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INFLUENCE OF IMPLEMENTATION OF TECHNOLOGICALLY ADVANCED EVACUATION MODELS ON THE PROCESS OF DECREASING THE RISK DURING ACCIDENTS IN AN LNG TERMINAL

Summary. The continuing growth of the LNG (liquid natural gas) industry has led to a rapid increase in the construction of LNG terminals and the need for accurate risk assessment models as accidents involving LNG are potentially hazardous and pose a major threat. One aspect of risk modeling - evacuation of people to the safe zones of an LNG terminal - is a complex problem that has yet to receive sufficient attention. The aim of this paper is to illustrate how the implementation of a technologically advanced evacuation model may decrease risk during potential accidents in an LNG terminal.

1. INTRODUCTION

From 1878 to 2014, 1,100 energy-related accidents occurred, resulting in more than 210,000 human fatalities and reaching almost $350 billion in property damages [1]. Some of these data include accidents in the LNG industry, the use of which is increasing along with the generally expanding need for energy in the world**.** An LNG terminal accident is potentially a very hazardous event and risk assessment including the timely evacuation of people, although complex, is of crucial importance. According to the National Fire Protection Association - NFPA 59A (Standard for the Production, Storage, and Handling of Liquefied Natural Gas), at least two accesses must be provided in each protective enclosure and be located to minimize the escape distance in the event of emergency [2]. The Fire Protection Handbook of National Fire Protection Association - NFPA, as a factor that contributes injury lists Escaped difficulties, such as choosing in appropriate exit route [3]. The European Standard EN 1473 “Installation and equipment for liquefied natural gas – Design of onshore installations” states that the escape routes shall be laid out to encourage an intuitive response from personnel to lead them from high-hazard areas to low-hazard areas and shall consider that there may be panic in an emergency situation [4]. In such situations, the probability of selection of the wrong escape route by individual is brought up to a maximum. Occupational Safety and Health Administration (OSHA) standards explicitly require employers to have emergency action plans for their workplaces.

According to their Principal Emergency Response and Preparedness Requirements and Guidance, Emergency action plans, at a minimum, must include escape procedures and escape routes [5]. The selection of an escape route by an individual who does not have all the information on the external influences on the accident is too complex.

Vanem [6] have carried out analyses of accidents with LNG tankers where the risk models include the success levels of the evacuation. Tanabe and Miyake [7] have focused their research on the influences on the risk reduction concept on the basis of design criteria for emergency systems for LNG plants. The multi-year progress of hazard warning systems is described by Sorensen [8] and indicates a lack of research into evacuations to safe harbors as a protective action. There are an extensive number of studies that show comparable results of different known modeling softwares referring to LNG leak accidents. The significant conclusion is that such programs demand a great deal of time to initiate to analyze an actual or even a current incident [9]. Safety analyses include evacuation as a factor for mitigation of the consequences of an accident. The need for the development of structural measures for disaster risk reduction, which includes evacuation, indicates that special attention should be paid to this type of evasive action, which has not been the case so far in terms of LNG terminals. The creation of a database with information on the extent of the gas dispersion that links the zones of the LNG terminal, depending on the time spent after the occurrence of the accident, is of crucial importance for a rapid safety reaction. The creation of safe evacuation routes available at the time of the accident is essential and solves the previously mentioned weaknesses.

The following will present and detail the significance of advanced evacuation models during their incorporation into safety analyses.

2. EVACUATION

The conservative approach during the application of risk analyses in the case of an accident involving LNG leakage and dispersion of the gas assumes that the effects on the people near the accident may be different– lesser– than previously presumed. This is not just due to the uncertainties in modeling incident outcomes or modeling limitations that may lead to conservative assumptions and results, but also certain factors such as topography and physical obstruction, although especially the evasive actions taken by people.

Some of the possible evasive actions are evacuation, escape, sheltering, and medical treatment [10]. Evacuations occur frequently. People are evacuated from their homes, businesses, ships, etc., in response to actual or predicted threats of hazards such as hurricanes, floods, tsunamis, volcanic eruption, and release of hazardous or nuclear materials, fires, and explosions [11]. Evacuation is a way of increasing the distance between the population and a hazard, and is the main counter measure to toxic chemical releases. Evacuation describes the extraction of persons from a specific area because of a real or an anticipated threat or hazard.

During the last decade, the warning process and response, organizational response, behavior in evacuations, evacuation planning, and management have been more in focus than in the past. The stress has been on the quality of information, the timing of message delivery, and the level of compliance with warnings.

While analyzing evasive actions when an LNG accident is in question, the terms evacuation and escape may be merged and called ‘escape through technologically advanced evacuation’.

Where there is difficulty in identifying an escape route to a safe haven, the probability of escape during a sudden release of LNG from an LNG vessel is very low. Prugh (1985) [12] illustrates the effectiveness of evacuation as a function of the warning time, area to be evacuated, and the density of the population. This chart may be used to identify the efficiency of the evacuation for various large scale releases, including LNG releases, where sheltering at the location is less desirable. Escape using technologically advanced evacuation was developed and described [13]. This method uses QRA (quantitative risk analysis) to create a database and to gain experiences for a specific LNG terminal and its environment, with the objective to set the logic used by the managing computer device that uses Fuzzy logic [14 - 16] in the process of determination (in real time) of the fastest and safest evacuation route for an individual. The behaviour of the evaporated natural gas from the LNG pool may be calculated using a Fire Dynamics Simulator (FDS) on the basis of Computational Fluid Dynamics (CFD) modeling of the dispersion of the natural gas into the surrounding environment [17 - 21]. An extensive number of analyses are carried out and graphically presented using the DNV PHAST Risk and Safety program, which was used to simulate the consequences of the dispersion of natural gas, including individual and societal risks [22, 23]. In addition, through the use of these programs, the impact of the LNG leak accident can be analyzed and linked depending on the time that has passed since the accident. This model of advanced evacuation (which falls under the previously indicated escape through the technologically advanced evacuation category) plays a definitive role in the degree of success of an evacuation and is expressed through the decrease of the percentage of individuals who have not been evacuated; i.e., an increase in the percentage of successful escapes. This directly reflects on $P_{f,i}$ (probability of fatality), resulting in its decrease. Another very crucial consideration is that with the technologically advanced evacuation, people located in the LNG terminal are evacuated as a group through the evacuation routes created for each individual separately (Fig. 1) as opposed to the usual evacuations intended for a group of people (Fig. 2). This means that in advanced evacuation, each location on the terminal has a predefined and calculated evacuation way based on potential consequences magnitudes and could vary based on the type of consequences. Classical evacuation procedures are usually fixed and based on architectural properties of the place or building.

Fig. 1. Advanced evacuation

Fig. 2. Usual evacuation

3. PROBABILITY OF FATALITY

With the objective to simplify the process of the calculation of individual and social risk, the value referring to the probability of fatality is set at 0 or 1. The probability of fatality, presented graphically, is in the form of a curve. See Fig. 3.

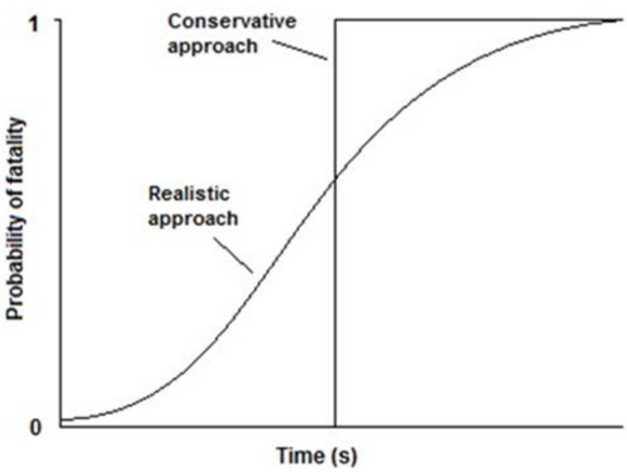

Fig. 3. Probability of fatality

If the conservative approach of determination of the probability of fatality is to be excluded, the same varies depending on the remoteness of the accident and its influence, with a value ranging between 0 and 1. The probability of fatality in a situation in which a technologically advanced evacuation model is in place is in direct correlation to the safe time or difference between the time needed for the individual to reach the safe zone and the time needed for the impact of the accident to reach the final foreseen limit or point. The greater the difference, or the greater the safe time, the greater the probability for the individual to reach the safe zone without being impacted by the accident. Optimally, the value of the probability of fatality is decreasing.

Fig. 4 shows the location of an accident with LNG leakage, the standardized location of work of the employees in the terminal, as well as a safe area in which the impact of the accident is down to zero.

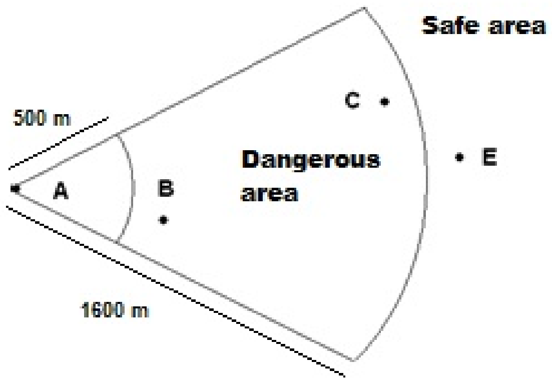

Fig. 4. Accident, employees, dangerous, and safe area

Point A represents the location of the accident. The probability of fatality in the zone of Point A has a value of 1. Points B and C represent accurately determined locations of the employees in the LNG terminal, where the value for the probability of fatality for these two points would range between 0 and 1 (under a conservative approach of determination of the probability of fatality, the zone in which B and C are located would have a value of 1). Point E represents the target or the objective to be reached, located in an area where the impact of the accident equals 0.

The dependency of the probability of fatality on the safe time as an example is shown in Fig. 5. This method of determining the probability of fatality enables the identification of a more realistic value of the probability of fatality, in reference to the conservative principle, having the value 0 or 1.

The use of a technologically advanced evacuation model represents a guarantee that these time calculations and differences are applicable in real/actual cases. This will influence the previously stated time difference, decreasing the probability of fatality. Consequently, all of this will also influence the Individual Risk and the Societal Risk by moving the F-N curve to a more acceptable position in the ALARP (As Low As Reasonably Practicable) zone.

All of this enables the technologically advanced evacuation model to be widely accepted as an evasive action to be used with the objective of mitigation of the consequences of accidents.

4. RISK CALCULATION

The objective of performing the QRA is to identify the potential impact of an LNG leakage accident on the workers in the terminal as well as on the population near the terminal. Risk calculations include calculations of individual risk and societal risk [24].

Individual risk (IR) is the frequency at which an individual may be expected to sustain a given level of harm from exposure to specified hazards. The calculation of IR at a location near an LNG plant or inside an LNG plant assumes that the contributions of all incident outcome cases are additive.

The total IR at each point is equal to the sum of the individual risks at that point of all of the incident outcome cases associated with the plant.

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

$$IR_{x,y,i} = f_i \cdot P_{f,i} \tag{2}$$

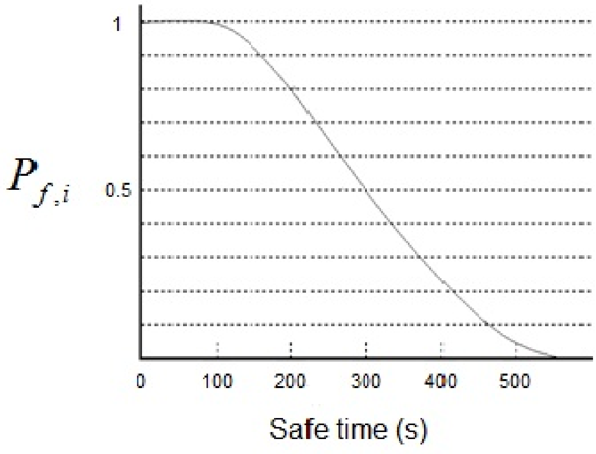

Fig. 5. Dependence of the probability of fatality ($P_{f,i}$) on the safe time

Where (f_i - Frequency of incident outcome case i); ($P_{f,i}$ - Probability of fatality for incident outcome case i) (x, y - Geographical location); (i - Incident outcome case), (n -Total number of incident outcome cases considered in the analysis).

Societal risk is the relationship between the frequency and the number of people suffering from a specified level of harm in a given population from the exposure to specified hazards. A common form of societal risk is an F-N curve (frequency-number) and is the plot of cumulative frequency versus the number of fatalities.

$$N_i = \sum_{x,y} P_{x,y} \cdot P_{f,i} \tag{3}$$

where (N_i - Number of fatalities resulting from incident outcome); ($P_{x,y}$ - Number of people at the geographical location x, y); ($P_{f,i}$ - Probability of fatality).

$$F_N = \sum_i F_i \tag{4}$$

for all incidents outcome case i for which $N_i \geq N$

(F_n - Frequency of all incident outcome cases affecting N or more people)

(F_i - Frequency of incident outcome case i)

5. EXAMPLE OF A RISK CALCULATION PROBLEM

The following section will review the model of an LNG terminal in a case in which there is an accident on a moored LNG tanker with leakage of LNG over the water. The LNG leakage accident is considered to be a consequence of intentional breach.

The area around the accident according to SANDIA [25] may be divided into three impact zones: Zone 1 is a distance up to 500m from the accident in which the probability of fatality for all present individuals is 1. Zone 2 is a distance ranging from 500 to 1600 meters from the accident. In this case, two options will be reviewed for interpretation of the probability of fatality (Case I – 1 or 0; Case II – values between 0 and 1). Zone 3 is a distance greater than 1600m from the center of the accident, where the probability of fatality will have a value of 0.

The risk calculation was applied to a simple example, with the goal of making the calculations easily comparable; the final results (F-N curve) will be presented with an option where the evacuation is not incorporated into the calculations (Case I) and an option by (F-N curve) incorporating an advanced evacuation with a real/actual approach with a determination of $P_{f,i}$ (Case II).

The risk assessment was performed for an LNG terminal at a time of an accident on an LNG carrier during the process of offloading. In this case, highly simplified results for frequency, probability, and consequence and effect estimation will be used.

This sample calculation applies the following conditions:

All hazards originate at a single point;

The atmospheric stability class and wind speed are always the same. Half of the time, the wind blows from the south and half of the time the wind blows from the north;

The people are located inside the LNG terminal. Their locations will be presented later in the example;

The probability of fatality from a hazardous incident at a particular location is: for Case I (either 0 or 1) and for Case II (between 0 and 1).

The incident outcome from the accident of the LNG carrier is the release of the LNG onto the water [26]. In this case, the event tree logic model (Fig. 6) will be used to determine additional possible outcomes and to estimate the frequency for the incidents. For this example, only two outcomes are assumed to occur. If the vapour cloud from the LNG released ignites, there is a pool fire. If the vapour cloud does not ignite, the result is vapour cloud downwind dispersion from the release point.

For this example, it is assumed that the frequency for the Incident is $3*10^{-5}$ events per year and the ignition probability is around 33% [24]. The wind blows toward north 50% of the time, while it blows toward south 50% of the time. The following Fig. 6 shows the Frequency estimates for the example incident.

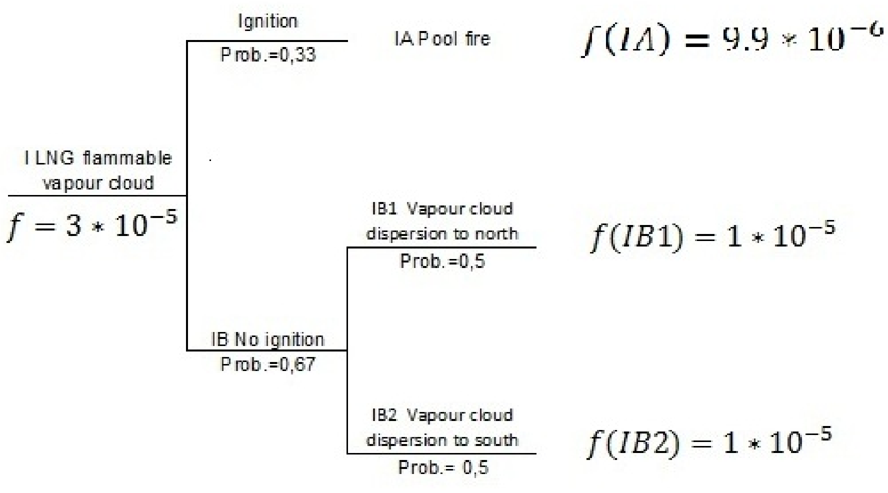

Fig. 6. Frequency estimates for the example incident

The very simple impact zone (Fig. 7) estimates for the identified incident outcome cases will be defined:

Case I and Case II: Incident outcome case IA (pool fire) **-** the pool fire is centered at the mid-point of the LNG carrier. All persons within 500 meters of the pool fire center are killed (probability of fatality = 1). All persons beyond this distance are unaffected (probability of fatality = 0).

Case I: Incident outcome cases IB1 and IB2 (LNG vapour cloud dispersion) – all persons in the pie-shaped (90 degrees) segment of a radius of 1600 meters downwind are killed (probability of fatality = 1). All persons outside this area are unaffected (probability of fatality = 0).

Case II: Incident outcome cases IB1 and IB2 (LNG vapour cloud dispersion) – all persons in the pie-shaped (90 degrees) segments of a radius of 1600 meters downwind are injured or unaffected (probability of fatality = between 0 and 1). All persons outside this area are unaffected (probability of fatality = 0).

5.1. Case I – The evacuation is not included in the calculation

Fig. 7 shows the impact zones from the incident.

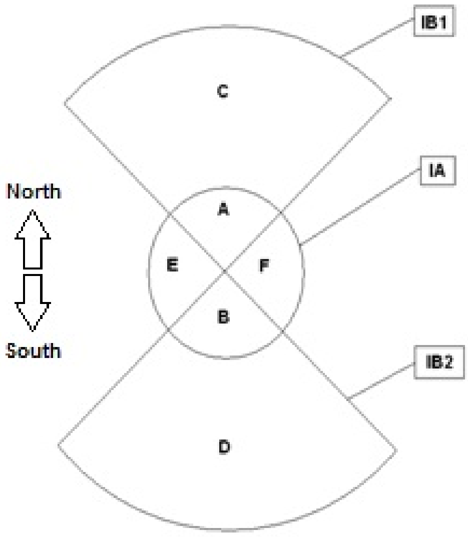

Fig. 7. Impact zones

Fig. 8 shows the number and location of people in the area surrounding the LNG terminal (Case I). The total individual risk of fatality at each geographical area is determined by adding the IR from all incident outcome case impact zones that affect that area.

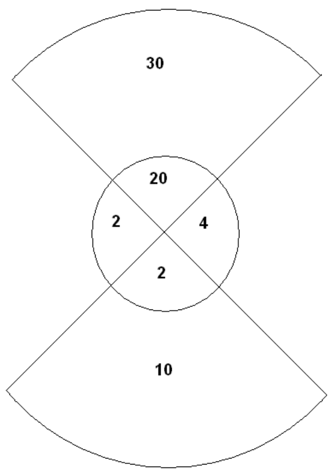

Fig. 8. Number of people and their location for Case I

The maximum IR is the highest value of IR in any geographical area (Table 1).

Table 1

Individual risk of fatality in each geographical area for Case I

Area	Incident outcome case	f_i (per year)	P_{fi}	IR_i (per year)
A	IA	$9.9 * 10^{-6}$	1	$9.9 * 10^{-6}$
	IB1	$1 * 10^{-5}$	1	$1 * 10^{-5}$
				$\sum IRi = 1{,}99 * 10^{-5}$
B	IA	$9.9 * 10^{-6}$	1	$9.9 * 10^{-6}$
	IB2	$1 * 10^{-5}$	1	$1 * 10^{-5}$
				$\sum IRi = 1{,}99 * 10^{-5}$
C	IB1	$1 * 10^{-5}$	1	$1 * 10^{-5}$
				$\sum IRi = 1 * 10^{-5}$
D	IB2	$1 * 10^{-5}$	1	$1 * 10^{-5}$
				$\sum IRi = 1 * 10^{-5}$
E	IA	$9.9 * 10^{-6}$	1	$9.9 * 10^{-6}$
				$\sum IRi = 9.9 * 10^{-6}$
F	IA	$9.9 * 10^{-6}$	1	$9.9 * 10^{-6}$
				$\sum IRi = 9.9 * 10^{-6}$

During the societal risk estimation, the first step while generating the F-N curve is to calculate the number of fatalities as a result of every incident outcome case (Table 2). The next table (Table 3) summarizes the cumulative frequency results. Those data are plotted to obtain the societal risk F-N curve (Fig. 9).

Table 2

Estimated number of fatalities for Case I

Incident outcome case	Frequency per year	Estimated number of fatalities
IA	$9.9 * 10^{-6}$	28
IB1	$1 * 10^{-5}$	50
IB2	$1 * 10^{-5}$	12

Table 3

Cumulative frequency results for Case I

Estimated number of fatalities	Incident outcome case	Total frequency per year
12+	IA,IB1,IB2	$2{,}99 * 10^{-5}$
28+	IA,IB1	$1{,}99 * 10^{-5}$
50+	IB1	$1 * 10^{-5}$
>50+	none	0

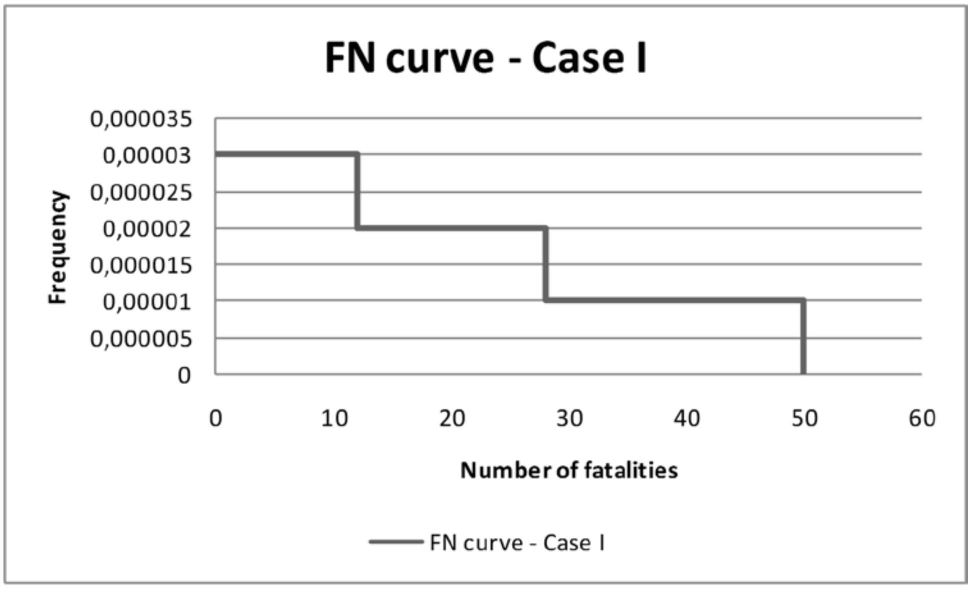

Fig. 9. F-N curve for Case I

5.2. Case II results – Advanced evacuation with actual access of determination of $P_{f,i}$

In Case II, the frequency analysis remains the same. Fig. 9 shows the number and location of people in the area surrounding the LNG terminal (Case II).

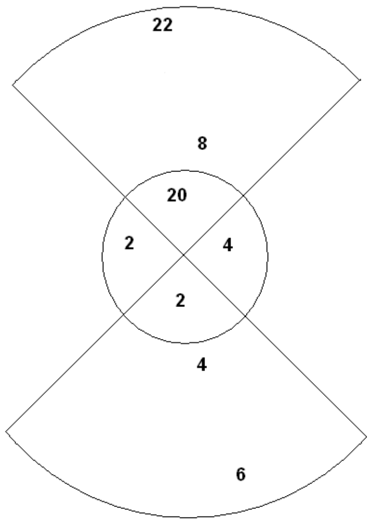

Fig. 10. Number of people and their location for Case II

The maximum IR is the highest value of IR in any geographical area (Table 4).

The final value of the probability of fatality for IB1 is obtained as the mid-value of the probability of fatality for all locations from IB1 where people are located. The individual probability of fatality for the people in IB1 and IB2 is determined in Fig. 5 according to their estimated safe time.

While generating the F-N curve during the societal risk estimation, the objective is to calculate the number of fatalities as a result of every incident outcome case (Table 5) and to summarize the cumulative frequency results (Table 6). Those data are plotted to obtain the societal risk F-N curve (Fig. 11).

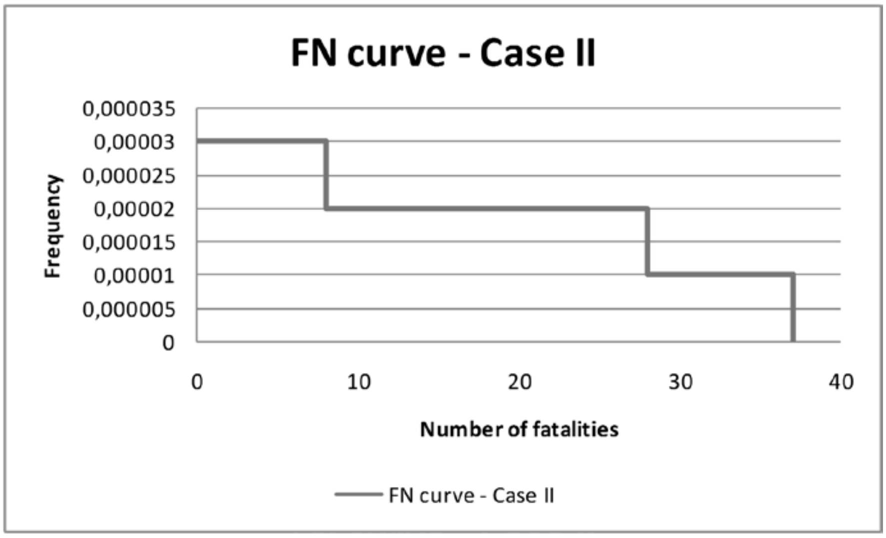

Fig. 11. F-N curve for Case II

Table 4

Individual risk of fatality in each geographical area for Case II

Area	Incident outcome case	f_i (per year)	P_{fi}	IR_i(per year)
A	IA	$9.9 * 10^{-6}$	1	$9.9 * 10^{-6}$
	IB1	$1 * 10^{-5}$	0,57	$5{,}7 * 10^{-6}$
				$\sum IRi = 1{,}56 * 10^{-5}$
B	IA	$9.9 * 10^{-6}$	1	$9.9 * 10^{-6}$
	IB2	$1 * 10^{-5}$	0,6	$6 * 10^{-6}$
				$\sum IRi = 1.59 * 10^{-5}$
C	IB1	$1 * 10^{-5}$	0,57	$5{,}7 * 10^{-6}$
				$\sum IRi = 5{,}7 * 10^{-6}$
D	IB2	$1 * 10^{-5}$	0,6	$6 * 10^{-6}$
				$\sum IRi = 6 * 10^{-6}$
E	IA	$9.9 * 10^{-6}$	1	$9.9 * 10^{-6}$
				$\sum IRi = 9.9 * 10^{-6}$
F	IA	$9.9 * 10^{-6}$	1	$9.9 * 10^{-6}$
				$\sum IRi = 9.9 * 10^{-6}$

Table 5

Estimated number of fatalities for Case II

Incident outcome case	**Frequency per year**	**Estimated number of fatalities**
IA	$9.9 * 10^{-6}$	28
IB1	$1 * 10^{-5}$	37
IB2	$1 * 10^{-5}$	8

Table 6

Cumulative frequency results for Case II

Estimated number of fatalities	Incident outcome case	Total frequency per year
8+	IA,IB1,IB2	$2.99 * 10^{-5}$
28+	IA,IB1	$1.99 * 10^{-5}$
37+	IB1	$1 * 10^{-5}$
>37+	none	0

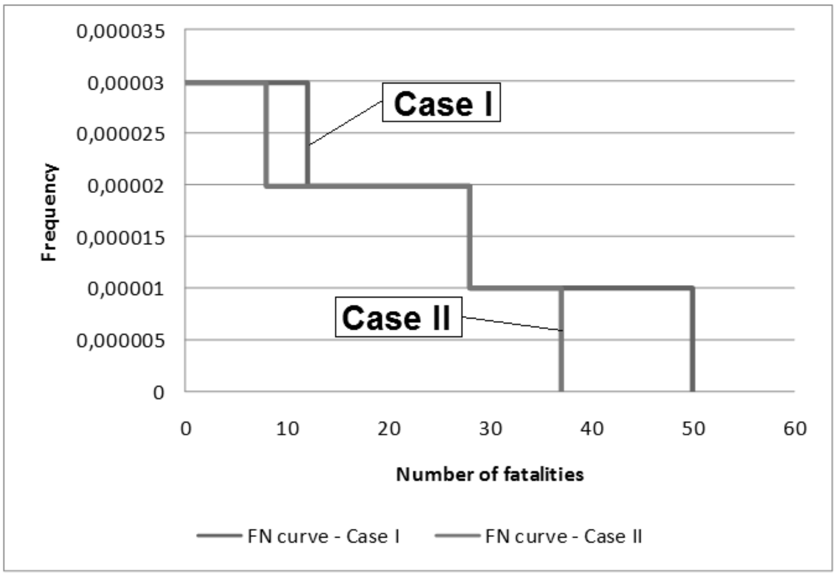

Fig. 12. Comparison of F-N curves for Case I and Case II

The objective of the development and use of the technologically advanced evacuation model is the forecasted removal of the people from hazardous areas to safe zones. A successful evacuation is expressed through the presentation of the realistic or the actual value of the probability of fatality (between 0 and 1). The influence on the F-N curve can be seen in Fig. 12 (F-N curves for Case I and Case II), where the F-N curve for Case II has a more acceptable positioning in the F-N area than in Case I.

6. CONCLUSION

The development of the technologically advanced evacuation model aimed for people both in and near LNG terminals, which could be used in situations of LNG leakage accidents, provides the possibility of eliminating potential errors during the selection of evacuation routes by an individual or a group of people. In addition, the determination and creation of the evacuation route that is considered the shortest and the safest decreases the probability of fatality. The difference during the use of the probability of fatality with a conservative approach during the determination of the value (0 or 1) and, on the other hand, the conservative but sufficiently realistic selection of the value for the probability of fatality (between 0 and 1) is quite evident and we present both using a simple example. A high-quality, accurately defined technologically advanced evacuation model should eliminate any underestimation of the value of the probability of fatality as well as ensure that this approach to the execution of risk analyses will provide conservative but at the same time more realistic values.

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