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CASE HISTORY—PEER-REVIEWED

Fire and Explosion Risks in Petrochemical Plant: Assessment, Modeling and Consequences Analysis

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Abstract The oil and gas industry is a theater of major accidents such as fire, explosion and dispersion of toxic substances. The physicochemical properties of exploited materials in this industry and its operating techniques can contribute to the escalation of these hazards. The aim of this study is to assess and model the fire and explosion hazards of liquefaction natural gas in Algeria as long as this later plays an important role in gas industry and global energy markets in the next several years. The first step used in this study is the hazard identification using HAZID tool. This step is completed by DOW's F&EI as a second step to predict and quantify mathematically the fire and explosion damages in the Scrub Column and the MCHE the most critical systems in the LNG unit. In order to better understand the hazards severity of these risks, PHAST software is used to model and simulate the accident scenarios. The results will reveal that the two principal equipments of liquefaction unit (Scrub Column–MCHE) present an important risk as per HAZID and they present a severe risk as per DOW's F&EI. The modelization of fire and explosion scenarios using PHAST software gives us a real image about these hazards which presented by Fireball, Flash Fire, Early and Late explosion. The combination of HAZID, DOW's F&EI and PHAST simulator leads to better risk assessment, and helps in creating preventive measures, and taking serious decisions to reduce and limit fire and explosion risks in order to save human life as a first goal, environment and installations as a second goal and to avoid the financial and economic loss of Algeria.

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Keywords HAZID · F&EI · PHAST · Liquefaction unit · Scrub column · MCHE

Abbreviations

ESD	Emergency shut down
F1	General process hazard factor
F2	Special process hazard factor
F3	Process unit hazard factor
F&EI	Fire and explosion index
FHA	Fire hazard analysis
FMEA	Failure modes and effects analysis
GL1K	Liquefaction natural gas complex—Skikda
HRA	Human reliability analysis
HAZID	Hazard identification
HAZOP	Hazard and operability analysis
LFL	Low flammable limit
LMR	Liquid mixed refrigerant
LNG	Liquefied natural gas
LPG	Liquefied petrol gas
MCHE	Main cryogenic heat exchanger
MF	Material factor
MR	Mixed refrigerant
NFPA	National fire protection association
PHA	Process hazard analysis
SIL	Safety integrity level
VCE	Vapor cloud explosion

Introduction

Liquefied natural gas plays an important role in gas industry and global energy markets in the next several years [1]. The industry of gas (production, treatment, transport and storage) is one of the industries which is associated with dangerous accidents especially fire and explosion accidents because they use products under different temperatures and pressures.

In this context, we can mention VCE accident initiated in a boiler of the natural gas (LNG) trains in the petrochemical complex GL1K of Skikda. This most serious accident in Algeria occurred in the LNG complex—Skikda on January 19, 2004, caused the death of 27 people and injured 80 as the besides financial loss of millions of dollars. Therefore, it is a must to assess and evaluate these risks to minimize them.

There are generally three types of hazard evaluations:

1. Process hazard analysis (PHA) using techniques such as the following:
   - Hazard and operability analysis (HAZOP)
   - Hazard identification (HAZID)
2. Fire hazard analysis (FHA)
3. Special analysis
   - Failure modes and effects analysis (FMEA)
   - Human reliability analysis (HRA) [2].

In addition to risks analysis methods, there are also risk indexing methods, such as Dow Fire and Explosion Index, Mond Fire, Explosion and Toxicity Index, Safety Weighted Hazard Index (SWeHI), Hazardous Waste Index (HWI) and Inherent Safety Index. By comparing these indexes with other risk analysis methods, the risk indexing methods are easy and simple; they consider risk as a quantity that can be measured and expressed mathematically, using a real accident data of studied system [3].

In our study, we have combined two types of analysis method to evaluate fire and explosion risks in the LNG complex:

A semi-quantitative method (HAZID tool) and a quantitative method (Dow F&EI as a predictive tool).

The combination of these two methods leads to better risk management. The first (HAZID method) is a tool for identifying risks, their sources, their causes and their consequences. It allows the identification of any type of risk for any system. Unlike other analytical methods that are dedicated to identifying and analyzing a specific hazard, such as HAZOP, which permits to identify and assess the continuous processes hazards [4] for hydraulic systems, HAZID is dedicated to identify and analyze any types of risks for any system.

The use of HAZID method needs to divide the technological process or plant into elements and analyzes these elements according to harmful factors [5] based on keywords used to cover the inherent dangerous, in order to discover system problems and define the risk level [6].

The second is Dow's Fire and Explosion Index; it helps to predict and quantify realistic process fire and explosion risk and its contents. This index is widely applied in the hazard evaluation design of chemical processes, including the production, storage and processing of flammable, explosive and active materials [7]; it has been proved to be accurate and reliable, and been extensively considered as one of the most important risk index [8]. Dow index is a quantitative method which is based on chemical properties of materials that are used in the process under study such as flash points, boiling points, material factors and NFPA ratings.

To better understand the severity of fire and explosion hazards in the LNG industries, we modeled and simulated risk scenarios with PHAST simulator to show hazards effects on fire radiation curves and overpressure caused by the explosion [9]. This modeling will give a real image to

Table 1 Probability categories

Scale	Frequency	Probability
1	Improbable (possible, perhaps an event in the world)	1 time every 1000 years
2	Improbable (possible, perhaps an event in the world)	1 time every 100 years
3	Rare	1 time every 10 years
4	Probable (happens from time to time)	1 time every year
5	Frequent	10 or more times per year

Table 2 Gravity categories

Scale	People	Environment	Equipment
1	Light injury (injury with first aid)	Light damage to environment	Low damage
2	Injury resulting loss of time (medical treatment)	Environmental local damage for a short period	Average damage
3	A permanent handicap (Extended hospitalization)	Return of ecological resources duration is less than 2 years	Considerable damage
4	A death	Return of ecological resources duration is from 2 to 5 years	Serious damage
5	Several deaths	Return of ecological resources duration is more than 5 years	Demolition of the plant or large parts of the complex

the fire and explosion risks and provide safety decisions that play an important role in its mitigation

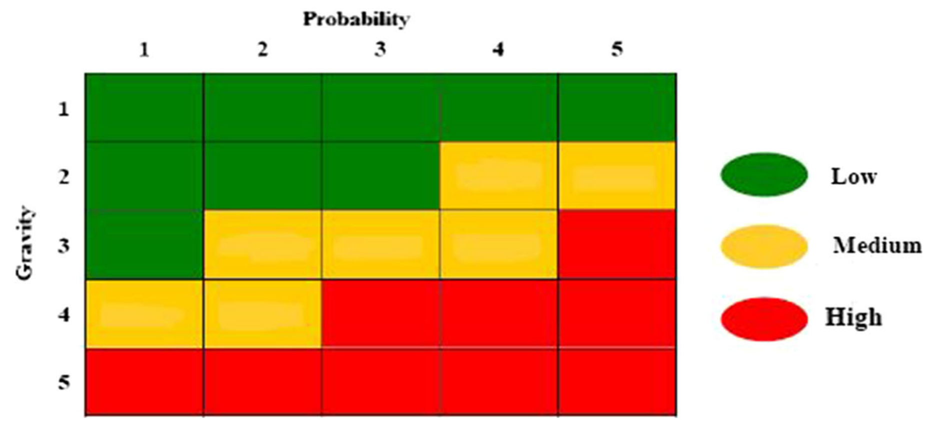
The identification, evaluation, quantification and modelization of fire and explosion risks in the LNG Unit by the combination of HAZID, DOW's F&EI and PHAST software allow us to predict fire and explosion accident damages, and help us to decide what action can prevent or limit the effects of these hazards.

Methodology

HAZID Method

The hazard identification (HAZID) is a semi-quantitative method used to identify sources, causes and consequences of risks by adopting keywords that define the dangers in the unit under study [10]. This approach is based on event

Fig. 1 Risk matrix



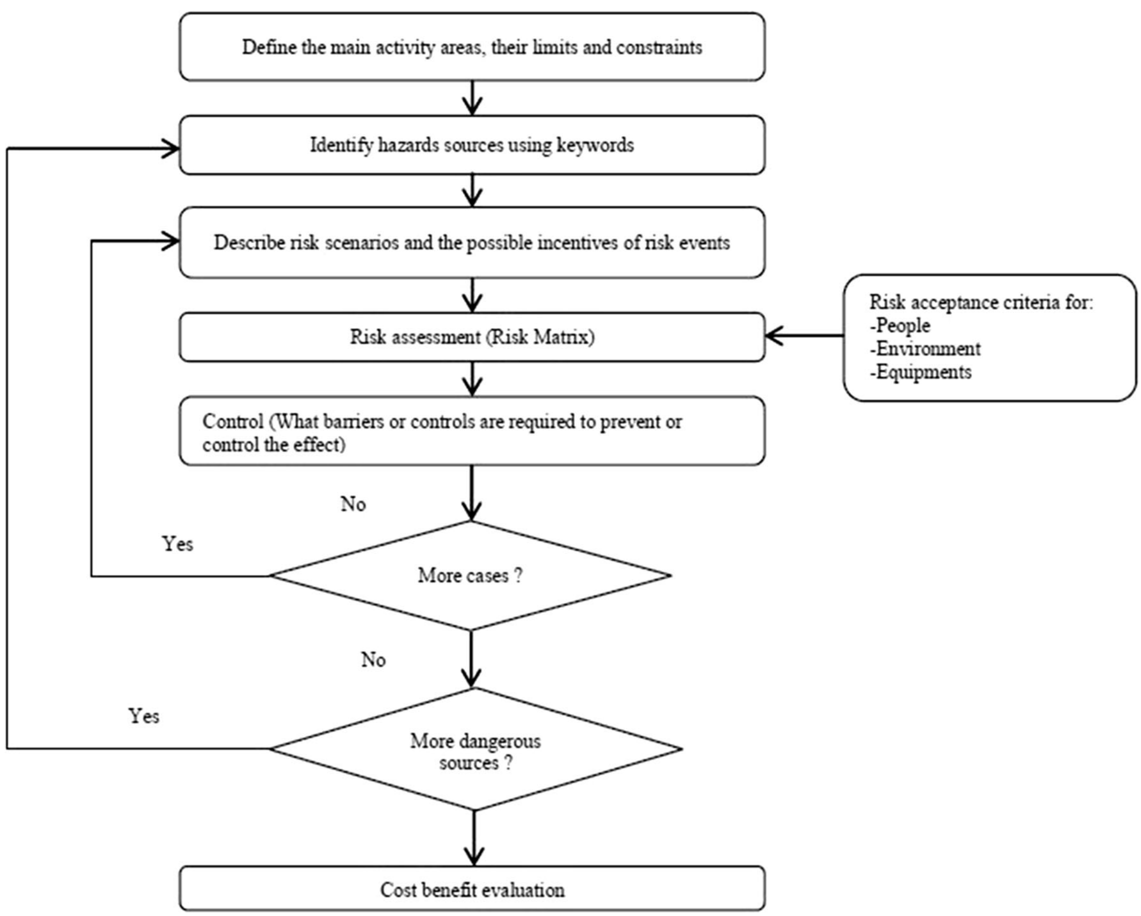


Fig. 2 HAZID methodology

Table 3 Keywords of HAZID analysis

Category	Keywords
Organization	Ignition source inside the unit and in the neighborhoods of this one-heaters with burner, zones of welding
Principal inventories of dangerous substances	Document principal inventories liquids or flammable gas, fuels or oxygen
Principal systems of security	Devices of monitoring of fires and pollutant gas, ESD system, isolating valves, SIL systems
Maintenance and inspection	Work around danger inventories/in confined spaces.
External environment	Winter (cold, snow), flood, earthquakes
Dangers related to construction	Dangers related to rising, high temperature, congestion, traffic control

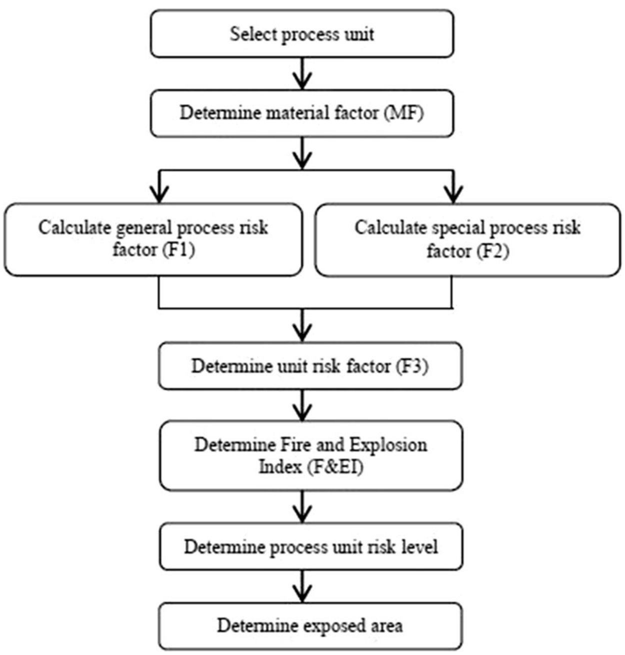


Fig. 3 Dow's F&EI procedure [12]

probability and gravity for various consequences including personnel safety, environmental impact and equipment to determine the risk level [11].

After the determination of possible causes, consequences and protections available for each scenario identified, the probability must be ranked on a scale of 1 to 5 (Table 1). The gravity of the potential impact on people, environment and equipments must be classified also on a scale of 1 to 5 (Table 2). The risk ranking is defined by the product of the gravity and the probability in order to classify the risk as low, medium or high according to risk matrix (Fig. 1).

The HAZID methodology and its keywords that help to identify the liquefaction unit hazards are illustrated in Fig. 2 and Table 3.

Table 4 F&EI risk levels

F&EI	Degree of hazard
1–60	Light
61–96	Moderate
97–127	Intermediate
128–158	Heavy
159-up	Severe

Dow's Fire and Explosion Index

Dow's F&EI Hazard Classification Guide was developed by the American Institute of Chemical Engineers in 1994 for giving a relative value to the risk of individual process unit losses due to potential fires and explosions in the chemical industries [12].

This index consists to predict and quantify damages caused by fire and explosion accidents [13], to identify the most sensitive equipment that can contribute to the escalation of an incident. It provides key information to facilitate the risk management.

The procedure of DOW's F&EI is shown in Fig. 3, while the different risk levels of F&EI are shown in Table 4.

PHAST Software Tool

PHAST(Process Hazard Analysis Software Tool) is a hazard analysis tool developed by DNV software. It is the most applied tool in industrial hazard assessment for modeling and simulating different scenarios and source terms in industrial hazards as line rupture, vessels rupture, leaks, etc. PHAST plays a necessary role to make the employer in the actual situation of the simulated risk which helps him in taking necessary to reduce and mitigate the risk effects.

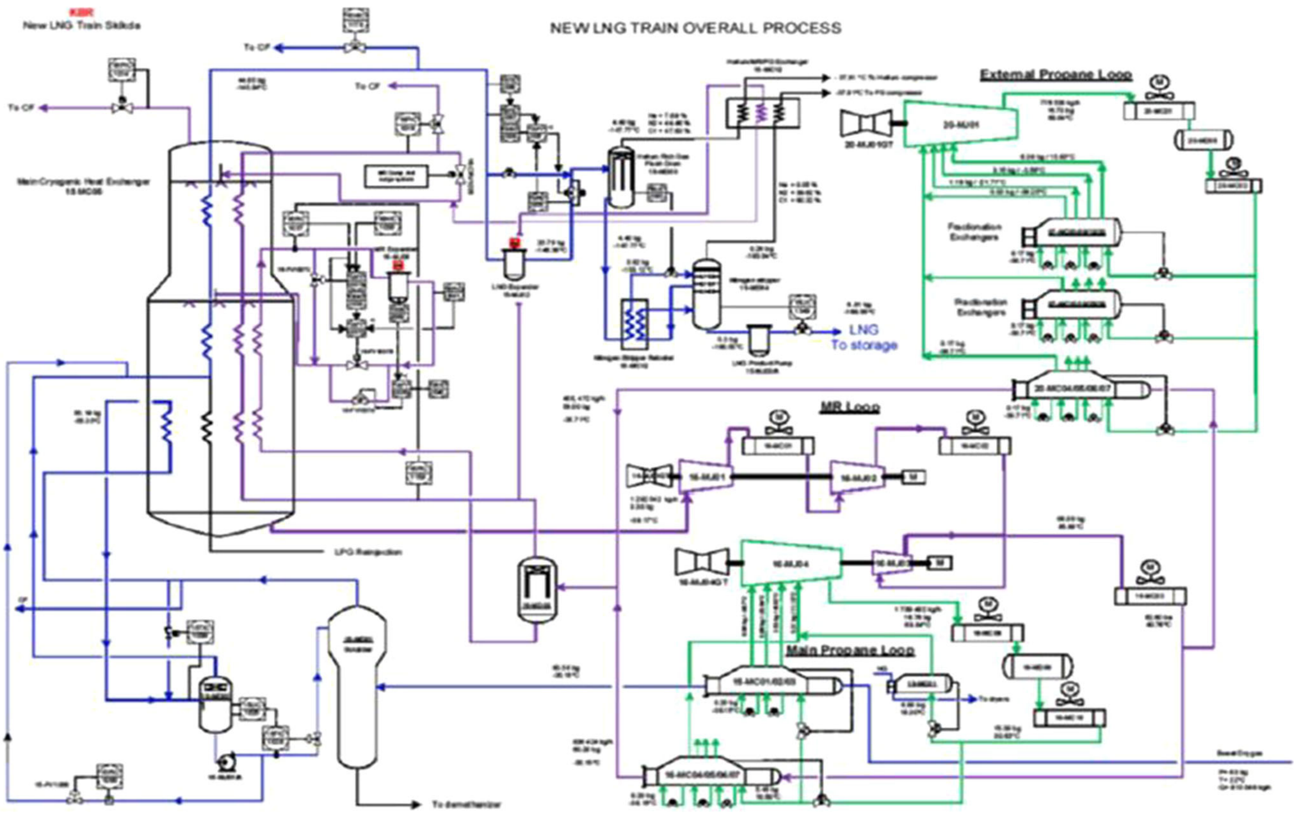


Fig. 4 Flow diagram in liquefaction process [17]

Case Study

After destruction of three natural gas liquefaction trains by fire and explosion accident on 2004, a new train is built to replace them; this later contains the following units:

- CO_2 removal unit
- Drying unit
- Mercury removal unit
- Liquefaction unit
- Fractionation unit to withdraw heavy hydrocarbons from the gas and to product ethane, propane, butane and the gasoline
- Storage unit

In our study, we will assess the fire and explosion hazards of the liquefaction unit which is considered as the heart of the natural gas liquefaction process. The two principal equipments of this unit are Scrub Column and MCHE.

The Scrub Column

It removes heavy hydrocarbons from feed gas to prevent plugging in MCHE. The Scrub Column not only increases recovery rates of ethane and propane, which are used as refrigerant for liquefaction process, it also helps to produce LNG product that meets sales gas specifications. There are two product streams leaving Scrub Column: the bottom product stream and the overhead stream.

- The bottom product stream is cooled in Scrub Column Bottoms Cooler and carries heavy hydrocarbons to Fractionation Unit, which separates this stream into its components of ethane, propane, butane, isopentane and condensate (natural gasoline) products.
- The overhead stream of the Scrub Column is mixed with LPG, which is recycled from the Fractionation Unit, and it is sent to the warm bundle of MCHE [14].

The Main Cryogenic Heat Exchanger (MCHE)

Its objective is to cool the natural gas received from Scrub Column overheading to − 146 °C.

The MCHE is composed of three similar spiral bundles, which are arranged vertically: The lower bundle is referred as the warm bundle. It operates in the range from − 39 to − 55 °C temperature. The middle bundle operates in the range from − 55 to − 130 °C temperature. The top bundle is referred as the cold bundle and operates in the range from − 130 to − 146 °C temperature.

The gas travels from the Scrub Column, through the warm bundle of MCHE and emerges at about − 55 °C as two-phase stream. The liquid portion is used as reflux for the Scrub Column. The vapor portion comes back to the MCHE middle bundle where it is further cooled from about − 55 °C to about − 129 °C, and then it enters the cold bundle where it is cooled further to − 146 °C as what it is shown in Fig. 4 [15].The feed gas travels through the LNG tube circuit in an upward direction and emerges from the top as LNG at about 44 barg and − 146 °C.

The refrigeration for the liquefaction process occurring in the MCHE is provided by Mixed Refrigerant (MR) system.

- The liquid portion of the MR passes through the tubes of the "heavy MR" of warm and middle bundles. After passing through the MR Expander, the stream returns to the top of the middle bundle and "rains down" over the outside of the MCHE tube bundles at low pressure (approximately 3 to 4 Barg) and provides cold liquid refrigerant at approximately − 134 °C for the lower portion of the MCHE (middle and warm bundles).
- The vapor portion of the MR passes through the "light MR" of warm bundle, middle bundle and cold bundle. After passing through the "cold J–T valve," the stream combines with some cold MR from the LMR/helium-rich gas exchanger. The combined stream "rains down" over the outside of the cold, middle and warm bundles of the MCHE at low pressure (approximately 3 to 4 barg) and provides cold liquid refrigerant starting at approximately − 154 °C for all three bundles of the MCHE [16, 17].

Results

A. HAZID Analysis Results
[Table 5]
B. Dow's F&EI Results
[Tables 6 and 7]
C. PHAST Software Results

In this study, PHAST is used to simulate and model different scenarios of fire and explosion in the liquefaction unit of LNG complex in Algeria.

These scenarios are:

- Fireball
- Flash fire
- Early and late explosion

1. Fireball
[Figs. 5 and 6]
2. Flash fire
[Figs. 7 and 8]
3. Early explosion overpressure
[Figs. 9, 10, and 11]
4. Late explosion overpressure
[Figs. 12 and 13]

Discussion of Results

HAZID Analysis

The HAZID results indicate the following scenarios:

- Risk of raised temperature in fuel gas which can cause the explosion of the electrical heater 15ML02;
- Loss of containment;
- Formation of potential rejection that can be an ignition source;
- Formation of vapor rejections in the MCHE;
- Asphyxiation risks;
- Some damages caused by environmental factors.

The risk degree is different from scenario to another; we can note that the most critical risk was presented by the formation of potential rejection in the Scrub Column (15MD01), the Balloon of backward flow of Scrub Column (15MD02) and the MCHE (15MC02).

The tolerable risk was presented by the raised of gas temperature in the electrical heater (15ML02), the loss of containment in propane coolers (15-MC 01/02/03), in GNL toward storage via (15-MJ03), for the principal safety systems such as gas detection and ESD systems, and in the MCHE (15MC05) according to external environment keywords.

The only acceptable scenario was presented by the asphyxiation risk with an occurrence probability equal to 3 and gravity equal to 2; this risk can appear during the maintenance and inspection works.

For these risk scenarios, we proposed some specific protection and preventive controls as the following:

Dow's F&EI

The hazards quantification of Scrub Column and MCHE by DOW's F&EI shows that the two systems present a severe risk with an index of fire and explosion equals to 206,724 for Scrub Column, and 230,496 for MCHE, as illustrated in Table 6.

Table 7 indicates that the area of exposure is equal to 10934, 04 m^2 for MCHE; this value is more than the area of exposure of Scrub Column, which is equal to 9637, 16 m^2. Therefore, the damage result from MCHE accident is more than those resulting from the Scrub Column. They present some relative ideas about hazard severity in the unit; they also help in taking all the necessary precautions in order to reduce its gravity (Table 8).

Table 5 HAZID worksheet for the liquefaction unit (Color Table online)

Danger/ problem	Causes	Consequences	Protection/ control prevention	Risk matrix		
				P	G	R
Organization						
Ignition source inside the unit and in the neighborhoods - heaters with burner, zones of welding.	Electric heater 15ML02	Risk of raised temperature in fuel gas	Used only for operation starting	4	3	
Principal inventories of dangerous substances						
Document principal inventories - liquids or Flammable gas, fuels or, oxygen.	Propane coolers (15-MC 01/02/03)	Loss of containment	1. Welded nozzles to minimize leakpoints . 2. Detection of gases 3. System of fire detection	3	3	
	Scrub Column 15-MD01	Potential rejection involving an ignition	1. Gas detection in place. 2. Maintenance Program and standard exploitation procedures	3	4	
	Balloon of backward flow of the Scrub Column 15-MD02	Potential rejection involving an ignition	1. Gas detection in place. 2. Maintenance Program and Procedures of standard exploitation	3	4	
	MCHE 15-MC05	Vapor rejection	1.Gas detection in place. 2.Maintenance Program and Procedures of standard exploitation	3	4	
	GNL towards storage via 15 - MJ03	Potential presses raw wool in pump suction	1 . Time of valve closing must be limit to avoid a pressure blow 2.Change of ambient temperature detection to indicate a GNL rejection	3	3	
Principal safety systems						
Devices of monitoring of the fires and pollutant gas, ESD system, isolating valves, SIL systems.	1. Gas detection and ESD systems 2.Impact on the tubes which are involving a rejection of GNL	Loss of containment	Changeof ambient temperature detection to indicate a GNL rejection	2	4	
Maintenance and inspection						
Work around dangerous inventories / in confined spaces.	Lid of inspection pit on the MCHE;entry in a confined space	Confined Space Asphyxiation Risk	Entry licence in confined spaces	3	2	
External environment						
Winter (cold, snow, ice), flood, earthquakes	15-MC 05 is the grand and higher tank in the complex	Tank damage risk of following with the impact of wind	Specifications for wind resistance in vessels design	2	3	
Dangers related to construction						
Dangers related to rising, high temperature,congestion, traffic control.	Overhead travelingcrane for compressors	Damage caused by a fall of an object	Revised 3D model to evaluate the access and space available	2	3	

Table 6 Dow's F&EI worksheet

Process unit		Scrub column	MCHE
Material factor		21	21
1. General process hazards	Penalty factor range	Penalty factor used	Penalty factor used
Base factor	1	1	1
A. Exothermic chemical reaction	0.30 to 1.25		
B. Endothermic processes	0.20 to 0.40		
C. Material handling and transfer	0.25 to 1.05	0.50	0.50
D. Enclosed or indoor process units	0.25 to 0.90	0.60	0.60
E. Access	0.20 to 0.35	0.20	0.35
F. Drainage and spill control	0.25 to 0.50		
General process hazards factor (F1)		2.30	2.45
2. Special process hazards			
Base factor	1	1	1
A. Toxic material(s)	0.20 to 0.80		
B. Sub-atmospheric pressure (< 500 mm Hg)	0.50		
C. Operation in or near flammable range			
1. Tank farms storage flammable liquids	0.50		
2. Process upset or purge failure	0.30		
3. Always in flammable range	0.80	0.80	0.80
D. Dust explosion	0.25 to 2.00		
E. Pressure		0.68	1.00
F. Low temperature	0.20 to 0.30		
G. Quantity of flammable/unstable material			
1. Liquids or gases in process		1.30	1.28
2. Liquids or gases in storage			
3. Combustible solids in storage, dust in process			
H. Corrosion and erosion	0.10 to 0.75	0.20	0,10
I. Leakage-joints and packing	0.10 to 1.50	0.30	0.30
J. Use of fire equipment			
K. Hot oil heat exchange system	0.15 to 1.15		
L. Rotating equipment	0.50		
Special process hazards factor (F2)		4.28	4.48
Process unit hazards factor (F1 × F2) = F3		9,844	10,976
Fire and explosion index (F3 × MF) = F&EI		206,724	230,496

Table 7 Process unit risk analysis summary

	Scrub column	MCHE	Statement of calculation
1. Fire and explosion index (F&EI)	206,724	230,496	F3 × MF
2. Radius of exposure	55.40 m	59.01 m	R = F&EI × 0.84
3. Area of exposure	9637.16 m^2	10,934.04 m^2	Area = πR^2

PHAST Software

Fire Ball

All rejections with immediate ignition are modeled in Fireball form if the rejection is instantaneous or very rapid (< 20 s). In this context and according to PHAST results, the diameter of the fireball is 455,831 m. It is an important

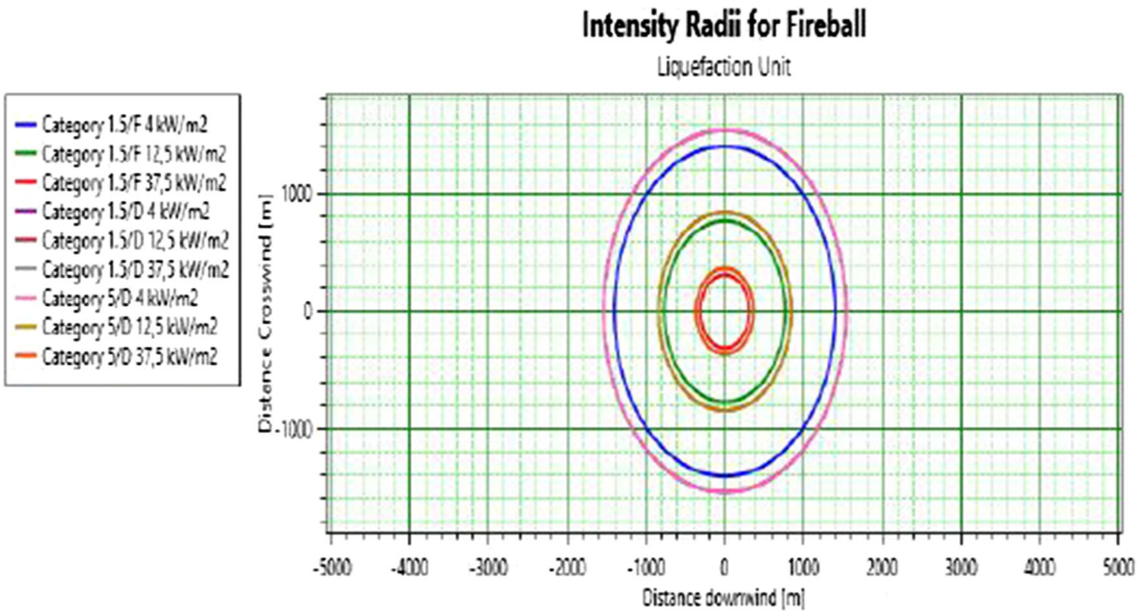


Fig. 5 Intensity radiation for fireball

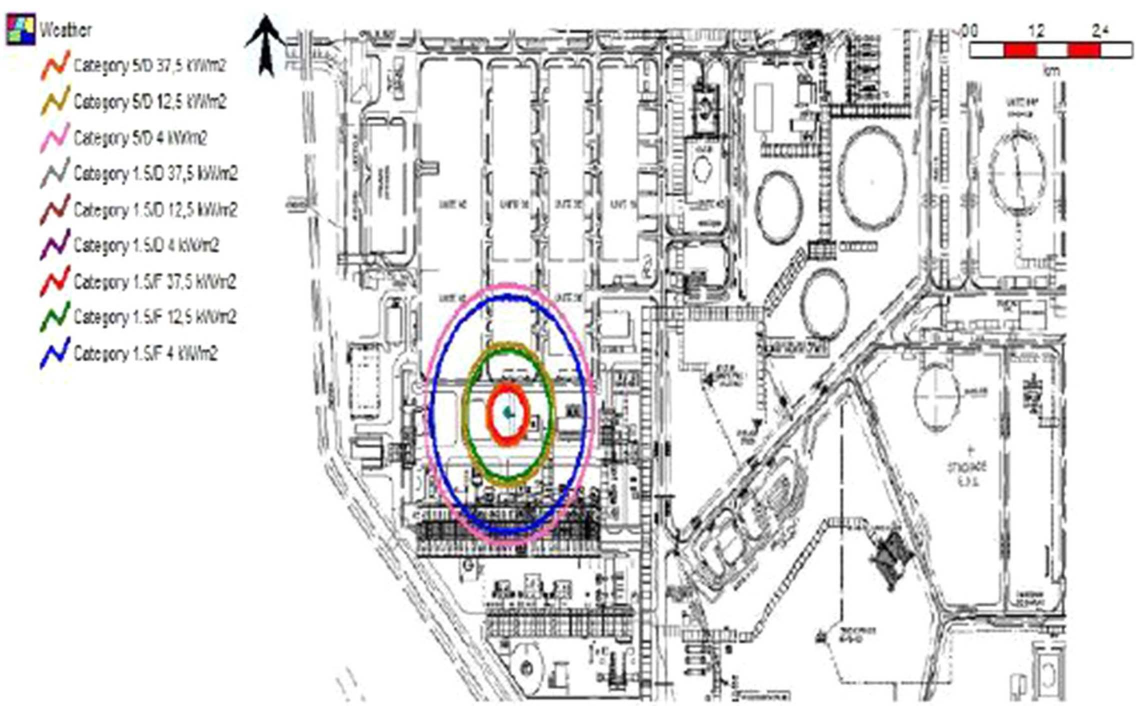


Fig. 6 Intensity radiation of fireball on the LNG unit (surface plan)

distance which demonstrates serious consequences for human life, environment and buildings.

The fireball intensity radiation is one of the essential events of assessment radiation [18] as long as the degree of damage depends on radiation level. According to Fig. 5 and Fig. 6 which show different levels of Fireball intensity radiation scenario, we notice that the intensity radiation does not depend only on intensity level, but it depends also on atmospheric conditions that are presented by the 1.5/F and 5/D categories. The first category which presents a stable atmosphere with weak winds, average cloud and limited turbulences gives a downwind distance of 1404,33 m (blue contour) for 4KW/m^2.

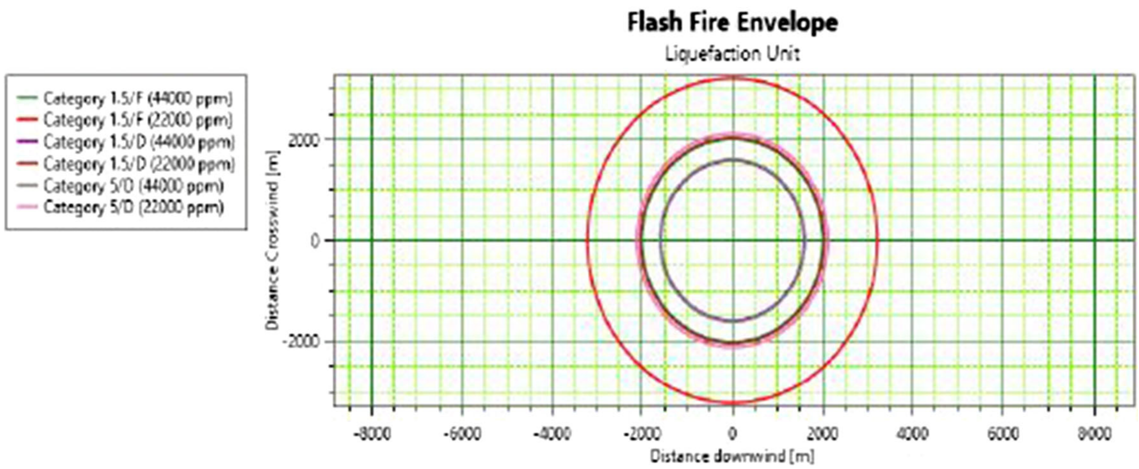


Fig. 7 Flash fire envelope

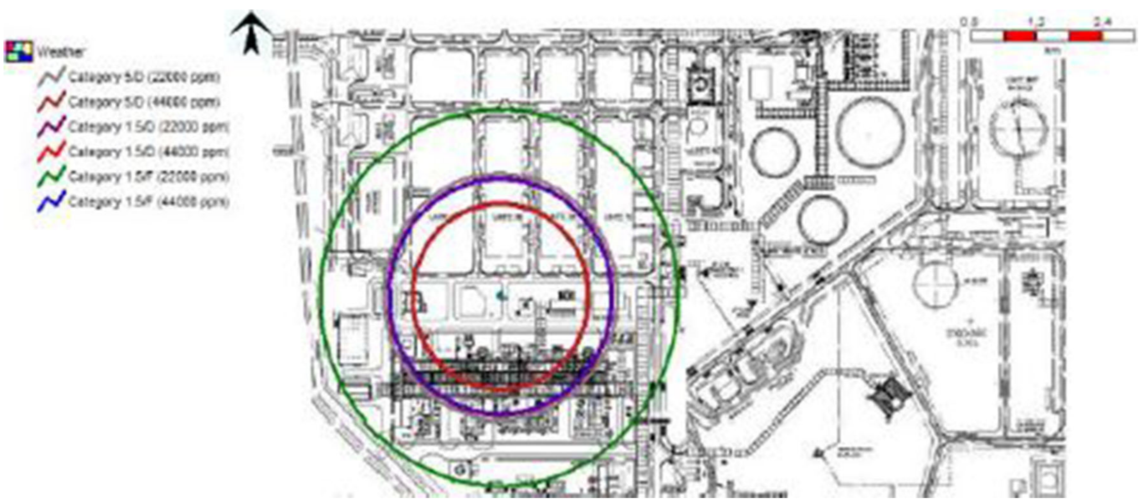


Fig. 8 Flash fire effects of on the LNG unit (surface plan)

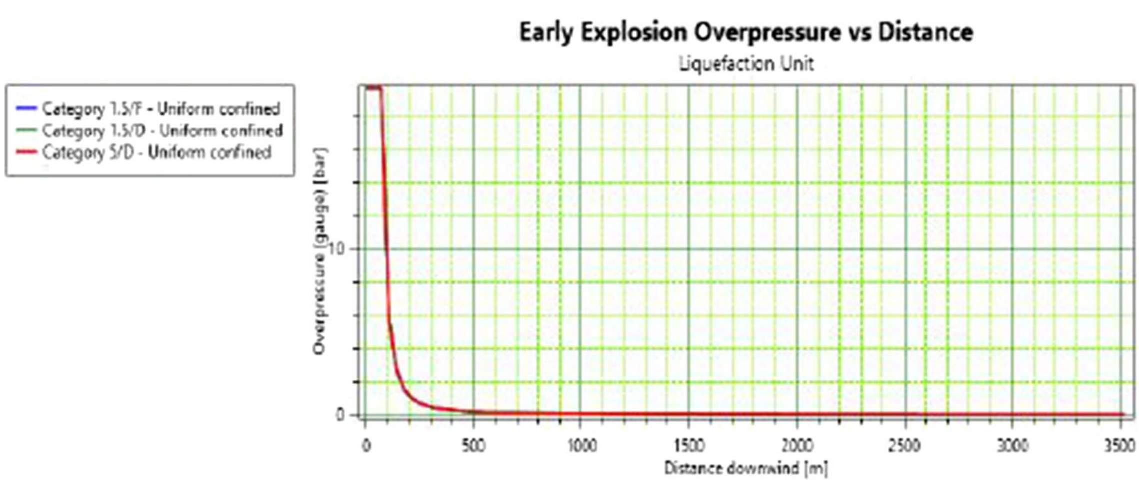


Fig. 9 Early explosion overpressure VS distance

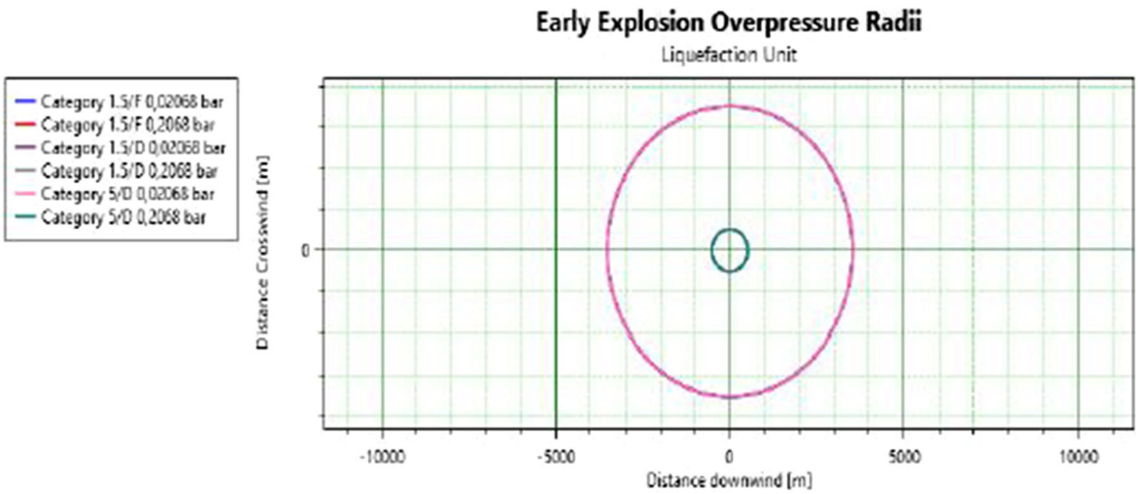


Fig. 10 Early explosion overpressure radiations

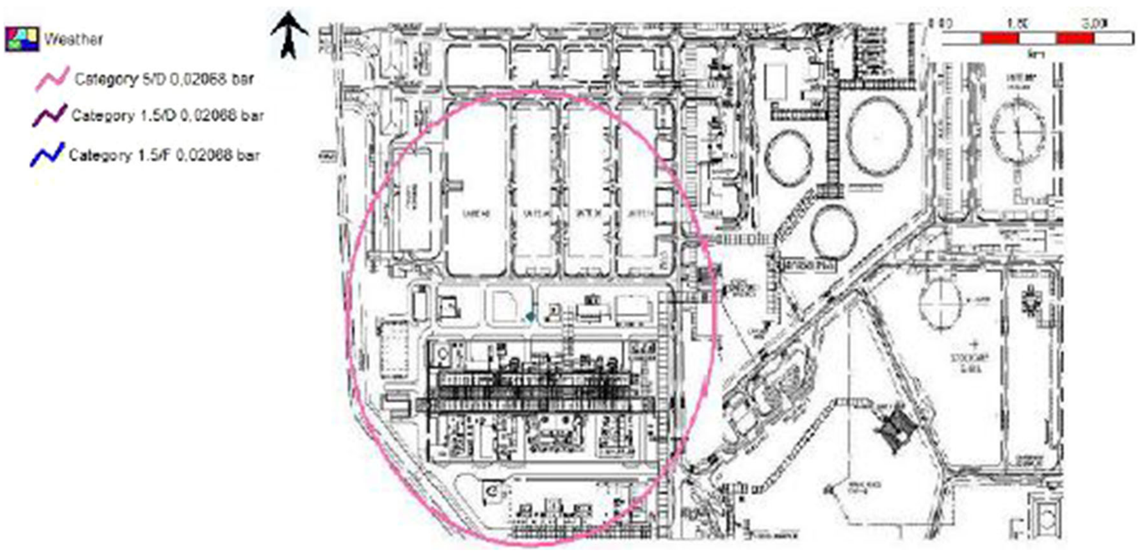
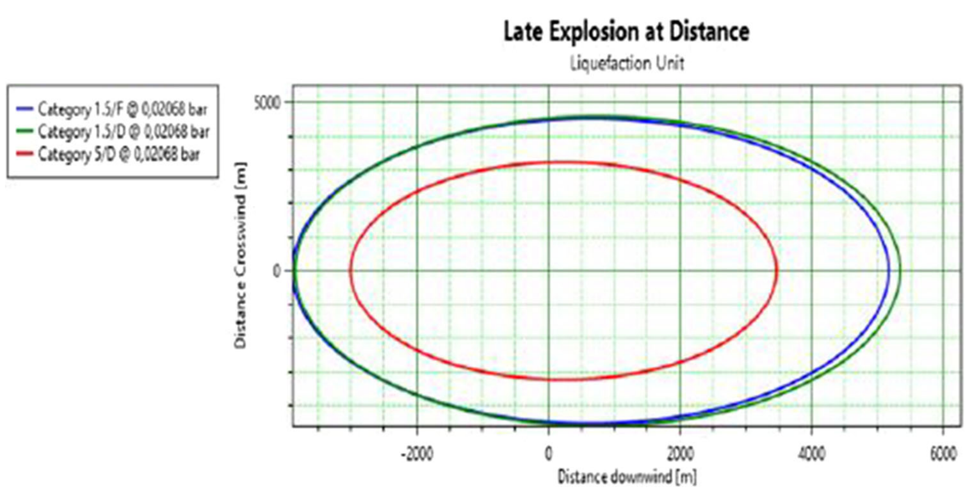


Fig. 11 Early explosion overpressure radiation (surface plan)

Fig. 12 Late explosion at distance



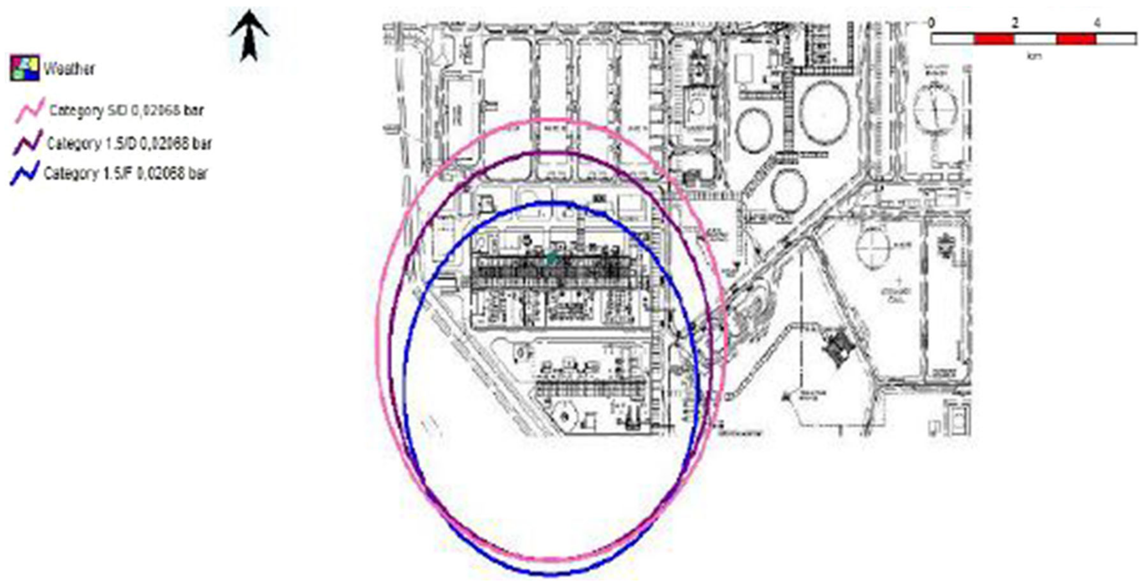


Fig. 13 Late explosion worst-case radiation (surface plan)

Table 8 Protection and preventive controls

Keywords Categories	Protection and preventive controls
Organization	The use of the electrical heater only for starting the liquefaction operation
Principal inventories of dangerous substances	Must be employ welded nozzles to minimize leak points
	Gas detection and fire detection systems
	Respect the maintenance program and standard exploitation procedures.
	Time of valve closing must be limited to avoid a pressure blow
	Temperature detection to indicate GNL rejections.
Principal safety systems	Temperature detection to indicate GNL rejections
Maintenance and Inspection	Respect the entry license in confined spaces
External Environment	Specifications for wind resistance in vessel design

The 5/D category presents a stable and neutral atmosphere with winds and strong cloudy cover that provide average turbulences which play an important role in radiations level. In this category, the distance for 4KW/m^2 is 1540, 73 m (Hot pink contour). It is a very important distance having serious consequences.

According to the results of Figs. 5 and 6, we note that fireballs can emit large amounts of heat, causing property damage, injury or death in a much larger area than the radius of fire [19].

Flash Fire

The damage caused by the flash fire should be limited to the materials ignition, which ignite easily. Moreover, it generally does not create overpressures. So, their damage is limited exclusively to thermal impacts.

The results of potential events of flash fires are presented in Figs. 7 and 8. They indicate that the wind velocity and atmospheric stability can have a significant effect on the flash fire envelope dispersion which determines the final distance from LFL concentrations. For a concentration of 22,000 ppm, the longer distance to LFL is presented by the red contour which corresponds to category 1.5/F.

For a concentration of 44,000 ppm, the longer distance to LFL is presented by the green contour which corresponds to category 1.5/F.

Figure 8 confirms that the flash fire is the advancing face of flame of an ignited vapor cloud although it presents significant dangers to people. (Any personnel located in or out of flash fire envelope is regarded as immediately died.)

Early Explosion

According to Fig. 9 which shows the relationship between overpressure and downwind distance, the blast wave declines according to travelled distance, while the value of overpressure becomes zero in 500 m.

Figures 10 and 11 illustrate different blast-wave overpressures in different contours that correspond to diverse damage degrees from overpressure in a natural gas explosion [20]; these damages are related to two important values of pressure which are: 0, 02068 bar and 0, 2068 bar. The first value (0, 02068 bar) can cause limited damages for human and structure. The affected area in this case is about 3523, 28 m from the center of the explosion, but the second one (0, 2068 bar) is capable of causing catastrophic damages for human, environment and structure since the distance to overpressure of 0, 2068 bar is 513,417 m.

These consequences indicate that the atmospheric conditions have not any influence on blast-wave overpressure explosion; therefore, this later depends on the quantity of flammable materials not the atmospheric conditions.

Late Explosion

Figure 12 shows the distance for various weather conditions for a blast-wave overpressure of 0, 02068 bar.

For the 1.5/F category, the distance from the explosion center is 2490 m (blue contour).

For the 1.5/D category, the distance from the explosion center is 1860 m (green contour).

For the 5/D category, the distance from the explosion center is 1550 m (red contour).

Figure 13 corresponds to late explosion's worst-case radiation for 0, 02068 bar. The results indicate that the fatal zone was shown with blue contour (1, 5/F category); this area is considered as a zone of 100% death if we compared it with other affected zones:

The zone which defined by a purple contour corresponds to 1, 5/D category.

The zone which defined by a purple contour corresponds to 1, 5/D category.

0, 02068 bar is a weak pressure but it can cause catastrophic consequences that can go beyond the LNG unit and can act on the surrounding complexes; these effects lead to severe damages for human, environment, structure and financial loss.

Conclusion

This study combined different risk assessment techniques to assess and evaluate liquefaction unit hazards of the LNG complex of Skikda (Algeria):

- A hybrid technique (HAZID) for identifying the hazards scenarios that can result fire or explosion accidents, theirs causes, location and protection measures.
- A prediction and quantification tool (DOW's F&EI) which predicts and quantifies mathematically the fire and explosion damages in the Scrub Column and MCHE the most critical systems in the LNG unit.

In order to make this assessment a real image and better understanding of hazards severity, PHAST software was used to model, simulate and predict fire and explosion hazards effects that are:

- Fireball
- Flash fire
- Early and late explosion

The results obtained from this study allowed us to state control and preventive measures for reducing and limiting the fire and explosion accident in order to save human life as first goal, environment and installations as a second goal and to avoid the financial loss in the considered petrochemical plant.

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