difficulty in performing their work. Domino accidents are caused by the propagation of a primary accident scenario occurring in an installation to the nearby installations, consequently resulting in more intense damage than that of the primary accident scenario. If we use conventional probability values for risk assessment of an asset operating in harsh environments this will lead to risk underestimation. In this paper domino effect analysis of LNG cargo ships is carried out considering harsh environmental conditions. Modified human error probabilities are calculated considering various environmental factors affecting the operator performance. Performance of hardware safety barriers are also evaluated considering harsh environmental conditions. Possible escalation scenarios are identified and risk indices are calculated using modified probability values. Individual risk value is increased by 9 times and the PLL value increased by 8.4 times when the ship operates in a harsh environment.

1. INTRODUCTION

Domino accidents are caused by the propagation of a primary accident scenario occurring in an installation to the nearby installations, consequently resulting in more intense damage than that of the primary accident scenario. Domino effects can be considered as very low-frequency, very high consequence events. So, neglecting the domino effect in a quantitative risk analysis will lead to risk underestimation. Sometimes it becomes inevitable to operate an industrial facility in a harsh environmental condition, where people find difficulty in working and safety barriers become unavailable. The events like floods, earthquakes, adverse environmental conditions are examples of such a scenario. One of the main objectives of domino effect analysis to estimate the escalation probability. In a situation where the harsh environmental condition is existing, models used for evaluating possible escalation scenarios may fail to obtain accurate escalation probabilities and consequently results in risk underestimation. To overcome this limitation effects of various environmental factors are also taken into consideration in evaluating possible escalation scenarios.

In this study, LNG cargo ships are considered for analysis. LNG is a green fuel and is a very good substitute for other fossil fuels like coal. Liquefied natural gas (LNG) is composed of mostly methane and is a cryogenic liquid at approximately -162 ºC. When vaporized, its flammability range is between approximately 5% and 15% by volume. Hazards associated with LNG include cold burns due to cryogenic temperature, fire, explosion, metal embrittlement, asphyxiation, and confined space hazards. The Density of LNG is less than water so they will float on water in case of any leakage from the storage vessel. The volume of LNG increases 600 times when its phase changes from liquid to vapour, due to this natural gas is transported over long distances in liquid form. LNG shipping is an economic way of transporting large quantities of natural gas from the production site to LNG storage terminals. LNG is transported and stored at normal atmospheric pressure, and LNG carriers are purpose-built tank vessels for transporting LNG at sea.

The design and operation of LNG cargo ships are governed by the IGC code published by IMO.LNG is stored in a liquid-tight vessel which acts as a primary barrier against cargo leakage. Secondary barriers (if provided), inert spaces, and thermal insulation act as additional protection layers to prevent cargo leakage. IGC code classifies cargo tanks into five major categories: - Integral tanks, membrane tanks, semi-membrane tanks, independent tanks, and internal insulation tanks. Independent tanks are further classified into Type A, Type B, and Type C tanks. Internal insulation tanks are further subdivided into Type1 and Type 2 tanks.

If LNG absorbs heat from the surroundings as it will tun into gaseous state, known as boil off gas. In some cases, the boil off gas is used in engine rooms otherwise it is reliquefied. In order to reliquefy the gas reliquefaction systems are used. A single-stage direct reliquefaction cycle of LNG vapour. Boil-off vapours from the cargo tank enter into the compressor, where its pressure and temperature are increased to a higher value. High- pressure high -temperature LNG is condensed against seawater in a condenser. The condensed liquid is then discharged into the cargo tank via an expansion valve.

Collision, grounding, contact, fire or explosion, incidents while loading/unloading of the cargo are the possible scenarios that may lead to leakage of cargo of an LNG cargo ship. In this study compressor room fire is considered as the primary scenario. The possibility of escalation of this fire scenario to the cargo tanks is analysed considering harsh environmental conditions existing in the sea. Domino scenarios are evaluated considering both normal and harsh environmental conditions and the results are compared.

2. LITERATURE REVIEW

Domino accidents can be defined as "a phenomenon in which a primary unwanted event propagates within an equipment ('temporally'), or/and to nearby equipment ('spatially'), sequentially or simultaneously, triggering one or more secondary unwanted events, in turn possibly triggering (higher-order) unwanted events, resulting in overall consequences more severe than those of the primary event" (Reniers and Cozzani 2013). Domino effects can be considered as very low frequency, very high consequence events. (Khakzad, 2015; Necci et al., 2015).

Darbra et al. (2010) studied 225 accidents involving domino effects that occurred in process/storage plants and during the transportation of hazardous materials from 1961 to 2007. Among these accidents, 5.8% were triggered by natural disasters (10 lightning, 1 earthquake, 1 extreme temperature, and 1 flooding) and,1 event was triggered by an intentional attack. Abdolhamidzadeh et al. (2011) examined 224 accidents that occurred from 1910 to 2008 in the process industries, found that 43% of the documented domino accidents were initiated by fires and 57% were initiated by explosions. Among the domino events triggered by fires, pool fire (80%) was the most frequent scenario found to initiate a domino accident chain. Among explosions, VCE (vapor cloud explosion) has been the most frequent cause. Another historical study shows that most of the escalation events in industrial accidents are attributable to long-lasting stationary fires (i.e., pool fires and jet fires) (Gomez-Mares et al., 2008). The analysis also indicated that 44% of jet fire accidents had occurred in transportation, 36% in process plants, 11% during loading/unloading operations and, 9% in storage plants.

SAFEDOR is a research program sponsored by the European Commission as an integrated project (IP) in their 6th Framework Programme. One of the aims of this project is to foster innovative ship design for cleaner and safer maritime transport. As a part of the SAFEDOR project, various hazards associated with LNG cargo ship operation had been identified and risk values are estimated. The study suggests that the compressor room is the most probable location in the cargo area for a fire to begin, and such fires will be specific to LNG carriers. For a compressor room fire, the following consequences are most likely to happen: If the fire protection systems may fail in preventing or extinguishing the fire or explosion, which might damage the cargo containment system and will result in the leakage of LNG. For such a scenario there is a great possibility that the ship will not survive. In the event of an escalating fire, the crew needs to evacuate and failure to do so in time might result in several fatalities (Vanem et.al 2009).

Increasing energy demand has accelerated LNG explorations, many such are in progress particularly in the Artic region. Artic regions are characterized by adverse climatic conditions or harsh environments. Harsh environments are those environmental conditions at which people find it hard to perform their duties effectively and cause a reduction in the integrity of industrial facilities as compared to normal climatic conditions (Khan et al.,2015). In other words, harsh environments possibly reduce the performance of safety barriers and the availability of emergency resources. (Landucci et al., 2017). Safety barriers, such as hardware systems and emergency response, are critical elements aimed at preventing the propagation of this type of scenario. Harsh environmental conditions may strongly affect the integrity of safety barriers and considerably delay an emergency response, and causes an increase in risk profile (Chen et.al 2020).(Landucci et al., 2017) proposed a methodology for the analysis of domino and cascading events in oil & gas facilities operating in harsh environments introducing the analysis of the environmental effect on the performance of safety barriers, accounting for various environmental conditions like cold weather, extreme snow, wind, fog effects, wave heights, sunlight hours, distance from home. (Bucelli et.al 2018) extended this methodology to analyse cascading events that occur in offshore oil and gas platforms and facilities. This study focuses on to performance assessment of safety barriers for preventing cascading effects in an LNG cargo ship during harsh environmental conditions.

3. MATERIALS AND METHODS

The methodology adopted for this work is illustrated in Fig 1

3.1 SHIP SPECIFICATION

Wartsila LNG cargo ship is selected for analysis. Fig 2 gives detailed drawing of the ship. Technical specification of the ship is given below:

- Total capacity = 20000 m3
- 2×7500 m^3 Bilobe and 1×5000 m^3 Bilobe type C Cargo tanks
- Length overall approx. = 147.25 m
- Deadweight max = 12500DWT
- Gross Tonnage = 17250 GT
- Net Tonnage = 5180 NT

- Design Speed = 15.0 Knots
- Main Engine: 2 stroke Wartsila 1×5950 KW
- Design Draught = 18.1t
- Length PP =138.70 m
- Breadth moulded = 25.30 m
- Depth moulded = 17.60m
- Draught = 7.80 m
- Maximum vapour pressure = 4bar
- Minimum cargo temperature = -163 ºC
- Generator sets (6L20DF) = 3×1065 KW
- Emergency generator = 3× 150 KW

CARGO EQUIPMENT

- Deep well pumps
- Cargo heating / Vaporization equipment
- Nitrogen generator unit
- Reliquefaction unit for LNG
- Gas combustion unit
- Elevated manifold

ACCOMMODATION

24 persons in full HVAC cabins.

Figure 1 Methodology Adopted for present study

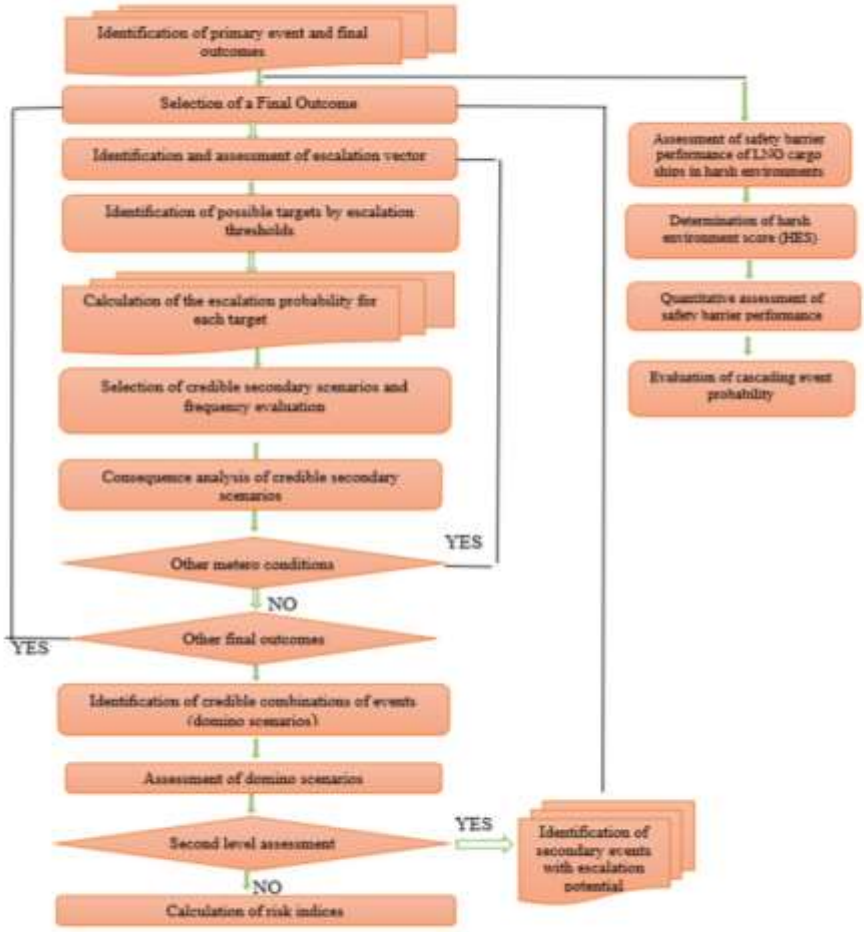
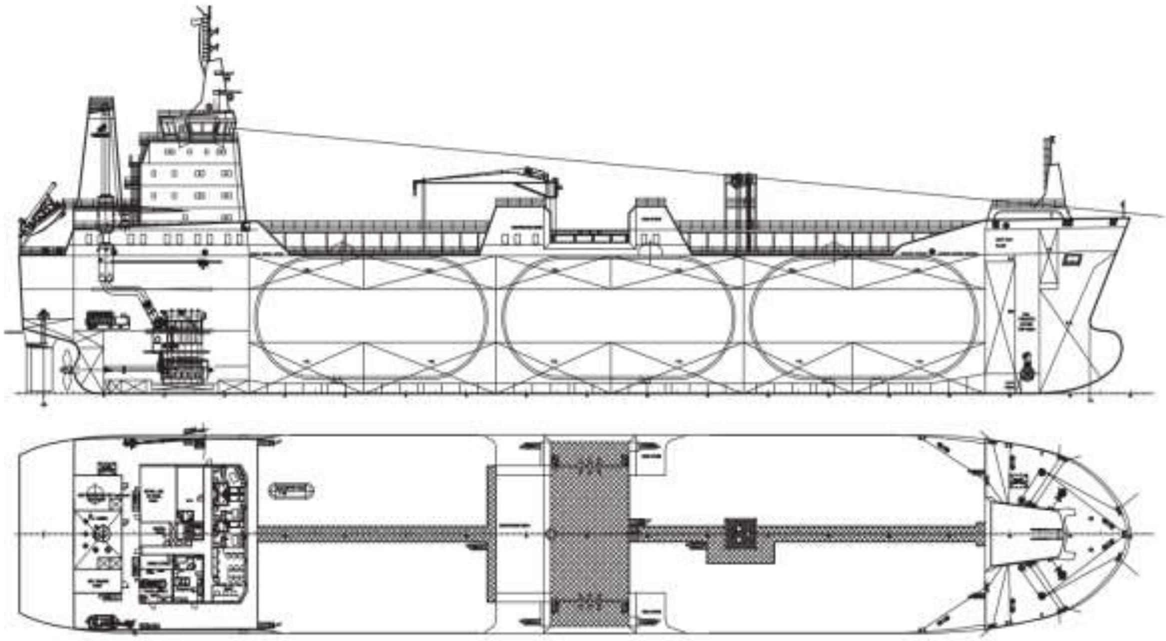


Figure 2 Detailed drawing of Wartsila LNG cargo ship



3.2 PFD VALUES FOR SAFETY BARRIERS

Safety Barrier	PFD Value (Y^{-1})	Reference
DCP Extinguishing system	1.2×10^{-2}	Idaho Chemical Processing Plant Failure Rate Database; Idaho National Engineering Laboratory 1995.
WDS (Water Deluge System)	4.33×10^{-2}	AIChE–CCPS. Layer of protection analysis: simplified process risk assessment. New York, 2001.
PFP (Passive Fire Protection Coating)	1×10^{-3}	AIChE–CCPS. Layer of protection analysis: simplified process risk assessment. New York, 2001.
Emergency Response Operations	1×10^{-1}	AIChE–CCPS. Layer of protection analysis: simplified process risk assessment. New York, 2001.

Table 1 PFD values for safety barriers

3.3 FIRE AND EXPLOSION FREQUENCY IN LNG CARGO SHIPS

Fire and explosion frequency in LNG cargo ships = **3.5×10^{-3}** per ship year (SAFEDOR project).

3.4 METEOROLOGICAL CHARACTERIZATION OF BARENTS SEA

(According to the parameters required for HES evaluation).

Environmental Factors	Meteorological Data	Reference
Environmental Temperature (ºC)	Minimum average Temp: -7.7 ºC (265.45 K). For the South-West area: typical Temp range from -15 to -20º C	ISO 2010 NORSOK 2007
Extreme wind speed (Annual speed range (m/s) at 10 m above sea level	Maximum wind speed at 10 m on the sea level: 26.6 m/s. Annual range:25–28 m/s Dominant direction during winter: North East.	ISO 2010
Waves height	Significant wave height: 15 m	NORSOK 2007
Snow (snowfall (m/year)	Average snowfall during winter (December–May): 0.21 m	Norwegian Meteorological Institute, 2017
Fog/Snow effect (Minimum visibility distance (m))	64 day/year with visibility lower than 2000 m due to snow precipitation 76 day/year with visibility lower than1000 m due to fog.	ISO 2010
Sunlight hours (sunshine duration (h/year))	1200-1600 h/year	Landsberg and pinna 1978

Distance from home, fear of unknown	High	Sudefeld and steel 2010

Table 2 Meteorological characterization of the Barents Sea

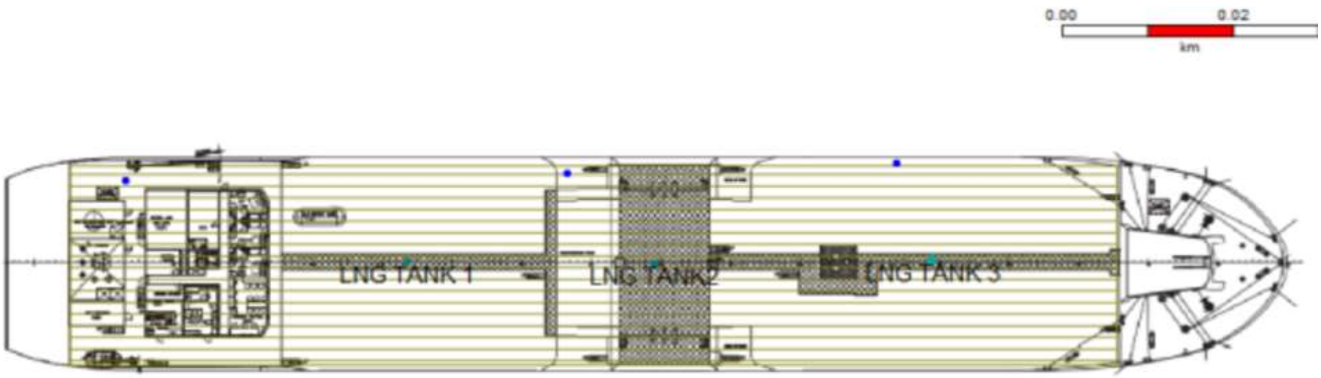
4. RESULTS AND DISCUSSION

4.1 IDENTIFICATION OF PRIMARY EVENT

SAFEDOR study identifies five credible scenarios that may lead to a breach of cargo they are; collision, grounding, contact, fire or explosion, incidents while loading or unloading the cargo. If any of the first three incidents occur breach of cargo will be due to the mechanical failure of the ship. No safety barrier available in the ship can delay or prevent the mechanical failure of the ship. Incidents due to the loading and unloading of the cargo are not associated with the voyage. But in case of a fire and explosion scenario safety barriers available in the ship can prevent or delay the escalation provided they perform their intended function effectively.

SAFEDOR studies suggest that the compressor room is the most probable location in the cargo area for a fire to begin, and such fires will be specific to LNG carriers. For a compressor room fire, the following consequences are most likely to happen: If the fire protection systems may fail in preventing or extinguishing the fire or explosion, which might damage the cargo containment system and will result in the leakage of LNG. For such a scenario there is a great possibility that the ship will not survive. In the event of an escalating fire, the crew needs to evacuate and failure to do so in time might result in several fatalities. So, compressor room fire has been identified as the primary event for the domino accident scenario.

Figure 3 Layout of LNG cargo ships indicating the location of storage tanks and risk ranking points



4.2 CALCULATION OF HEAT LOAD

The intensity of heat radiation due to jet fire in a compressor room is evaluated using Mundan and Croce jet flame model.

Input parameters

- Hole size = 25.4 mm (API standard)
- Outlet pressure = 10bar
- Heat capacity ratio=1.32
- Heat of combustion= 50MJ/Kg
- Flame temperature = 2200º C
- Molecular weight =16 Kmol/Kg (Molecular weight of Methane is considered as LNG is consisted mostly methane)

As natural gas vapors are lighter than air they will rise up, here a vertical flame is considered. Considering breakpoint of the jet as the bottom of the flame then flame height is given by:

$$\frac{L}{d_J} = \frac{5.3}{C_T}\sqrt{\frac{Tf/Tj}{\alpha_T}}\left[C_T + \left(1 - C_T\right)\frac{M_a}{M_f}\right]$$

Where;

L is the length of the visible turbulent flame measured from the breakpoint (m)

dJ is the diameter of the jet, that is, the physical diameter of the nozzle (m) CT

CT is the fuel mole fraction concentration in a stoichiometric fuel-air mixture (unitless)

Tf,Tj are the adiabatic flame temperature and jet fluid temperature, respectively (K)

αT is the moles of reactant per mole of product for a stoichiometric fuel-air mixture (unitless)

Ma is the molecular weight of the air (mass/mole)

Mf is the molecular weight of the fuel (mass/mole)

The combustion reaction is $CH_4 + 2O_2 + 7.52\ N_2 \longrightarrow CO_2 + 2H_2O + 7.52\ N_2$

CT = 1/ (1 + 2 + 7.52) = 0.095, Tf/Ti = 2200/298 = 7.4 and aT = 1.0. The molecular weight of air is 29 and for methane 16. Substituting we get

$$\frac{L}{d_J} = \frac{5.3}{0.095}\sqrt{\frac{8.28}{1}\left[0.095 + \left(1 - 0.095\right)\frac{29}{16}\right]} \quad = 212$$

Diameter of the issuing jet = 25.4 mm,

Flame length is (212) (25.4 mm) = 5.384 m

The discharge rate of the methane for the choked flow of gas through a hole is given by

$$M_{choked} = C_D\, AP_1 \sqrt{\frac{K\, g_c\, M}{R\, T_1}\left(\frac{2}{K+1}\right)^{\frac{K+1}{K-1}}}$$

$$= 1\times5.06\times10^{-4}\times10\times10^{5}\times\sqrt{\frac{1.32 \times 9.81 \times 16 \times 0.341}{8314 \times 265.45}}$$

= 2.86 Kg/s.

$$\text{View factor} = \frac{1}{4\pi x^2}$$

$$= \frac{1}{4 \times \pi \times 20}$$

$$= 3.97 \times 10^{-3}\ m^2$$

The radiative flux received by LNG tanks is given by;

$$E_r = \tau_a Q_r F_p = \tau_{a\,\eta\,m\,\dot{\Delta} H_c\ F_P}$$

Where,

E_r is the radiant flux at the receiver (energy/area-time)

Ta is the atmospheric transmissivity (unitless)

Qr is the total energy radiated by the source (energy/time)

Fp is the point source view factor

η is the fraction of total energy converted to radiation (unitless)

ṁ is the mass flow rate of the fuel (mass/time)

ΔH_c is the energy of combustion of the fuel (energy/mass)

Substituting these values into the above equation we get

$$E_r - 1 \times 0.2 \times 2.86 \times 50000 \times 3.97 \times 10^{-3}$$

$$= 113.79\ KW/m^2$$

The amount of heat energy received by LNG storage tanks 1 & 2 are 113.79 KW/m^2. The threshold limit value of radiation intensity necessary to damage process equipment is 37.5 KW/m^2. As the calculated intensity of radiation is above the threshold limit value, definitely there will be escalation.

4.3 EVALUATION OF HARSH ENVIRONMENTAL SCORE (HES)

Evaluation of HES involves four steps

1. Stressor's identification
2. Identifying external factors associated with each stressor
3. Weighing of external factors
4. Evaluation of harsh environmental score (HES)

4.3.1 SELECTION OF A SITE FOR ANALYSIS

In this study, the Barents Sea has been selected for analysis. Barents Sea is a part of the Northeast Passage (NEP), an important sea route through artic connecting the Atlantic and Pacific oceans. Summary of stressors, external factors, and penalty system for HES evaluation are shown in Table 3.

Stressors	External Factors	Range	Penalty
Coldness or warmth, Ice for slippery, difficulty in breathing	(1) Environmental Temperature (°C)	>45	0.8
		4 to 45	0
		-4 to 4	0.2
		-10 to -4	0.6
		-30 to -10	0.8
		<<-30	1
Combined weather effect	(2) Extreme wind speed (annual speed range (m/s) at 10 m above sea level	0 to3.3	0
		3.3 to5.5	0.2
		5.5 to 8	0.4
		8 to 10.8	0.6
		10.8 - 13.9	0.8
		>13.9	1
	(3) Waves height (significant waves height (m)	<0.1	0
		0.1 to 0.5	0.2
		0.5 to 1.25	0.4
		1.25 to 2.5	0.6

		2.5 to 4	0.8
		>4	1
	(4) Snow (snowfall (m/year)	0 to 0.125	0
		0.125 to 0.5	0.2
		0.5 to 1	0.4
		1 to 1.5	0.6
		1.5 to 2	0.8
		>2	1
Low visibility	(5) Fog/Snow effect (Minimum visibility distance (m))	<50	1
		50 to 200	0.8
		200 to 500	0.6
		500 to 1000	0.4
		1000 to 2000	0.2
		>2000	0
	(6) Sunlight hours (sunshine duration (h/year))	<1200	1
		1200 to 1600	0.8
		1600 to 2000	0.6
		2000 to 2400	0.4
		2400 to 3000	0.2
		>3000	0
Remoteness	Distance from home, Fear of unknown	Low	0
		Medium	0.5
		High	1

Table 3 Summary of stressors, external factors, and penalty system for HES evaluation

4.3.2 IDENTIFICATION OF STRESSORS AND ASSOCIATED EXTERNAL FACTORS

From the meteorological characteristics of the Barents Sea, we can identify the following external factors that are relevant to the Barents Sea;

1. Environmental Temperature (ºC)

2. Extreme wind speed
3. Waves height
4. Snow (snowfall (m/year)
5. Fog/Snow effect
6. Sunlight hours
7. Distance from home

4.3.3 CALCULATING THE WEIGHTS OF EACH EXTERNAL FACTORS

Weights of external factors are calculated using the analytical hierarchy process (AHP).

1- Equal importance

3- Moderate importance

5- Strong importance

7-Very strong importance

9-Extreme importance

2,4,6,8- Intermediate importance

1/3,1/5,1/7,1/9 – Values of inverse comparison

Using the above scales pairwise comparison matrix has been prepared

	Environmental Temp	Extreme Wind Speed	Wave Height	Snow Fall	Snow/ Fog Effects	Sunlight Hours	Distance From Home
Environmental temp	1	2	2/3	2	5	5	5
Extreme wind speed	1/2	1	2/5	1	3	3	3
Wave height	1.5	2.5	1	2.5	7	7	7
Snow fall	1/2	1	2/5	1	3	3	3

Snow/fog effects	1/5	1/3	1/7	1/3	1	1	1
Sunlight hours	1/5	1/3	1/7	1/3	1	1	1
Distance from home	1/5	1/3	1/7	1/3	1	1	1

Table 4 Pairwise comparison matrix for AHP

	Environmental Temp	Extreme Wind Speed	Wave Height	Snow Fall	Snow/ Fog Effects	Sunlight Hours	Distance From Home	Criteria Weight
Environmental temp	0.243	0.267	0.230	0.267	0.208	0.208	0.208	0.238
Extreme wind speed	0.122	0.133	0.138	0.133	0.125	0.125	0.125	0.218
Wave height	0.366	0.33	0.346	0.33	0.292	0.292	0.292	0.321
Snow fall	0.122	0.133	0.138	0.133	0.125	0.125	0.125	0.218
Snow/fog effects	0.049	0.044	0.049	0.044	0.042	0.042	0.042	0.044
Sunlight hours	0.049	0.044	0.049	0.044	0.042	0.042	0.042	0.044
Distance from home	0.049	0.044	0.049	0.044	0.042	0.042	0.042	0.044

Table 5 Normalised pairwise comparison matrix

Now we need to evaluate the consistency of calculated weights. For this purpose, each element in the column of the pairwise comparison matrix with the criteria value. The matrix obtained is shown below.

	Environmental temp	Extreme wind speed	Wave height	Snow fall	Snow/ Fog effects	Sunlight hours	Distance from home	Weighted sum	Weighed sum/ Criteria weight
Environmental temp	0.238	0.256	0.214	0.256	0.22	0.22	0.22	1.624	6.82
Extreme wind speed	0.119	0.128	0.091	0.128	0.132	0.132	0.132	0.862	6.73
Wave height	0.357	0.32	0.321	0.32	0.308	0.308	0.308	2.242	6.98
Snow fall	0.119	0.128	0.091	0.128	0.132	0.132	0.132	0.862	6.73
Snow/fog effects	0.0595	0.042	0.045	0.042	0.044	0.044	0.044	0.3205	7.284
Sunlight hours	0.0595	0.042	0.045	0.042	0.044	0.044	0.044	0.3205	7.284
Distance from home	0.0595	0.042	0.045	0.042	0.044	0.044	0.044	0.3205	7.284

Table 6 Matrix for consistency check

<u>Consistency check</u>

$$\lambda_{\max} = \frac{49.112}{7}$$

=7.016

$$\text{Consistency index} = \frac{\lambda_{\max} - n}{n-1} = \frac{7.016 - 1}{6} = 2.673\times 10^{-3}$$

$$\text{Consistency ratio} = \frac{consistency\ index}{Random\ index} = \frac{2.673 \times 10^{-3}}{1.32}$$ < 0.1 so it is consistent

4.3.4 EVALUATION OF HES

The Success likelihood index method is a widely used technique used for evaluating human error probabilities. In the application of SLIM, experts are asked to assign a weight to each Performance Shaping Factor (PSF) affecting the human reliability for a given task under consideration. The weighted sum of task ratings is named the Success Likelihood Index (SLI), ranging from zero to one. The numerical values of SLI represent the "relative distance" from the ideal condition for performing the task: SLI approaching to unity represents a situation close to the ideal condition, while a zero value of SLI represents the extreme adverse condition. SLI is transformed to a corresponding human error probability (PFD) estimate according to the following expression:

$\text{Log}_{10}(\text{PFD}) = a_o + \text{SLI} \times b_o$

"a_o" and "b_o" coefficients in the equation are determined assuming two known values of PFD for tasks having SLI = 0 and SLI = 1. In the present study, the HES score is considered as a simplified ranking of the PSFs affecting the emergency response in a harsh environment. The harsh environmental score is the weighted sum of penalties S, of the N external factors considered.

$\text{HES} = \sum_{i=i}^{i=n} W_i\ S_i$

Weights for each environmental factor and their respective penalties are summarised below:

Environmental Factors	Weight(W)	Score (S)
Environmental temp	0.238	0.8
Extreme wind speed	0.218	1
Wave height	0.3211	1

Snow fall	0.218	0.2
Snow/fog effects	0.044	0.4
Sunlight hours	0.044	0.8
Distance from home	0.044	1

Table 7 Weights and score assigned to various environmental factors

$$\text{HES} = \sum_{i=i}^{i=n} W_i \; S_i = 0.87$$

4.4 QUANTITATIVE ASSESSMENT OF SAFETY BARRIER PERFORMANCE

The method used to modify the availability of safety barriers in the harsh environment is adopted from the work of Gao et al. (2010), which applied the "proportional hazard model" proposed by Cox (1972) to modify reliability data in Artic environment. Gao et al. (2010) suggest to modify as follows the failure rate of a component t in case of harsh environment (λ):

$$\lambda\,(z) = \lambda_0 \;\exp\,(-1.409 z_1 - 1.0132 z_2)$$

where λ_o is the failure rate in the normal environment (assumed as constant during the life cycle of the system under consideration) and z is the vector of covariates. the factors having a more significant influence on reliability performance. A binary nature was assumed for the covariates (+1 = good/desired and -1 = bad/undesired conditions), according to the rules summarized in Table 8. The correlation was obtained analysing the statistical failure data of a turbo-compressor. Gao et al. (2010) also proposed to extend the application of the above correlation to other types of equipment in the absence of specific data. To obtain baseline failure rate values for the hardware barriers (λ_o), the PFD database was used as a starting point. The failure rate of a component was derived applying the base relationship for the estimation of tested components unavailability to PFD_o the probability of failure on demand for a safety barrier at normal environment

$$\lambda_0 = \frac{2PFD_0}{\theta_0}$$

where λ_o is the baseline test interval, assumed equal to 1 year (8760 h) for industrial facilities located in normal environments. The modified PFD in the harsh environment is calculated as follows:

$$PFD = 0.5\,\lambda\theta$$

In this work test interval is considered as one year, assuming the ship will undergo maintenance every year.

Covariate	Definition	Values	
		+1	-1
Z_1	Protection conditions	Inadequate protection	Adequate protection
Z_2	Equipment quality	Poor quality	Good quality

Table 8 Covariate values for failure rate modification (adapted from Gao et al., 2010)

4.5 VALUATION OF EFFECTIVENESS OF SAFETY BARRIERS

In the methodology proposed by Landucci et al. (2015), the effectiveness of the emergency response system was quantified defining a time scale for emergency operations. The time scale was based on the examination of the different actions required to suppress the fire (alerting, deploying on-site measures, provide the required amount of extinguishing agent, etc.), which contribute to the evaluation of the time for final mitigation (TFM). Landucci et al. (2015) provided a simplified estimation of TFM, based on the type of target, the fire mitigation strategy, and the type of location considered (onshore /offshore facilities). TFM is site-specific and may be seriously affected by harsh environmental conditions, with a possible delay associated with increased deployment time, difficulties in reaching remote locations, availability of the extinguishing agents, difficulty of performing the task effectively, etc. After the estimation of the time scale for emergency, in order to establish the value of barrier effectiveness η, the TFM value is compared to the time to failure (TTF) of the target under analysis according to the methodology proposed in (Landucci et al., 2015). Effectiveness is defined as the probability that the safety barrier, once successfully activated, will be able to prevent the escalation. If the emergency response is activated but TFM results higher than TTF, the emergency team actions are significantly delayed and might fail to prevent escalation of primary unwanted scenario (here jet fire scenario) For such a situation effectiveness $\eta = 0$. If the emergency response is activated and TFM is lower than TTF, the mitigation action is successful and the fire escalation is prevented ($\eta = 1$).

TTFp= (TTF)Tank+(TTF)Fire protection coating

(TTF)unprotected tank = $2.783 \times 10^{-4} \exp (8.84\ V^{0.032} - 0.95 \ln (QHL)$

$(TTF)_{Fire\ protection\ coating}$ = 0 for Low performance coating

=70 min for High performance coating

Where TTF_p represents Time to failure of passive fire protection (min).

$$\text{Log10}(\tau_1) = -0.699\,(1-\text{HES}) + 1.176$$

$$\text{Log10}(\tau_2) = -0.699\,(1-\text{HES}) + 1.699$$

$\tau 1$= Time to alert

$\tau 2$= Time for firefighting intervention

$\tau 1 + \tau 2 < TTF$; effectiveness of emergency response system is 1; 0 otherwise.

Moreover, it is assumed that harsh environmental conditions don't affect the effectiveness of hardware safety barriers (Gao et al., 2010).

Results are summarized in Table 9

Parameter	Time (in minutes)
$(TTF)_{unprotected\ tank}$	0.397
$(TTF)_{Fire\ protection\ coating}$	70
TTF	70.397
τ_1	12.165
τ_2	40.56
$\tau_1 + \tau_2$	52.727

Table 9 Calculation of TTF and TFM

Gate type	Graphical Representation	Description

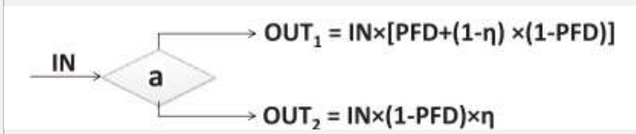
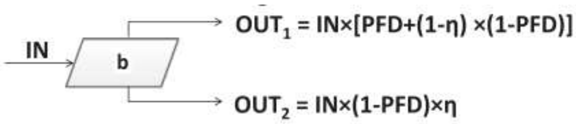
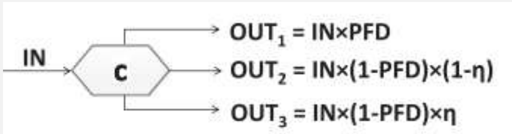
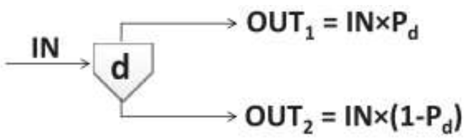
A		Simple composite probability: availability, expressed as the probability of failure on demand, is multiplied by a single probability value expressing the probability of barrier success in the prevention of the escalation
B		Composite probability distribution (gate type "b"): availability, expressed as the probability of failure on demand, is multiplied by a probability distribution expressing the probability of barrier success in the prevention of escalation, thus obtaining a composite probability of barrier failure on demand
C		Discrete probability distribution (gate type "c"): depending on barrier effectiveness, three or more events may originate from the gate describing barrier performance
D		Vessel fragility gate: based on the status of the target equipment (e.g., received heat load, status of protections etc.), the failure probably is computed through equipment vulnerability models based on probit functions

Table 10 Definition of gate types and associated operators (Launducci 2015)

Safety barrier	Gate Type	PFD value (Y^{-1})		Effectiveness	
		Normal conditions	Harsh environment (HES = 0.87)	Normal conditions	Harsh environment (HES = 0.87)
Pressure safety valve (PSV)	a	$1×10^{-2}$	$1.12×10^{-1}$	1	1
Water deluge system(WDS)	a	$4.33×10^{-2}$	$4.88×10^{-1}$	1	1

Fire protection coating (PFP)	a	1×10^{-2}	1.11×10^{-1}	1	1
Emergency response operations	c	1×10^{-1}	6.76×10^{-1}	1,0	1,0

Table 11 Availability and Effectiveness of safety barriers

4.6 VESSEL FRAGILITY MODELS

The vessel failure probability is evaluated from the probit equation shown below.

$Y = K_1 + K_2 \ln(TTF)$

$K_1 = 3.718 \ln(\tau_1) - 6.283 \ln(\tau_2) / \ln(\tau_1) - \ln(\tau_2)$

$K_2 = 2.565 / \ln(\tau_1) - \ln(\tau_2)$

The probit value can be converted into failure probability. Substituting the values to the above equation, we get vessel failure probability as 2×10^{-3} per year.

4.7 EVENT TREE

Based on the modified probability values, event trees are constructed for both harsh and normal environmental conditions.

Figure 4 Event tree for normal environmental conditions for a sequence of events followed by compressor room fire

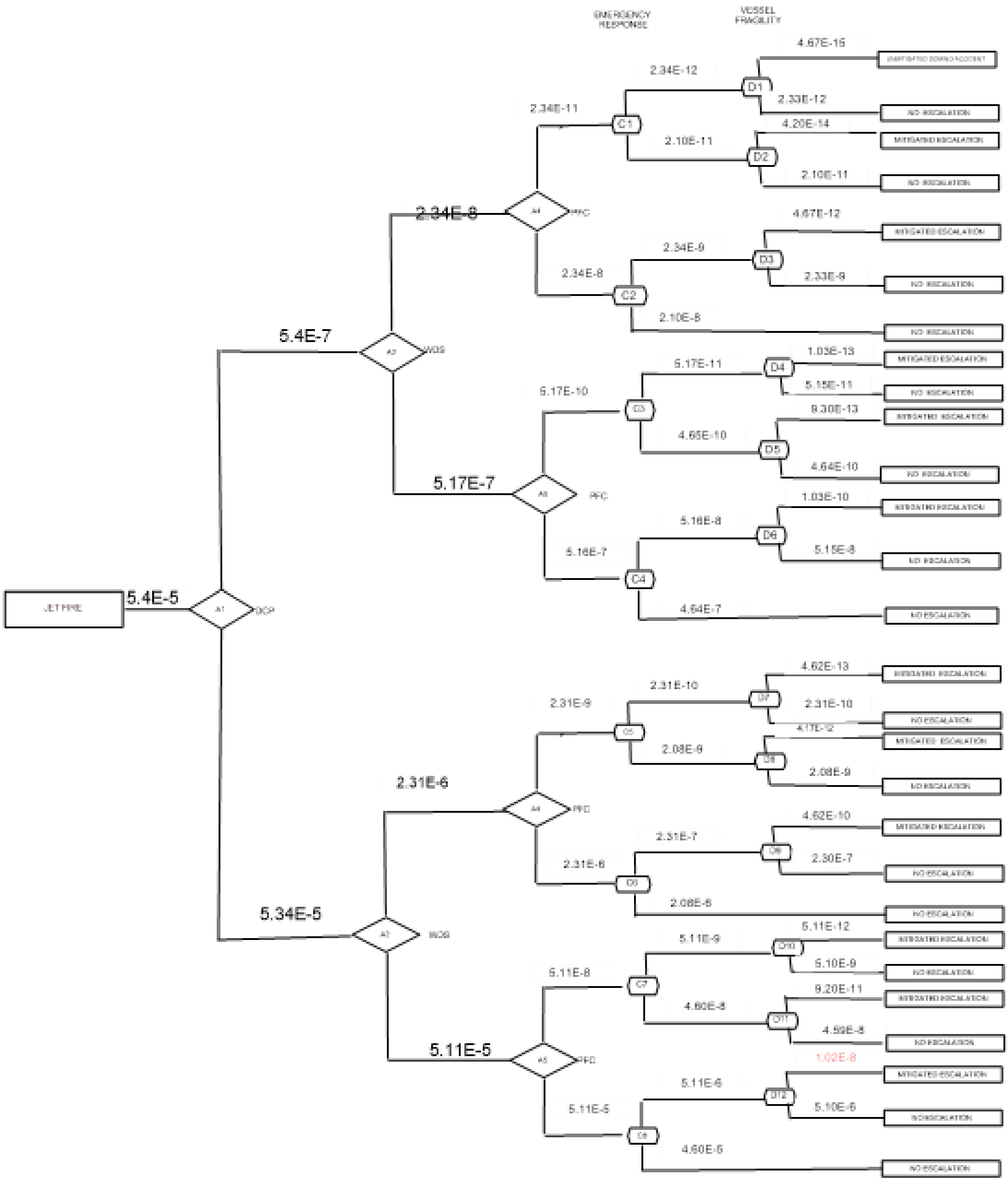
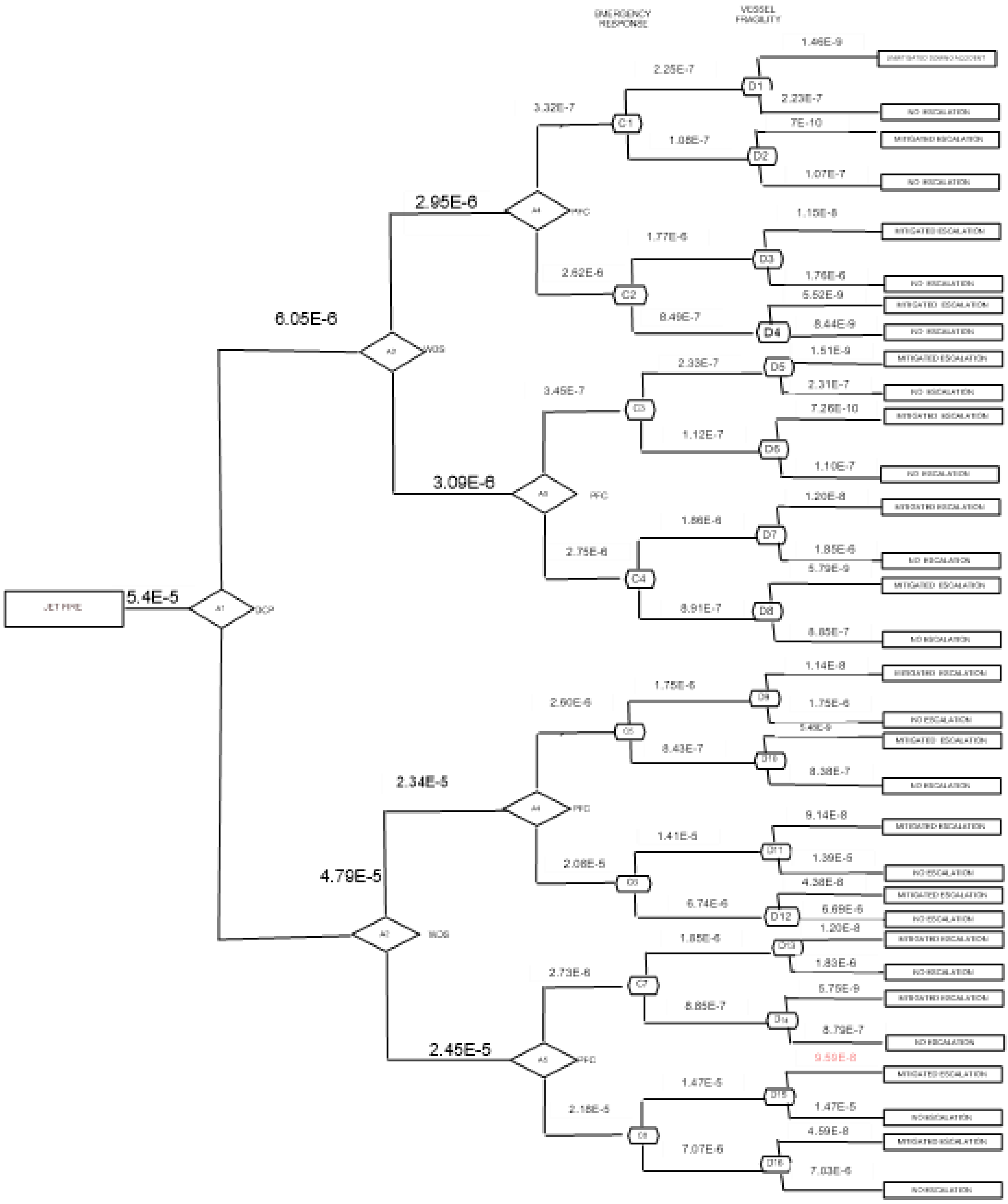

EMERGENCY RESPONSE
VESSEL FRAGILITY
JET FIRE
5.4E-5
A1
DCP
5.4E-7
A2
WDS
2.34E-8
5.17E-7
5.34E-5
2.31E-6
5.11E-5
PFC
2.34E-11
2.34E-12
2.10E-11
4.67E-15
2.33E-12
4.20E-14
2.10E-11
C1
C2
D1
D2
D3
D4
D5
D6
C4
2.34E-8
2.34E-9
2.10E-8
4.67E-12
2.33E-9
5.17E-10
5.17E-11
4.65E-10
1.03E-13
5.15E-11
9.30E-13
4.64E-10
5.16E-7
5.16E-8
4.64E-7
1.03E-10
5.15E-8
2.31E-9
2.31E-10
2.08E-9
4.62E-13
2.31E-10
2.08E-9
2.31E-8
2.31E-7
2.08E-6
4.62E-10
2.30E-7
5.11E-8
5.11E-9
4.60E-8
5.11E-12
5.10E-9
9.20E-11
4.59E-8
1.02E-8
5.11E-5
5.11E-6
4.60E-5
5.10E-6
MITIGATED ESCALATION
NO ESCALATION

Figure 5 Event tree for harsh environmental conditions for a sequence of events followed by compressor room fire



4.8 SELECTION OF A SECONDARY OUTCOME FOR ASSESSMENT

Those outcomes with the highest frequency are considered for domino effect assessment. The selected outcomes and their characteristics are listed in the Table

	Harsh Environment	Normal Environment
Frequency	9.59×10^{-8}	1.02×10^{-8}
Type	Mitigated domino	Mitigated domino

Table 12 Summary of outcomes considered for secondary for assessment

Unmitigated secondary scenario: It represents a domino scenario where all safety barriers are failed.

Mitigated domino scenario: The secondary scenario caused by escalation may be mitigated by the partial or ineffective activation of one or more barriers, leading to lessened consequences following the jet fire in the compressor room as compared to an unmitigated scenario.

No escalation scenario: The complete and effective mitigation of the jet fire in the compressor room leading to breaking the domino chain.

4.9 CONSEQUENCE MODELLING RESULTS

Consequences of catastrophic rupture of LNG cargo tanks1 &2 are evaluated with the help of Safeti software. Results indicate that the intensity of heat radiation at tank3 is sufficient to damage it. The results are shown below.

Figure 6 Dispersion of LNG from tank 1 following its rupture

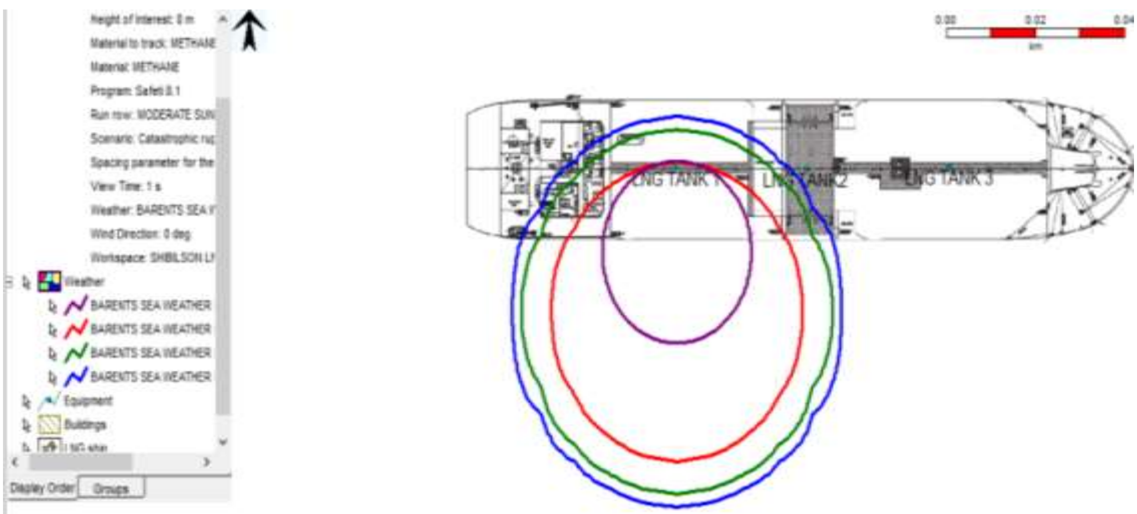


Figure 7 Intensity of heat radiation due to pool fire

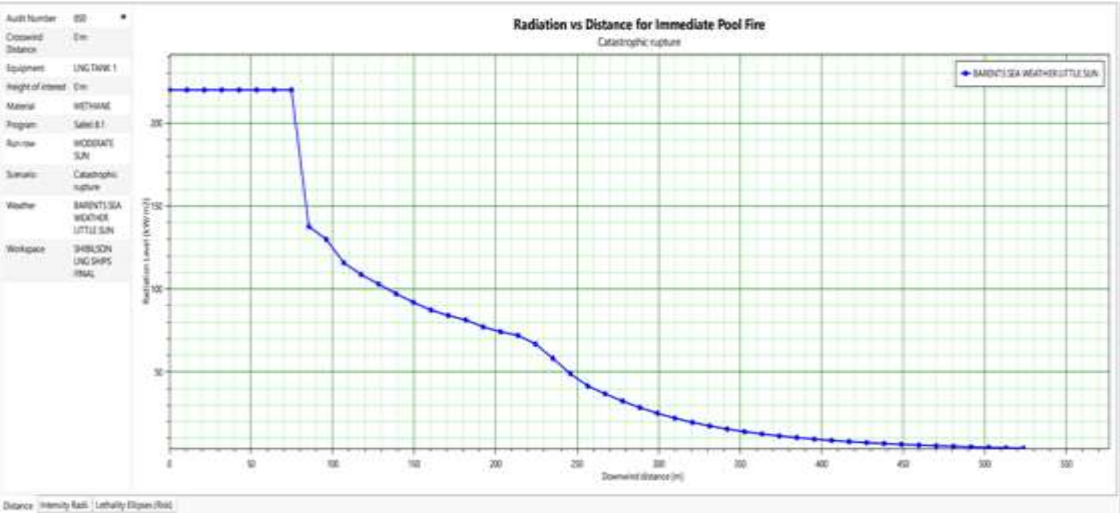


Figure 8 Fireball dimensions

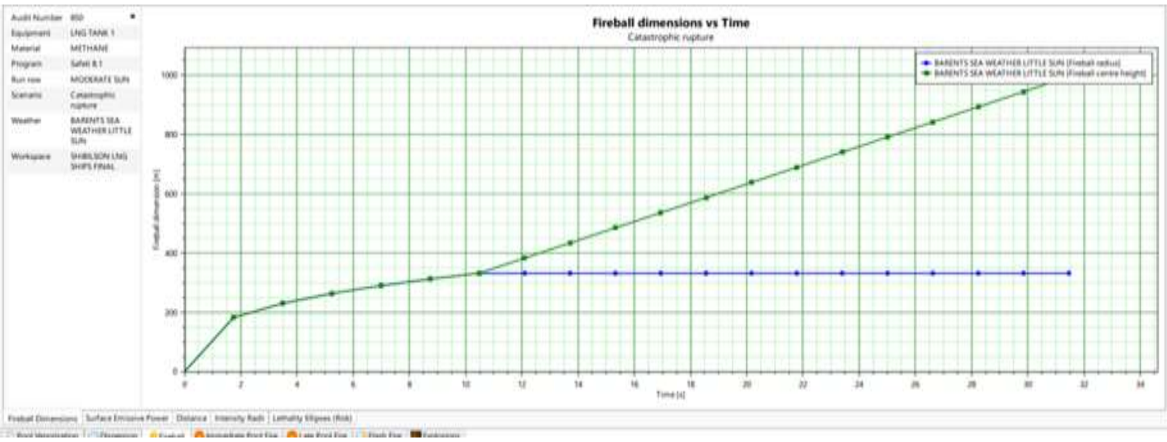
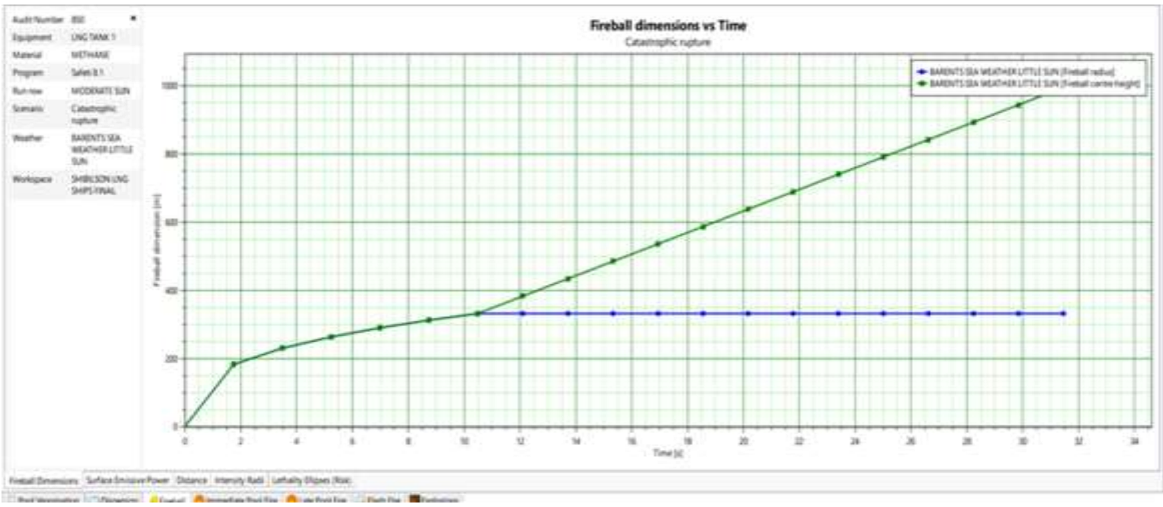


Figure 9 Flash fire envelope due to catastrophic rupture of LNG tank



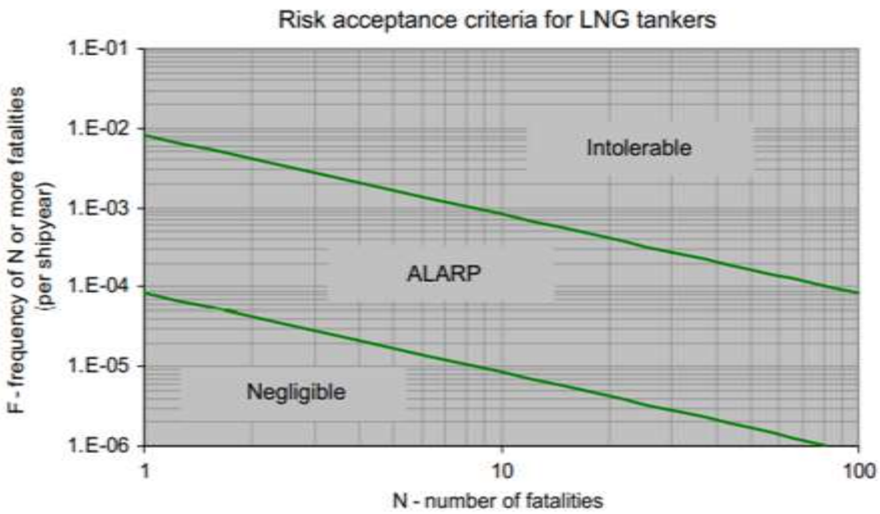
4.10 EVALUATION OF RISK INDICES

Risk indices are evaluated with the help of Safeti software. Safeti is a widely used software for quantitative risk analysis. The acceptable risk values are adapted from SAFEDOR project.

Classification	Risk Value
Intolerable risk per year	> 10^{-3} per year
ALARP area per year	10^{-6} to 10^{-3} per year
Negligible risk per year	<10^{-6} per year

Table 13 Individual risk acceptance criteria (Adapted from SAFEDOR project)

Figure 10 Societal risk acceptance criteria for LNG tankers (Adapted from SAFEDOR project)



4.10.1 INDIVIDUAL RISK VALUES

Individual risk represents the risk to a person in the vicinity of a hazard. The calculation of individual risk at a geographical location near an industrial facility assumes that the contributions of all incident outcome cases are additive. The total individual risk at each point is equal to the sum of the individual risks, at that point, of all incident outcome cases associated with the industrial facility.

$$IR_{x,y} = \sum_{i=1}^{i=n} IR_{x,y,i}$$

Where

$IR_{x,\,y,\,i}$ = the total individual risk of fatality at geographical location (x, y)

$IR_{x,\,y,\,i}$ = the individual risk of fatality at geographical location x, y from incident outcome case i (chances of fatality per year).

$IR_{x,\,y,\,i} = f_i\, P_{f,\,i}$

f_i frequency of incident outcome case i, from frequency analysis

$P_{f,i}$ = probability that incident outcome case i will result in a fatality at location x, y, from the consequence and effect models

n = the total number of incident outcome cases considered in the analysis.

The individual risk values obtained for three risk ranking points from Safeti software are shown below.

Risk Ranking Point	Individual Risk
1	2.37×10^{-7}
2	2.35×10^{-7}
3	2.35×10^{-7}

Table 14 Individual risk values for harsh environmental conditions

Risk Ranking Point	Individual Risk
1	2.37×10^{-8}
2	2.35×10^{-8}
3	2.35×10^{-8}

Table 15 Individual risk values for normal environmental conditions

4.10.2 SOCIETAL RISK VALUES

Some major incidents have the potential to affect many people. Societal risk is a measure of risk to a group of people. It is most often expressed in terms of the frequency distribution of multiple casualty events (F-N curve).

Figure 11 F-N curve for harsh environmental conditions

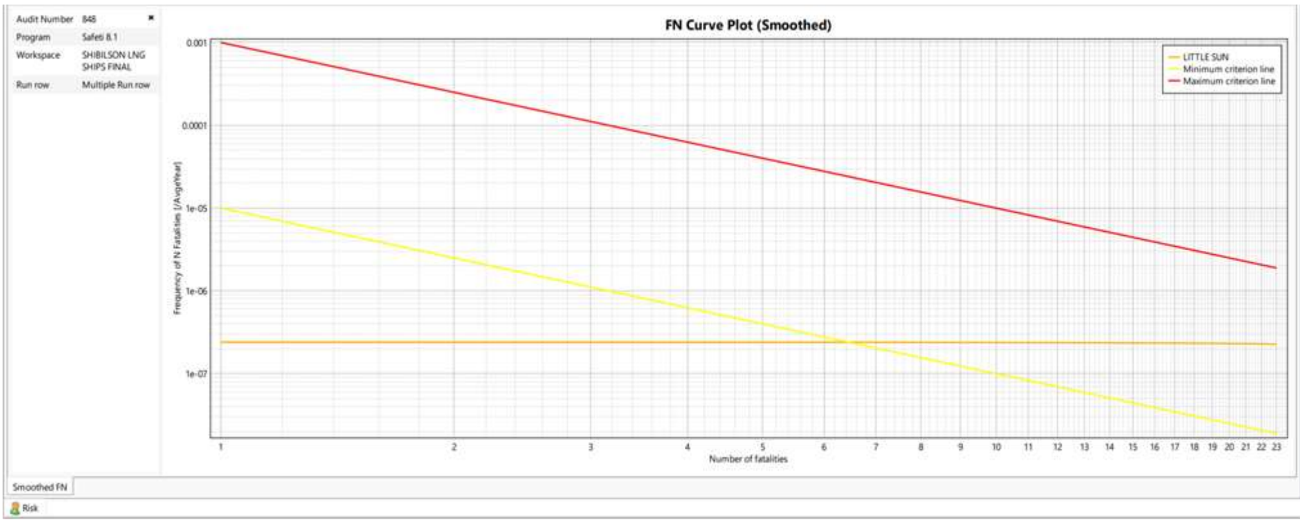
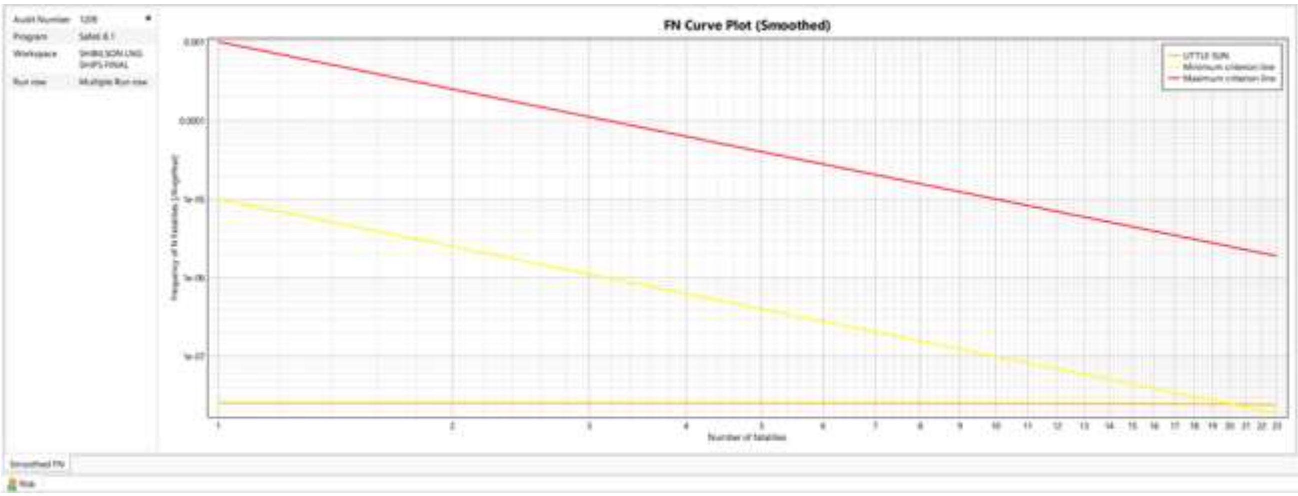


Figure 12 F-N curve for normal environmental conditions



4.10.3 POTENTIAL LOSS OF LIFE INDEX (PLL)

PLL values obtained from Safeti software are listed below.

	PLL

Harsh environment	5.66×10^{-6}
Normal environment	6.02×10^{-7}

Table 16 PLL values for normal and harsh environment

5.CONCLUSIONS

Domino accidents are considered as low frequency and high consequence events. Domino effect analysis mainly involves the identification and assessment of the escalation vector. If we use conventional probability values for risk assessment of an asset operating in harsh environments this will lead to risk underestimation. In this paper domino effect analysis of LNG cargo ships is carried out considering harsh environmental conditions. Modified probability values are used to obtain the risk estimates. Escalation probabilities and risk indices are calculated considering both harsh and normal environmental conditions. Based on extensive analysis following conclusions are reached.

1. Domino effect analysis of LNG cargo ships considering harsh environmental conditions shows that there is an increase in the probability of escalation [increase in escalation probability for secondary event considered for analysis is 8.57×10^{-8})]. SAFEDOR study neglected effect of harsh environmental conditions in risk assessment. Study shows that risk estimates obtained after considering harsh environmental factors shows only negligible difference.
2. Study shows that human error is the most important factor that contributes to the increase in the escalation probability [PFD=0.676]. Effective and timely emergency response will improve the risk profile of facilities operating in harsh environments.
3. LNG ships have a good safety record. It indicates that they are well designed, maintained, and operating with a well-trained crew.
4. Individual risk value is increased by 9 times and the PLL value increased by 8.4 times when the ship operates in a harsh environment.
5. Modified values of availability and effectiveness for each protection layer allow for a more detailed frequency assessment of escalation scenarios in harsh environmental conditions. Even though individual risk, societal risk values in a harsh environmental condition are more compared to normal ones, all risk values fall within the acceptable region.

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