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FIRE AND EXPLOSION CONSEQUENCE ANALYSIS OF OCCUPIED BUILDINGS IN AN LPG STORAGE FACILITY IN SOUTHERN NIGERIA

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ABSTRACT: *The purpose of this work was to carry out an evaluation of occupied buildings from the devastating impact of an explosion in a Liquefied Petroleum Gas (LPG) bulk storage facility with the intention to provide information on blast requirements of the buildings and make layout modification as needed using the consequence-based approach. The simulation was done using DNV's Process Hazard Analysis Software Tool (PHAST) and the process data were obtained from a process plant located in the Niger-Delta region of Nigeria. Three major scenarios; catastrophic rupture, full bore rupture was considered for a 6-inch pipe and fixed duration release of the stored LPG and propane gas using the TNO multi-energy method to determine the Maximum Credible Event on the occupied buildings within the facility From the study, the catastrophic rupture of LPG vessel #18 at 2/F weather category gave the worst impact with an overpressure effect of 0.7barg at a hazard distance of 166.959m. The thermal radiation intensity of 37.5KW/m*^{2} *due to Jet fire from the fixed duration release of Propane vessel #22 at 2/F weather category was found to produce the greatest consequence/impact at a hazard distance of 180.72m. The results from this work show that most of the occupied buildings within the location are in the vicinity of the effect zone of both explosion overpressure and Jet fire thermal radiation.*

KEYWORDS: Building Citing, Catastrophic Rupture, Explosions, Fire, Overpressure

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INTRODUCTION

The process industry has been fraught with a significant number of incidents where accidental releases of flammable material have led to fires and/or explosions resulting in multiple fatalities, both on-site and off-site and in order to keep safe from the damaging effects of these events, there is need for modelling shock waves, radiation and toxic effects. Explosions, defined as the sudden and violent release of energy that causes a blast with a high potential of damage are very significant in terms of their damage potential and often lead to fatalities and damage to property (Khan & Abbasi, 1999).

Liquefied petroleum gas (LPG) which includes propane, butane and a mixture of these gases is highly flammable and carries the risk of explosion because it is stored under pressure in huge quantities in bullet or storage tanks and dissipates in the atmosphere very quickly. It is heavier than air and would remain close to the ground, if released, and drift with the wind until either dispersed to concentrations below its lower flammability limit or it encounters an ignition source. Ignition of an LPG vapour cloud could cause a fireball/flash fire and/or a Vapour Cloud Explosion (VCE) in a congested or confined space. In addition, a Boiling Liquid Evaporating Vapour Explosion (BLEVE) event may also occur if the LPG storage tank or vessel is exposed to such heating conditions as a pool fire or a jet fire.

The location and design of occupied buildings within facilities housing these gases have become very paramount leading to the development of guidelines and standards which include the citing and design of control rooms and the location of other process plant buildings in order to avoid the devastating impacts of fire and explosion.

Gas explosions can occur inside process equipment or pipes, in buildings or off-shore modules, in open process areas or in unconfined areas. Figure 1 shows possible scenarios when combustible gases or evaporating liquids are accidentally released into the atmosphere.

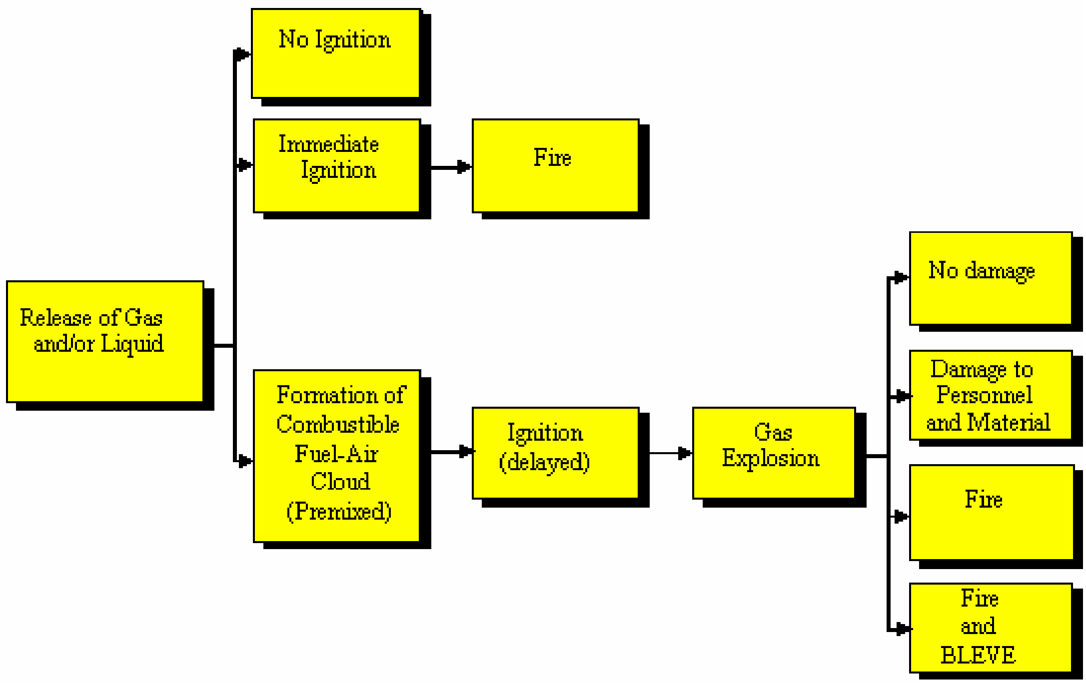

Fig 1: Event Tree of typical Consequences of Accidental Releases of Combustible Gas or Evaporating Liquid into the Atmosphere (Dag et al.,1992).

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Building Citing Evaluation

Process safety management systems help ensure that facilities are designed, constructed, operated, and maintained with appropriate controls in place to prevent serious accidents. Despite these precautions, buildings close to process plants have presented serious risks to the people who work in them. This observation is prompted by the fact that some buildings that were not designed and constructed to be blast resistant have suffered heavy damage, and in some instances have collapsed when subjected to blast loads from accidental explosions. Serious injury or fatality to the occupants resulted from the building damage. Experience indicates that personnel located outdoors and away from such buildings, if subjected to the same blast, may have a lower likelihood of serious injury or fatality. Building occupants have also been exposed to toxic vapours that enter through forced or natural convection ventilation, and thermal hazards that result from fires near buildings CCPS, 2012).

The first step in the assessment process is to determine if a building is, in fact, potentially subjected to an event of concern. If no event that could significantly impact the building can occur, no further evaluation is necessary.

All buildings used by on-site personnel are evaluated for inclusion in the building citing evaluation. This includes both existing permanent and portable buildings as well as new buildings. The scenarios selected for the building citing evaluation are those that can potentially result in hazards to the building occupants on the site.

Plant owners may choose a Consequence-Based approach or a Risk-Based approach for building-citing evaluation methods. The consequence-Based approach takes into account, for each building, only the impact of the Maximum Credible Event (MCE), irrespective of its frequency while the Risk-Based approach considers both the consequences and the frequencies of all the potential explosion scenarios able to impact a specific building.

Consequence-based

A consequence-based assessment evaluates potential damage to a building and/or potential injury to occupants without consideration of the likelihood that the postulated scenario will occur. The consequence-based method requires the selection of maximum credible event (MCE) scenarios to represent each applicable type of hazard (explosion, fire and toxic material release). Damage or occupant injury predictions are compared to consequence criteria that are established before the study is undertaken (CCPS, 1994).

The methodology, in this case, does not include consideration of the frequency with which an explosion, fire or toxic scenario may occur; rather, the analysis is limited to computation of the damage or injury that may result from the postulated scenario. A consequence-based assessment assumes an outcome for each scenario.

Risk-based

A risk-based assessment evaluates the impact of a wide range of scenarios from small to large and incorporates the likelihood of each scenario. The risk to occupants of a building is calculated as the sum of the risks from all of the scenarios. Risk criteria are first established using risk metrics such as risk to an individual building occupant and risk to occupants as a group (aggregate risk). The use of the risk-based approach requires the ability to determine the frequency associated with each potential scenario.

In this work, the consequence-based approach was applied for the evaluation of occupied buildings within the facility for the purpose of providing information on the blast requirements of the buildings or the need for layout modification.

Standards for Building and Equipment Citing and Separation

Building exposure criteria are based on the premise that there is a maximum blast loading that will cause a building response, which will result in tolerable consequences for the building occupants. The wide ranges in spacing criteria are available from various organisations including the Centre for Chemical Process Safety (CCPS), National Fire Protection Association (NFPA), etc., and the spacing between control room buildings and process units reflects standards which are designed to protect property and reduce business interruption and prevent the occurrence of fires CCPS, 2012). It is also common practice for companies to use Blast Resistant Modules (BRMs) for the protection of facilities.

Building Damage Levels (BDLs) are also used as evaluation criteria for existing buildings. Building damage can be represented as either continuous or discrete. In the use of the continuous function, reference is made to the "percentage of damage" while in the use of the discrete mode the damages are categorised into a number of damage states ranging from minimal damage to total collapse (Department of Defense Explosive Safety Board, 2009; Baker et al.,1996; Oswald and Baker, 2000).

The input data that are required for the assessment of these structures with regard to how vulnerable they may be to explosion include (Oil and Gas Producers, 2010):

- Peak pressure;
- Impulse;
- Load duration;
- Rise time (to peak pressure);
- Drag pressure;
- Approximate impulse duration for dynamic drag.

The general relationship between pressure and damage is shown in Table 1 while the effect of overpressure on the building occupants for different building types is shown in Table 2. Explosion damage evaluation

Table 1: Damage Estimates for Common Structures Based on Overpressure

Pressure		**Damage**
Psi(g)	**bar(g)**	
0.02	0.14	Annoying noise (137 dB if of low frequency 10-15 Hz)
0.03	0.21	Occasional breaking of large glass windows already under strain
0.04	0.28	Loud noise (143 dB), sonic boom, glass failure
0.1	0.69	Breakage of small windows under strain
0.15	1.03	Typical pressure for glass breakage
0.3	2.07	"Safe distance" (probability 0.95 of no serious damage[1] below this value); projectile limit; some damage to house ceilings; 10%window glass broken
0.4	2.76	Limited minor structural damage
0.5-1.0	3.4-6.9	Large and small windows usually shattered; occasional damage to window frames.
0.7	4.8	Minor damage to house structures
1.0	6.9	Partial demolition of houses, made uninhabitable
1.0-2.0	6.9-13.8	Corrugated asbestos shattered; corrugated steel or aluminium panels, fastenings fail, followed by buckling; wood panels (standard housing) fastenings fail, panels blown in
1.3	9.0	Steel frame of clad building slightly distorted
2	13.8	Partial collapse of walls and roofs of houses
2.0-3.0	13.8-20.7	Concrete or cinder block walls, not reinforced, shattered
2.3	15.8	Lower limits of serious structural damage
2.5	17.2	50% destruction of brickwork of houses
3	20.7	Heavy machines (3000 lb) in the industrial building suffered little damage; steel frame building distorted and pulled away from foundations
3.1 0-4.0	20.7-27.6	Frameless, self-framing steel panel building demolished; rupture of oil storage tanks
4	27.6	Cladding of light industrial buildings ruptured
5	34.5	Wooden utility poles snapped; tall hydraulic press (40,000 lb) in building, slightly damaged
5.0-7.0	34.5-48.2	Nearly complete destruction of houses
7	48.2	Loaded, lighter weight (British) train wagons overturned
7.0-8.0	48.2-55.1	Brick panels, 8-12inch thick, not reinforced, fail by shearing or flexure

9	62	Loaded train boxcars completely demolished
10	68.9	Probable total destruction of buildings; heavy machine tools (7,000 lb) moved and badly damaged, very heavy machine tools (12,000 lb) survive
300	2068	Limit of crater lip

Table 2: Overpressure versus Occupant Vulnerability for various Building Types (Clancy,1972; AIChE-CCPS. (1996).

Building type	Overpressure psi (bar)	Consequences	Vulnerability of occupants
A Wood-frame trailer or shack	1.0 (0.069)	Isolated buildings overturn. Roofs and walls collapse	0.1
	2.0 (0.14)	Near-total collapse.	0.4
	5 (0.34)	Buildings completely destroyed	1.0
B Steel-frame/metal siding pre-engineered building	1.25(0.09)	Metal siding anchorage failure	0.1
	1.5(0.10)	Sheeting ripped off and internal walls damaged. Danger from falling objects	0.2
	2.5(0.17)	Building frame stands, but cladding and internal walls destroyed as frame distort	0.4
	5 (0.34)	Building completely destroyed	1.0
C Unreinforced masonry bearing wall building	1.0(0.069)	Partial collapse of walls that have no breakable windows.	0.1
	1.25(0.085)	walls and roof partially collapse	0.2
	1.5(0.10)	Complete collapse	0.6
	3(0.21)	Building completely destroyed	1.0
D Steel or concrete frame with unreinforced masonry infill or cladding	1.0(0.069)	Failure of incident face	0.1
	1.5 (0.10)	Walls blow in.	0.2
	2.0(0.14)	Roof slab collapse	0.4
	2.5(0.17)	Complete frame collapse	0.6
	5(0.34)	Building completely destroyed	1.0
E Reinforced concrete or masonry shear wall building	4.0(0.28)	Roof and wall deflect under loading. Internal walls damaged	0.1
	6.0(0.41)	Building has major damage and collapses	0.4
	12(0.83)	Building completely destroyed	1.0

Atmospheric stability

This is a measure of the degree of atmospheric turbulence and resulting gas dispersion. Dispersion is usually affected by the conditions of the weather at the time of the release. The effect of these and plume behaviour changes according to the stability of the atmosphere and wind speed (Hanna et al., 1982; Pasquill & Smith, 1983; Slade, 1968). Atmospheric conditions are normally classified according to six Pasquill stability classes which are correlated to wind speed and quantity of sunlight and are classified by the letters A through F as shown in Table 4. During the day, increased wind speed results in greater atmospheric stability, while at night the reverse is true and this is because there is a change in vertical temperature profiles from day to night.

Table 4: Relationship between Turbulence and Weather Conditions

Relation of Turbulence Types to Weather Conditions					
	Daytime insolation			Night time conditions	
Surface wind speed ($m\ s^{-1}$)	Strong	Moderate	Slight	Thin overcast or >= 4/8 cloudiness	<= 3/8 cloudiness
< 2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

Conditions: A, extremely unstable; B, moderately unstable; C, slightly unstable; D, neutral (applicable to heavy overcast, day or night); E, slightly stable; F, moderately stable.

Local Terrain Effects

Terrain characteristics affect the mechanical mixing of air as it flows over the ground and thus has a significant effect on dispersion.

Table 5: Surface Roughness Parameter, z_o

Terrain Classification	Terrain description	Surface roughness, z_o, meters
Highly urban	Centers of cities with tall buildings, very hilly or mountainous area	3-10
Urban area	Centers of towns, villages, fairly level wooded Country	1-3
Residential Area	Area with dense but low buildings, wooded area, industrial site without large obstacles	1
Large refineries	Distillation columns and other tall equipment pieces	1

Small refineries	Smaller equipment, over a smaller area	0.5
Cultivated land	Open area with great overgrowth, scattered houses	0.3
Flat land	Few aces, long grass, f level grass plains	0.1
Open water	Large expanses of water, desert flats	0.001
Sea	Calm open sea, snow-covered flat, roiling land	0.0001

Explosion Scenarios

It is important to have an understanding of the physical and chemical properties of materials being handled in addition to the quantities of the materials to be handled in order to be able to do a proper evaluation of the materials and the site conditions that can result in potential explosion scenarios.

The explosion scenarios comprise of any of the followings:

1. Vapour Cloud Explosions (VCE).
2. Internal Explosions.
3. Condensed-phase Explosions/Other Uncontrolled Chemical Reactions
4. Boiling Liquid Evaporating Vapour Explosion (BLEVEs)/Pressure-volume Ruptures/Physical Explosions

Empirical explosion calculation:

Generally, three methods are used in calculating the energy of explosions. These include:

i- TNT-equivalent method;

ii- Multi-energy method:

iii- Baker-Strehlow-Tang method

i. TNT Equivalent method

In this method, the power of the vapour cloud explosion is assumed to be equal to an equivalent mass of TNT (tri-nitro toluene) that would produce the same explosive power. The mass of the flammable gas in the cloud at concentrations between the lower flammability limits (LFL) and the upper flammability limits (UFL) is estimated and the mass is multiplied by the heat of combustion so as to obtain the total available energy of the combustion. The overpressure, P_s (kPa), is defined as a function of a scaled distance Z, according to Equation (1) (Brasie and Simpson, 1977):

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$$Z = \frac{x}{M_{TNT}^{\frac{1}{3}}} \qquad (1)$$

where, x(m) is the distance from the centre of the explosion and M_{TNT} (kg) denotes the equivalent TNT mass, obtained according to Equation (2):

$$M_{TNT} = \frac{f_g \Delta H_c M_G}{\Delta H_{TNT}} \qquad (2)$$

In Equation (2), M_G (kg) denotes the mass of the flammable gas that takes part in the explosion; ΔH_C (kJ/kg) and ΔH_{TNT} (kJ/kg) are the heat of combustion of the flammable gas and the heat of combustion of *TNT* (= 4,760 kJ/kg) respectively. The dimensionless coefficient, f_E, stands for the fraction of the energy released as a shock wave, the value of which is usually between 0.01 and 0.1.

Another more recent expression used for the overpressure, P_s (kPa), of the shock wave, is:

$$P_S = \frac{80800(1+[\frac{Z}{4.5}]^2)}{\sqrt[2]{1+[\frac{Z}{0.048}]^2}\sqrt{1+[\frac{Z}{0.32}]^2}\sqrt{1+[\frac{Z}{1.35}]^2}} \qquad (3)$$

ii Multi-energy method

The most important assumption of this method is that the strength of the explosion blast, and thus the overpressure developed, depends upon the layout of the space where the cloud is spreading. More precisely, only the obstructed or partially obstructed regions (regions with a high equipment density) will contribute to a high-strength explosion blast. The remaining parts of the cloud will slowly burn, without a serious contribution to the strength of the blast (Berg van den and Lannoy, 1985); Mercx et l.,2016). In this scenario, the area surrounding the explosion centre must be separated into obstructed and non-obstructed regions (Berg van den and Lannoy, 1985). The scaled dimensionless overpressure, P_s', is given as a function of the scaled dimensionless distance, r'. Both these quantities are defined as follows (Berg van den and Lannoy, 1985):

$$P_S' = \frac{P_S}{P_a} \qquad (4)$$

$$r' = x\left(\frac{E}{P_a}\right)^{\frac{-1}{3}} \qquad (5)$$

where, P_s (MPa) denotes the overpressure caused by the explosion,

P_a (MPa), the ambient pressure (= 0.1 MPa),

x (m), the distance from the centre of the explosion, and

E (MJ), the total energy released by the explosion.

A coefficient of 10 refers to a high-strength explosion with a very high overpressure.

Where there is high equipment density in any area, the value of the coefficient of strength will then have a large value. Two cases of blast strength 10 and 3, have been evaluated according to the following equation:

$$P_s' = 10^{-b \log r' - c} \tag{6}$$

Table 6: Coefficients b and c (AIChE-CCPS. 1994).

Coefficient of strength of explosion	Range of r′	*B*	*c*
10	0.15< r′<1.0	2.3721	0.3372
	1.0<r′<2.5	1.5236	0.3372
	r′>2.5	1.1188	0.5120
3	r′<0.6	0	1.3010
	r′>0.6	0.9621	1.5145

iii. Baker-Strehlow-Tang method

The Baker-Strehlow method (Baker et al., 1996; Baker et al., 1998) is based on the idea of obstructed regions that were initially put forward by the multi-energy method. Three categories are considered based on the reactivity of fuels:

- High reactivity fuels: hydrogen, acetylene, ethylene oxide, and propylene oxide;
- Low reactivity fuels: methane and carbon monoxide;
- Medium reactivity fuels: all other gases and vapours.

Fire Scenarios

The fire scenarios can comprise any of the following:

1. Pool Fires

Pool fires occur when LPG burns with long smoky flame throughout the pool diameter causing intense radiation of heat which can lead to severe damage to the adjoining buildings, structures, plant vessels and equipment and which can lead to secondary fires. Damages resulting from pool fires are usually restricted to plant areas and near the sources of such fires. If a good plant layout is maintained, damage from pool fires can be minimised.

2. Jet Fires.

Jet fires can result if a jet of LPG escaping from pressure vessels or piping is ignited giving rise to jet flame. Damage from such fires is usually restricted to locations within the plant boundary. The Domino effect can, however, result if the ignited jet impinges on nearby vessels or equipment carrying LPG.

3. Flash Fires.

A flash fire can be defined as the non-explosive combustion of a vapour cloud resulting from the release of flammable material in combination with air. The source of ignition can be a spark from an electric source, a hot surface, friction between moving parts of a machine or even an open fire. Most of the time, flash combustion of a flash fire lasts no more than a few seconds.

Thermal Radiation Intensity Limits

The thermal radiation intensity limits proposed by the World Bank are shown in Table 7 (World Bank, (1988) and they are directly related to specific radiation effects on people and materials while the allowable thermal radiation flux with the exception of that contributed by the sun is shown in Table 8.

Table 7: Thermal Radiation Intensity Limits (World Bank. (1988).

Heat flux($kW \cdot m^{-2}$)	Effect on materials	Effect on humans
37.5	Equipment damage.	100% lethality in 1 min. 1% lethality in 10 s.
25	Minimum intensity for ignition of wood in prolonged exposure.	100% lethality in 1 min. Serious injuries in 10 s.
12.5	Minimum intensity for ignition, and melting of plastic tubes.	1% lethality in 1 min. 1st degree burns in 10 s.
4	Nil	No lethality. 2nd-degree burns are probable. Pain after exposure of 20 s.
1.6	Nil	Acceptable limit for prolonged exposure.

Table 8: Allowable Thermal Radiation Flux, Excluding Solar (EN BSI, 2007).

Equipment Inside Boundary	**Maximum Thermal Radiation Flux (kW/m^2)**
Concrete outer surface of adjacent storage tanks (a)	32
Metal outer surface of adjacent storage tanks	15
The outer surfaces of adjacent pressure storage vessels and process facilities	15
Control rooms, maintenance workshops, laboratories, warehouses, etc.	8
Administrative buildings	5

For pre-stressed concrete tanks, maximum radiation fluxes may be determined by alternative methods. The heat flux level can be reduced to the required limit by means of separation distance, water sprays, fireproofing, radiation screens or similar systems.

Explosion damage evaluation

The input data required for the assessment of the vulnerability of plants and structures include Peak pressure, Impulse, Load duration, Rise time (to peak pressure), Drag pressure, and approximate impulse duration for dynamic drag.

Processes involved in building evaluation

The processes involved in the evaluation of buildings fall into two major categories which are:

i. **The selection of the buildings:**

This has to do with determining if a building is potentially subjected to an event of concern and this covers both existing permanent and portable buildings in addition to new buildings.

ii. **Selection of Potential Incident Scenarios:**

A consequence-based assessment assumes an outcome for each scenario and hence relies on the use of a Maximum Credible Event (MCE) for assessment whereas a risk-based assessment considers a wide range of potential scenarios including both smaller (and more likely) scenarios as well as larger (and less likely) scenarios, which may in some cases exceed the MCE used in the consequence-based approach.

MATERIALS AND METHODS

Materials

The materials used in this work include, PHAST 7.2 software, a Map of the area under Consideration, General Plant Layout diagrams, a Process Operating Manual for the Facility, an Equipment specification sheet, Process Piping and Instrumentation Diagram (P&ID), Process Flow Diagram (PFD), Material and heat balance, Damage table due to Overpressure, Damage table due to thermal radiation intensity.

Methods

Data Sources

All data used in this study were obtained from a chemical process plant in the Niger-Delta region of Nigeria. In analysing these data, the location of existing buildings and storage units were located on the map of the facility.

Facility Description:

The facility in which the study was carried out consists of the following: LPG (mixed propane and butane) storage area consisting of 16 storage vessels (arranged in banks of 5, 5 and 6), Propane storage area consisting of 13 storage vessels (arranged in banks of 4, 4 and 5), LPG

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loading pumps (5no), Propane loading pumps (4no), Loading bay (consist of 8 loading bays), Weighbridge area, Dispatch office, Control room, Weighbridge operator cabin, Security cabin and, Drivers waiting room

The plant layout is shown in Figure 2.

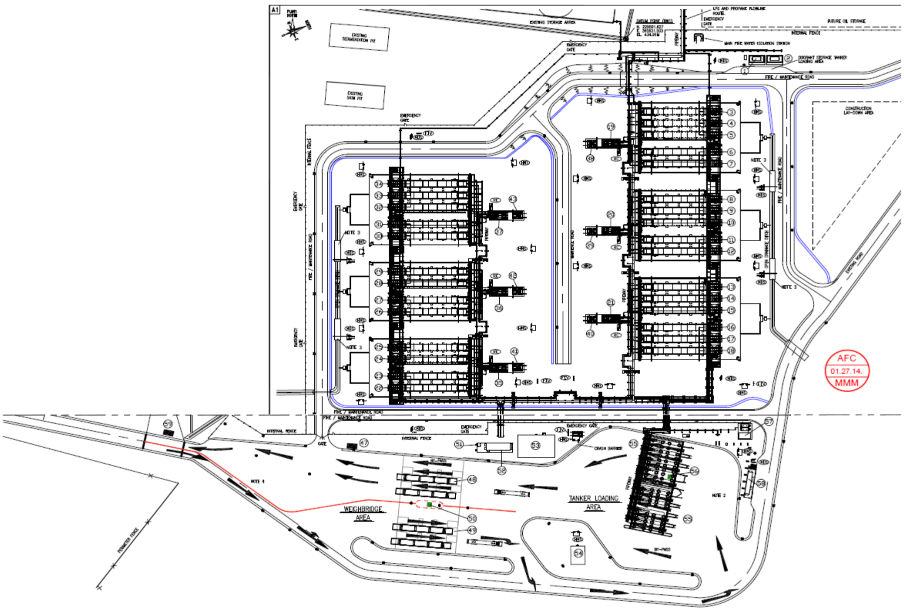

Fig 2: Plant Layout

The buildings in the facility modelled for in this study are shown in Figure 3.

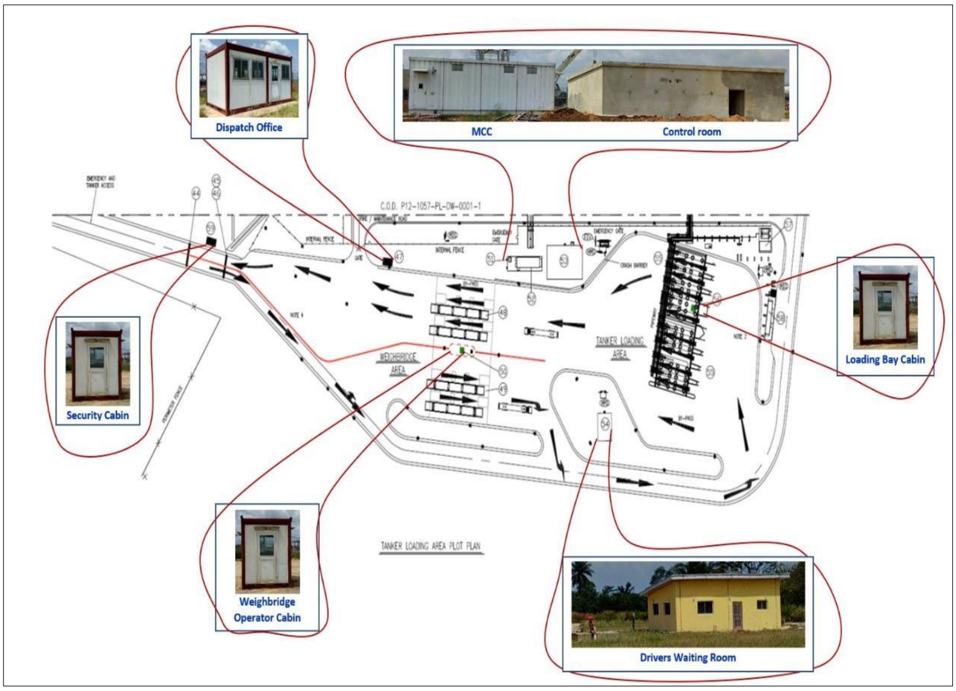

Fig. 3: Buildings Layout Plan

Modeling Steps

The steps adopted in this study are as follows (TNO, 1997):

Step 1: Building Evaluation and Selection: The result of this assessment is shown in Table 9.

Table 9: Process Facility Building Evaluation

Description of building	**Intended for occupancy?**	**Building Evaluation Required?**
Dispatch office – portable building	Yes	Yes
Control room – permanent building	Yes	Yes
Motor control centre (MCC)-Portable building	No	No
Weighbridge operator cabin – portable building	Yes	Yes
Security cabin – portable building	Yes	Yes
Drivers waiting room – portable building	Yes	Yes

Step 2: Scenario selection:

Scenarios based on the use of a Maximum Credible Event (MCE) are shown in Table 10.

Table 10: Selected Failure Cases

S/N	Failure Cases	Duration
1	Catastrophic Failure of vessel	
2	Fixed duration release (worst case release)	10min
3	Full bore failure of 6NPS (inches)/168.27 mm outline of bullet	

Step 3: Meteorological Condition:

The meteorological data were extracted from the plant document and shown in Table 11.

Table 11: Weather Conditions Selected

Time	**Remarks**	**Weather Condition**			
		Temperature in °C	**Wind speed m/s**	**Relative humidity (%)**	**Stability Class**
Day Time	Prevalent during the day, most times of the year	29	4	74	C
Night Time	Prevalent during the night, most times of the year	22	2	93	F

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***Surface Roughness:** Based on the facility terrain and structures present, the surface roughness of 1m was considered in the modelling as per Table 5.

Step 4: Identification of potential blast sources:

Extended spatial configuration of the LPG and Propane storage vessels as well as other process equipment within the study area, were identified as potential sources of the strong blast.

Step 5: Determination of obstructed region:

Obstacle analysis was carried out within the study area.

Step 6: Estimation of the source strength or class number for each region:

A source strength of 7 was considered to be conservative while the blast resulting from the remaining unconfined and unobstructed parts of a cloud was modelled by assuming a low initial strength of 2.

Step 7: PHAST Consequence modelling:

Three Scenarios were considered in the study.

Case One: Catastrophic rupture of LPG vessel #18 and Propane Vessel#22.

Table 12: Case 1 Input Data

Parameter	**Unit / Value**	**Unit / Value**
Gas	LPG	Propane
Vessel type	Cylindrical	
Tank diameter	130inches	
Vessel length (S/S)	123.6ft	
Weather data	4 m/s C and 2 m /s F	
Operating Temperature	104°F	102°F
Operating pressure	88psig	192psig
Filling ratio of vessel	85% (290 m^3)	85% (290 m^3)
Maximum liquid vessel height in storage	2.81m (110.5inches)	
Minimum height beneath storage vessel	1.1m (3.6ft)	
Height of tubing over storage vessel	0.5m	
Height of storage vessel	130-in (3.302m)	

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Case Two: Full-bore rupture of the LPG and Propane Vessel

Table 13: Case 2 Input Data

Parameter	**Unit / Value**	**Unit / Value**
Gas	LPG	Propane
Vessel type	Cylindrical	
Ruptured pipe	6inches	
Leak source	Vessel Discharge Line	
Weather data	4 m/s C and 2 m /s F	
Temperature inside vessel	104Of	102Of
Storage pressure	88psig	192psig
Filling ratio of vessel	85% (290m3)	85% (290m3)
Elevation	0.55m	
Outdoor release	Horizontal	
Tank Head	3.36m	

Case Three: Fixed duration release of LPG and Propane.

Table 14: Case 3 Input Data

Parameter	**Unit / Value**	**Unit / Value**
Gas	LPG	Propane
Vessel type	Cylindrical	
Leak duration	10 minutes (worse case release)	
Leak source	Vessel	
Weather data	4 m/s C and 2 m /s F	
Operating temperature	104Of	102oF
Operating pressure	88psig	192psig
Filling ratio of vessel	85% (290m3)	
Elevation	1.5m	
Outdoor release	Horizontal	
Tank Head	2.86m	

Material composition:

The gas composition data used in this study was obtained from the material balance of the process units and tabulated as follows.

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Table 15: Input Data for Gas Composition

LPG		**PROPANE**	
Composition	**Mole fraction**	**Composition**	**Mole fraction**
Propane	0.3321	Ethane	0.035
i-Butane	0.2977	Propane	0.9488
n-Butane	0.3562	i-Butane	0.0161
i-Pentane	0.0125	n-Butane	0.0001
n-Pentane	0.0016	-	-

Table 16: Distance of Occupied Buildings to LPG Vessel #18 and Propane Vessel #22

Description of building	**Distance LPG Vessel #18**	**Distance to propane vessel #22**
Dispatch office – portable building	178.35m	34.2m
Control room – permanent building	64.74m	35.28m
Weighbridge operator cabin – portable building	137.61m	62.27m
Security cabin – portable building	249.31m	115.24m
Drivers waiting room – permanent building	112.74m	101.84m
Loading bay cabin-portable building	69.03m	115.02m

Table 17: Overpressure Damage Criteria [10].

Peak side-on overpressure, Psi (Bar)	**Consequences to buildings**	**Possible building occupant injury consequences**
0.2 (0.015)	Threshold of glass breakage	No injury to personnel
>0.5 (>0.03)	Significant repairable cosmetic damage is possible	Possible personnel injury from glass breakage, falling light fixture etc.
>1 (>0.07)	Possible minor structural damage to buildings and severe damage to trailer-type buildings and unreinforced masonry load-bearing wall buildings	Personnel injury from debris is likely
>2 (>0.14)	Local failure of isolated parts of buildings and collapse of trailer-type buildings and unreinforced masonry load-bearing wall buildings	Possible serious injury or fatality of occupants

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>3 (>0.21)	Collapse of buildings	Probable serious injury of fatality of many occupants
>10 (0.70)	Probable total destruction of non-blast-resistant buildings	Probable 100% fatalities

Table 18: Damage Due to Radiation Intensity [19].

Radiation (kW/m^2)	**Effects on materials**	**Effects on humans**
37.5	Equipment damage.	100% lethality in 1 min. 1% lethality in 10 s.
25	Minimum intensity for ignition of wood in prolonged exposure.	100% lethality in 1 min. Serious injuries in 10 s.
12.5	Minimum intensity for ignition, and melting of plastic tubes.	1% lethality in 1 min. 1st degree burns in 10 s.
4	Nil	No lethality. 2nd-degree burns are probable. Pain after exposure of 20 s.
1.6	Nil	Acceptable limit for prolonged exposure.

RESULTS AND DISCUSSION

Consequence of Dispersion and Flash Fire

Tables 19 and 20 present the maximum LFL hazard distances for different failure cases considered for both LPG pressure vessel #18 and Propane Pressure Vessel #22.

By comparing the results obtained from both tables, it can be deduced that the worst-case dispersion is due to the fixed duration release case of LPG Vessel #18 at a weather category of 2/F, which gives a maximum LFL fraction hazard distance of 894.885m at a concentration of 8,522.46ppm. Furthermore, an increase in the mass, demands a significant increase in the hazard distance. The principal hazard arising from delayed ignition of LPG vapour cloud generated from this fixed duration release case results in a flash fire. This flash fire envelope covers the dispersion distance up to the lower flammability limit (LFL).

It is considered that there is no scope for escape for persons within the flammable limits of a flash fire: a fatality probability of 100% is assumed. Persons outside the flash fire envelope are assumed to be unaffected by a flash fire since flash fires are short-duration incidences and have low levels of thermal radiation outside the flash fire.

Table 19: Dispersion Distance for LPG Pressure Vessel #18

LPG PRESSURE VESSEL #18				
S/ no	**Failure case**	**Weather category**	**Consequence Downwind Distance (m)**	
			Distance to LFL [m] (at 17,044.9ppm)	**Distance to LFL Fraction [m]** (At 8,522.46ppm)
	Catastrophic Failure case	4m/s C	292.845	690.319
		2m/s F	253.888	676.019
	Full-bore rupture of 6inches discharge line case	4m/s C	246.488	336.46
		2m/s F	352.465	473.279
	Fixed duration release case	4m/s C	398.722	547.873
		2m/s F	648.31	894.885

Table 20: Dispersion Distance for Propane Pressure Vessel #22

PROPANE PRESSURE VESSEL #22				
S/ no	**Failure case**	**Weather category**	**Consequence Downwind Distance (m)**	
			Distance to LFL [m] (at 20,218.5ppm)	**Distance to LFL Fraction [m]** (At 10,109.2ppm)
	Catastrophic Failure case	4m/s C	169.442	382.012
		2m/s F	152.016	359.581
	Full-bore rupture of 6inches discharge line case	4m/s C	288.938	524.732
		2m/s F	276.401	573.877
	Fixed duration release case	4m/s C	291.48	575.985
		2m/s F	268.177	524.045

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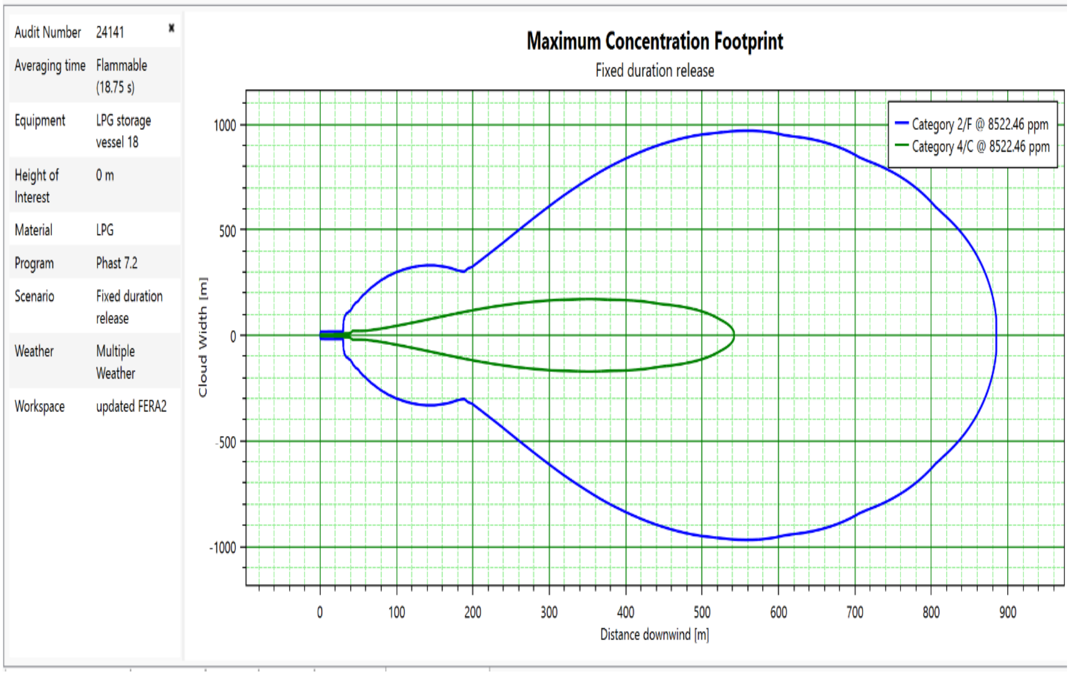
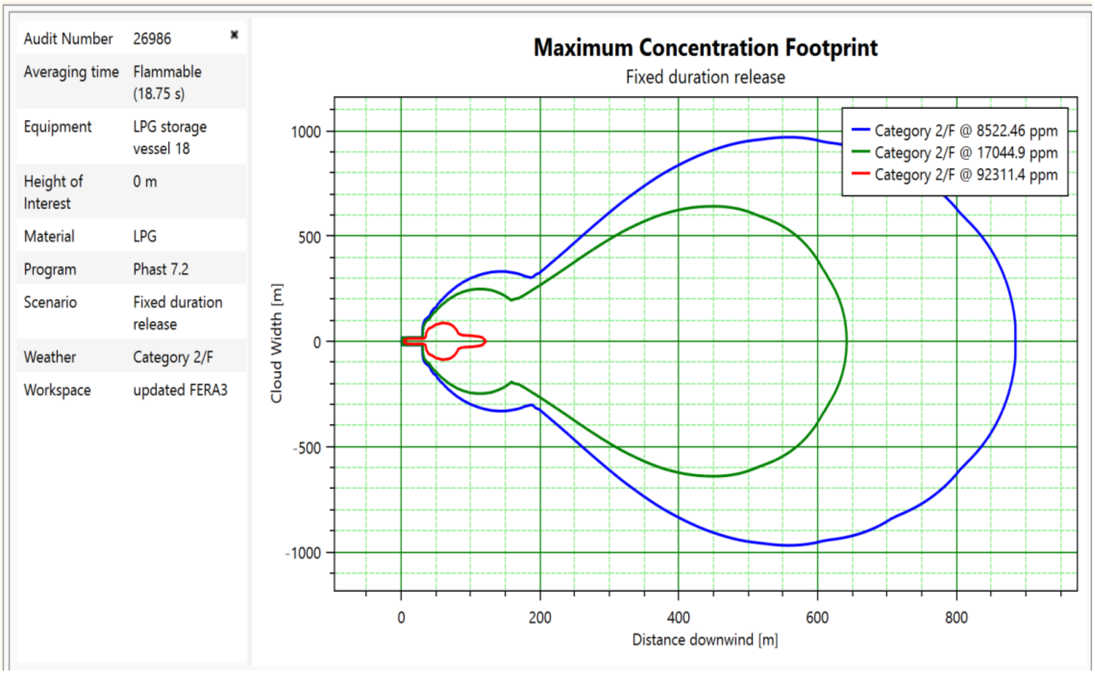


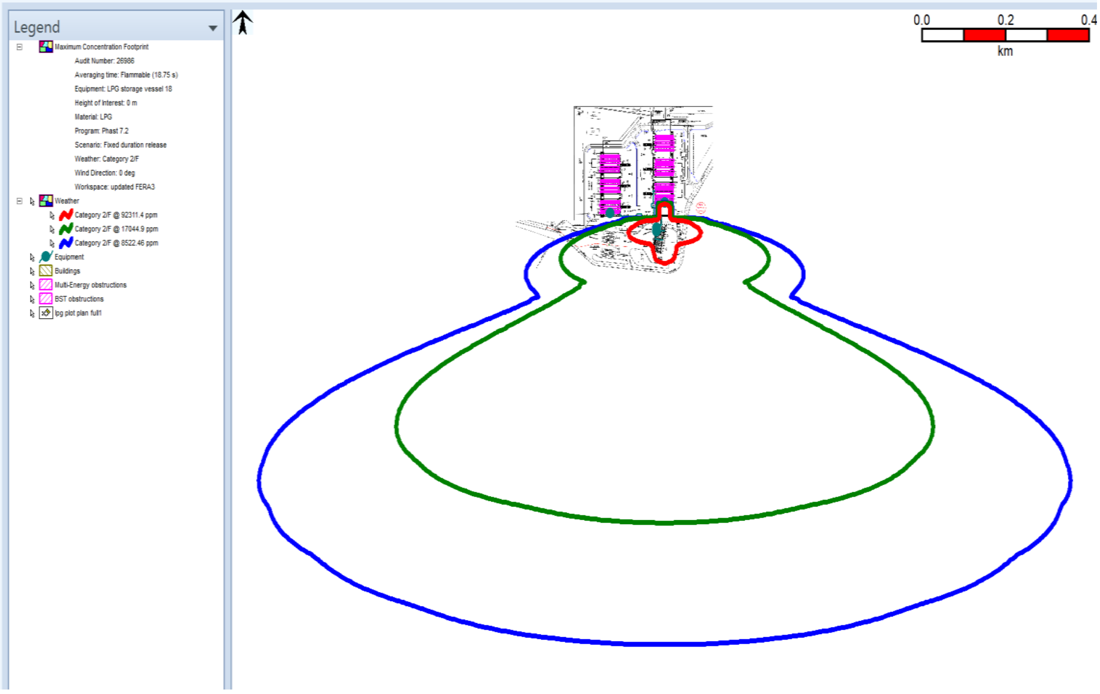
Audit Number	24141
Averaging time	Flammable (18.75 s)
Equipment	LPG storage vessel 18
Height of Interest	0 m
Material	LPG
Program	Phast 7.2
Scenario	Fixed duration release
Weather	Multiple Weather
Workspace	updated FERA2

Fig 4: Maximum Cloud Concentration Footprint for different Weather Conditions due to Fixed Duration Release of LPG Vessel #18



Audit Number	26986
Averaging time	Flammable (18.75 s)
Equipment	LPG storage vessel 18
Height of Interest	0 m
Material	LPG
Program	Phast 7.2
Scenario	Fixed duration release
Weather	Category 2/F
Workspace	updated FERA3

Fig 5: Maximum Cloud Concentration Footprint for 2/F Weather Condition due to Fixed Duration Release of LPG Vessel #18



Audit Number: 26986
Averaging time: Flammable (18.75 s)
Equipment: LPG storage vessel 18
Height of Interest: 0 m
Material: LPG
Program: Phast 7.2
Scenario: Fixed duration release
Weather: Category 2/F
Wind Direction: 0 deg
Workspace: updated FERA3

Fig 6: Maximum Cloud Concentration Footprint for 2/F Weather Condition due to Fixed Duration Release of LPG Vessel #18

Consequence of Explosion Overpressure

Figure 7 shows the overpressure contour envelope for multiple scenarios and weather direction

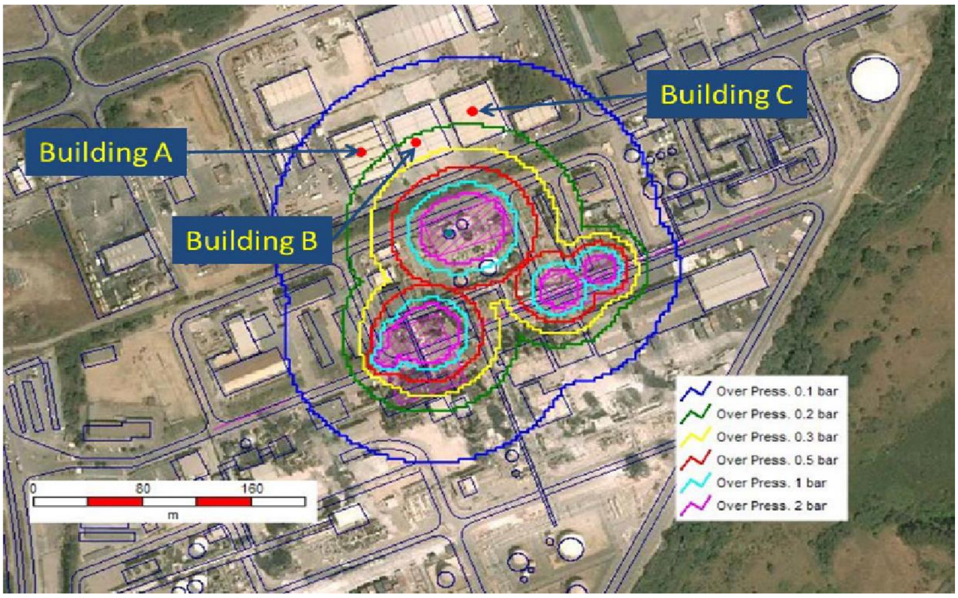


Fig 7: Side-on Overpressure Contour Envelope for Multiple Scenarios and Weather Directions

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Tables 21 and 22 show the results of Explosion overpressure versus distances for the various failure cases at different weather categories for both LPG storage vessel #18 and propane pressure vessel #22. Results from both tables show that the catastrophic rupture case of LPG vessel #18 with a weather category of 2/F has the highest overpressure effect contour/distance when compared to the other cases analysed. The hazard distance based on each of the overpressure selected were 850.57m (at 0.03bar), 251.793m (at 0.21bar) and 166.959m (at 0.7bar). An overpressure of 0.03barg was created at a distance of 850.57m downwind, which implies that all occupied buildings (non-blast) within this overpressure effect contour will experience significant repairable cosmetic damage and glass breakage as can be seen from Table 18. An overpressure of 0.21barg was created at a distance of 251.793m downwind, which implies that all occupied buildings within this overpressure effect contour will experience a collapse of their structure and thereby cause serious injury or fatality to many occupants as seen from Table 16. Also, an overpressure of 0.7barg was observed at a distance of 166.959 downwind, which implies that any occupied buildings (non-blast) within this overpressure effect contour will experience total destruction and Probable 100% fatalities of occupants as per seen in Table 18.

Table 21: Hazard Distance due to Explosion Overpressure Effect for LPG Pressure Vessel #18

LPG PRESSURE VESSEL #18					
S/no	**Failure case**	**Weather category**	**Consequence Downwind Distance (m)**		
			0.03barg	**0.21barg**	**0.70barg**
	Catastrophic Failure case	**4m/s C**	844.369	250.539	166.406
		2m/s F	850.57	251.793	166.959
	Full-bore rupture of 6inches discharge line case	**4m/s C**	378.531	156.314	128.177
		2m/s F	501.743	181.226	140.642
	Fixed duration release case	**4m/s C**	398.084	160.268	130.155
		2m/s F	470.276	174.864	137.459

Table 22: Hazard Distance due to Explosion Overpressure Effect for Propane Pressure Vessel #22

PROPANE PRESSURE VESSEL #22					
S/no	**Failure case**	**Weather category**	**Consequence Downwind Distance (m)**		
			0.03barg	**0.21barg**	**0.70barg**
	Catastrophic Failure	**4m/s C**	841.446	249.948	166.145
		2m/s F	847.526	251.177	166.688
2.	Full-bore rupture of 6inches discharge line	**4m/s C**	336.075	146.517	123.275
		2m/s F	361.454	152.862	126.45
3.	Fixed duration release	**4m/s C**	339.875	148.499	124.267
		2m/s F	358.322	152.299	126.133

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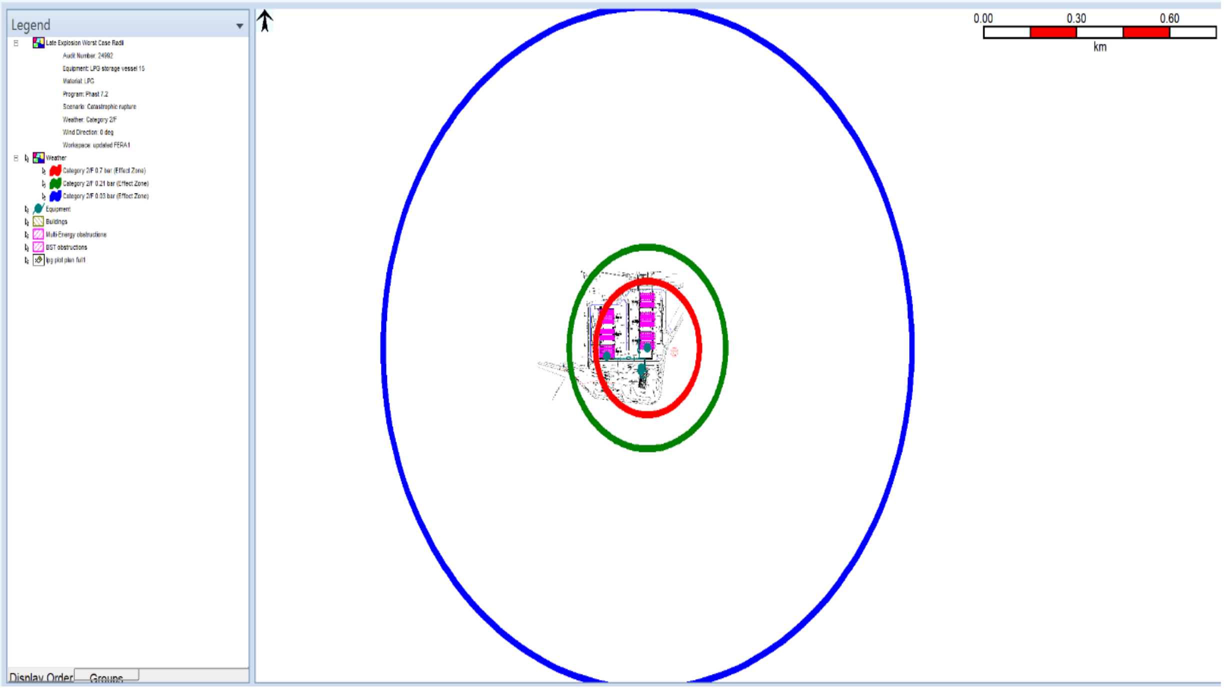
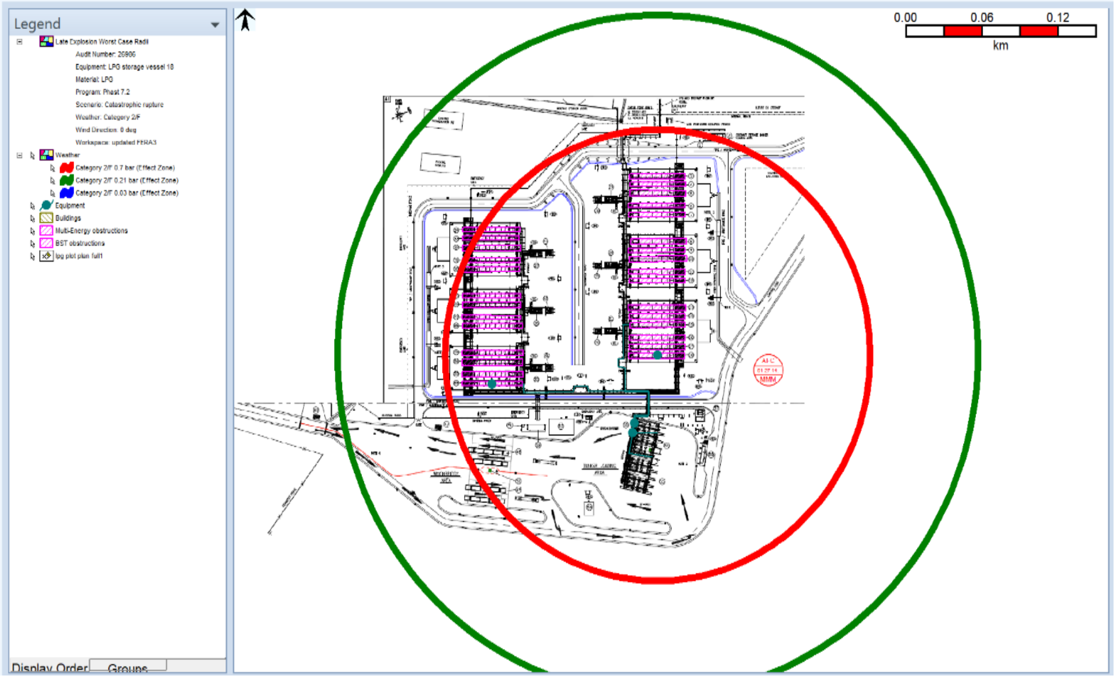


Legend
Late Explosion Worst Case Radii
Audit Number: 24992
Equipment: LPG storage vessel 15
Material: LPG
Program: Phast 7.2
Scenario: Catastrophic rupture
Weather: Category 2/F
Wind Direction: 0 deg
Workspace: updated FERA1
Weather
🟥 Category 2/F 0.7 bar (Effect Zone)
🟩 Category 2/F 0.21 bar (Effect Zone)
🟦 Category 2/F 0.03 bar (Effect Zone)
Equipment
Buildings
Multi-Energy obstructions
BST obstructions
lpg plot plan full1

Fig 8: Overpressure Region for 0.03 barg, 0.21barg and 0.7 barg Shock Wave due to Catastrophic Failure of LPG Vessel #18 for a Weather Category of 2/F



Legend
Late Explosion Worst Case Radii
Audit Number: 26986
Equipment: LPG storage vessel 18
Material: LPG
Program: Phast 7.2
Scenario: Catastrophic rupture
Weather: Category 2/F
Wind Direction: 0 deg
Workspace: updated FERA3
Weather
🟥 Category 2/F 0.7 bar (Effect Zone)
🟩 Category 2/F 0.21 bar (Effect Zone)
🟦 Category 2/F 0.03 bar (Effect Zone)
Equipment
Buildings
Multi-Energy obstructions
BST obstructions
lpg plot plan full1

Fig 9: Overpressure Contour of 0.7barg and 0.21barg Shock Wave due to Catastrophic Failure of LPG Vessel #18 for a Weather Category of 2/F

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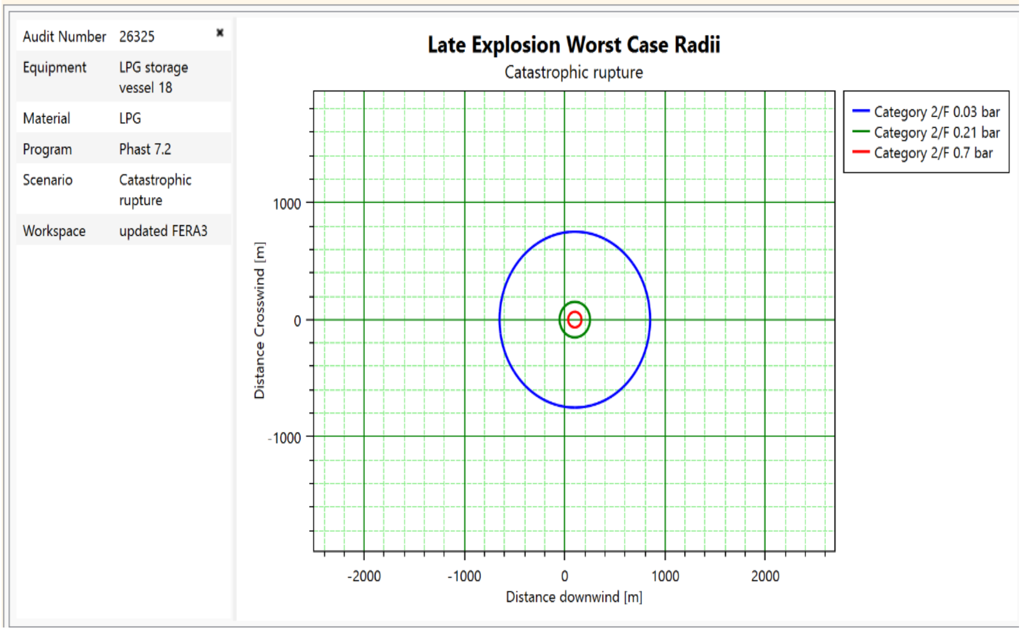


Audit Number	26325
Equipment	LPG storage vessel 18
Material	LPG
Program	Phast 7.2
Scenario	Catastrophic rupture
Workspace	updated FERA3

Fig 10: Explosion Worst Case Radii for Catastrophic Failure of LPG Vessel #18

Consequence of Thermal Radiation

Thermal radiation due to Jet fire

Tables 23 and 24 show the results of thermal radiation due to jet fire for the different failure cases and weather conditions for both LPG pressure vessel #18 and Propane pressure vessel #22. Based on the results, it can be deduced that the fixed duration release for Propane vessel #22 gave the highest intensity thermal load at a weather category of 2/F. The fixed duration release produced thermal radiation of 37.5 KW/m^2 at a hazard distance of 180.72 as seen in Table 24. This was observed to be the worst-case thermal radiation intensity at a maximum exposure duration of 20 seconds when contrasted with other thermal radiation levels. From Table 24, this thermal radiation intensity could cause 100% lethality to personnel because the building occupants will inevitably be exposed to intolerable temperatures indoors and evacuation will be impracticable, and the structural integrity of the building will be compromised if not designed to withstand such thermal load as well as damage to process equipment.

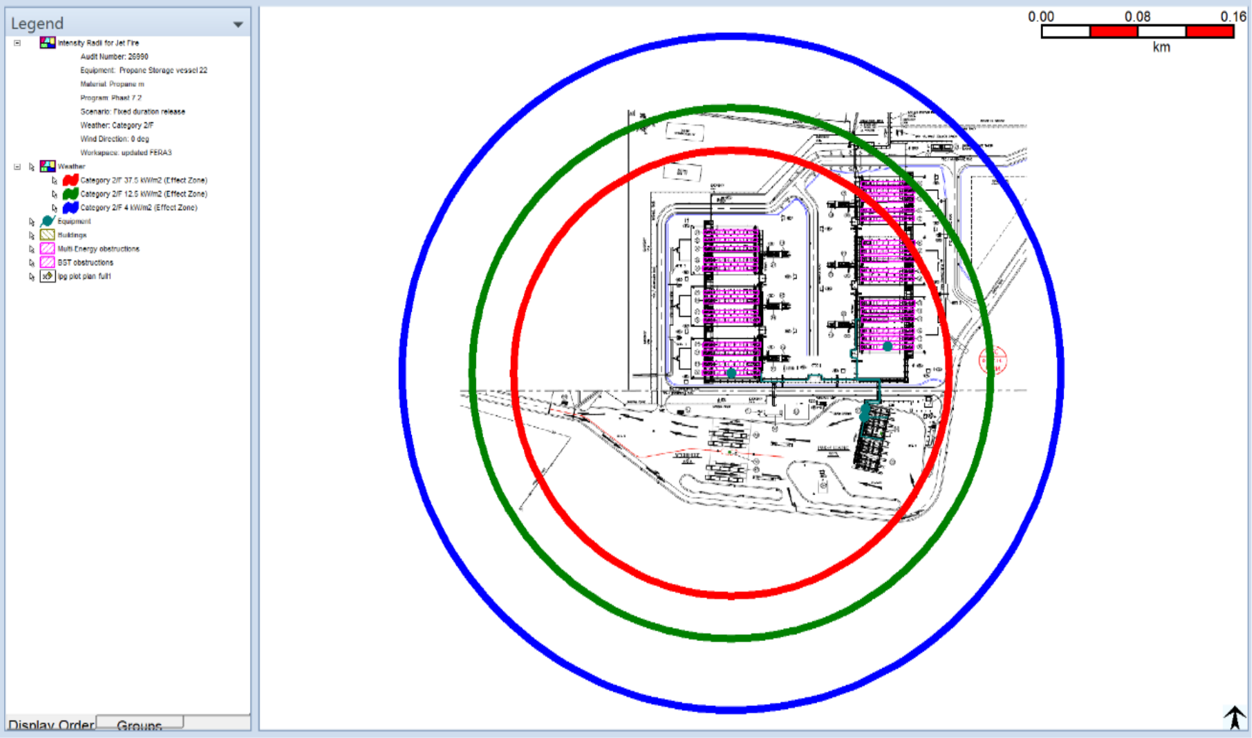
At thermal radiation of 12.5 KW/m^2, the fixed duration release produced a hazard distance of 215.246m as seen in Table 24 for 20 secs exposure duration. According to Table 18, this thermal radiation intensity could cause 1% lethality to personnel in 1min as well as the possibility of first-degree burn within 10 seconds and evacuation will be impeded. The building constructed with concrete/masonry will fail due to spalling, glass softening/crack, melting of plastic, and the furniture within the building is most likely to ignite. At thermal radiation of 4 KW/m^2, the fixed duration release produced a hazard distance of 273.331m as shown in Table 24 for 20 seconds exposure duration. According to Table 18, this thermal radiation intensity can affect personnel if the duration is longer than 20 sec.

Table 23: Hazard Distance due to Jet fire for LPG Pressure Vessel #18

LPG PRESSURE VESSEL #18						
S/no	**Failure case**	**Weather category**	**Flame length [m]**	**Consequence Downwind Distance (m)**		
				37.5 kW/m²	**12.5 kW/m²**	**4 kW/m²**
	Catastrophic Failure	**4m/s C**	No result	No result	No result	No result
		2m/s F	No result	No result	No result	No result
	Full-bore rupture of 6inches discharge line	**4m/s C**	78.9882	56.8917	78.0003	136.085
		2m/s F	95.7979	63.899	80.5435	136.552
	Fixed duration release	**4m/s C**	120.629	88.0542	122.567	213.298
		2m/s F	146.301	99.2318	128.337	218.142

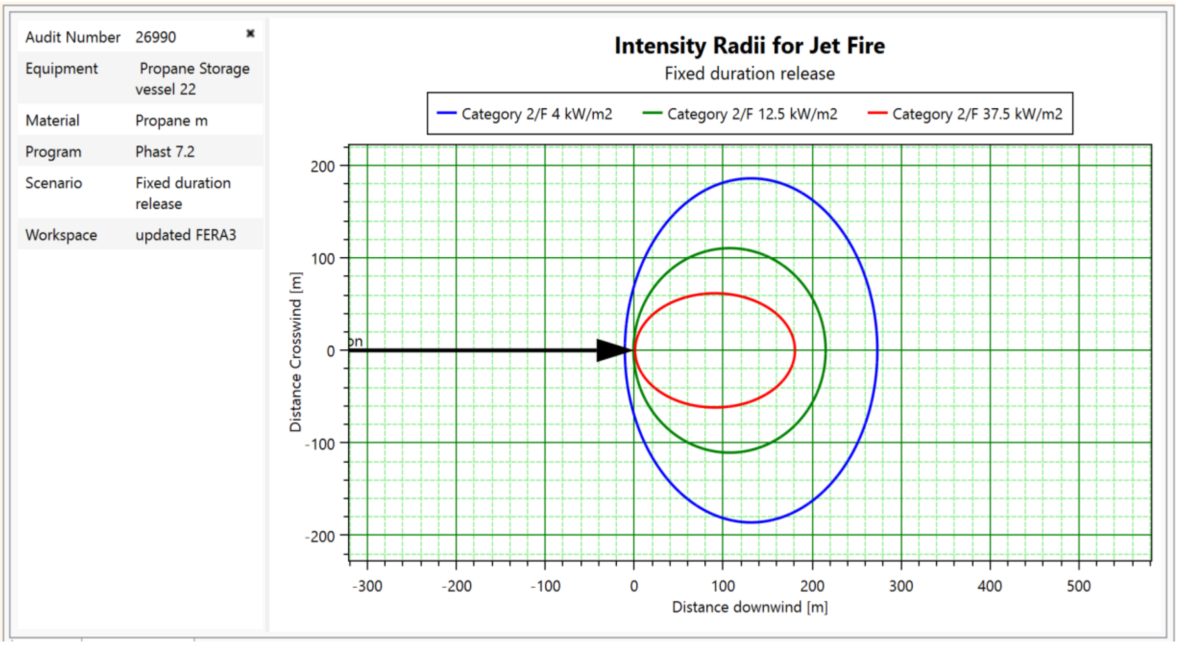
Table 24: Hazard Distance due to Jet fire for Propane Pressure Vessel #22

PROPANE PRESSURE VESSEL #22						
S/no	**Failure case**	**Weather category**	**Flame length [m]**	**Consequence Downwind Distance (m)**		
				37.5 kW/m²	**12.5 kW/m²**	**4 kW/m²**
	Catastrophic Failure	**4m/s C**	No result	No result	No result	No result
		2m/s F	No result	No result	No result	No result
	Full-bore rupture of 6inches discharge line	**4m/s C**	102.529	143.401	174.815	228.051
		2m/s F	124.348	163.164	194.186	246.378
	Fixed duration release	**4m/s C**	113.212	158.884	193.85	258.08
		2m/s F	137.305	180.72	215.246	273.331



Intensity Radii for Jet Fire
Audit Number: 26990
Equipment: Propane Storage vessel 22
Material: Propane m
Program: Phast 7.2
Scenario: Fixed duration release
Weather: Category 2/F
Wind Direction: 0 deg
Workspace: updated FERA3

Fig 11: Jet Fire Envelope due to Fixed Duration Release of Propane Vessel #22 for 2/F Weather Category



Audit Number	26990
Equipment	Propane Storage vessel 22
Material	Propane m
Program	Phast 7.2
Scenario	Fixed duration release
Workspace	updated FERA3

Fig 12: Intensity Radii for Jet Fire for Fixed Duration Release of Propane Vessel #22 for 2/F Weather Category.

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Thermal Radiation due to Fireball

Tables 25 and 26 show the results of thermal radiation due to fireball for the different failure cases and weather conditions for both LPG pressure vessel #18 and Propane pressure vessel #22. It can be deduced from both tables, that there was no fireball in other failure scenarios except for the case of catastrophic failure. From the results, the catastrophic rupture case for Propane vessel #22 gave the highest intensity thermal load at a weather category of 2/F.

At thermal radiation of 37.5 KW/m^2, the catastrophic failure of the Propane pressure vessel #22 produces a hazard distance of 191.986m (as shown in Table 26). This was observed to be the worst-case thermal radiation intensity at a maximum exposure duration of 20 secs when contrasted with other thermal radiation levels. According to Table 18, this thermal radiation intensity could cause 100% lethality to personnel, the building occupants will inevitably be exposed to intolerable temperatures indoors and evacuation will be impracticable. The structural integrity of the building will be compromised if not designed to withstand such thermal load and there can also be damage to process equipment. At thermal radiation of 12.5 KW/m^2, the catastrophic failure of the Propane pressure vessel #22 has a hazard distance of 495.767m as seen in Table 26 for a 20-second exposure duration. According to Table 18, this thermal radiation intensity could cause 1% lethality in 1min to personnel as well as first-degree burns within 10 seconds and evacuation will be impeded. The building constructed with concrete/masonry will fail due to spalling because such are not designed to withstand the thermal load. In addition, glass softening/cracking, melting of plastic, and ignition of furniture within the building are most likely to ignite. At thermal radiation of 4 KW/m^2, the catastrophic failure of the Propane pressure vessel #22 has a hazard distance of 914.854m as shown in Table 26 for a 20-second exposure duration. According to Table 18, this thermal radiation intensity can affect personnel if the duration is longer than 20 seconds.

Table 25: Hazard Distance due to Fireball for LPG Pressure Vessel #18

LPG PRESSURE VESSEL #18						
S/no	**Failure case**	**Weather category**	**Fireball diameter [m]**	**Consequence Downwind Distance (m)**		
				37.5 kW/m^2	**12.5 kW/m^2**	**4 kW/m^2**
	Catastrophic Failure	**4m/s C**	**311.837**	126.661	450.749	853.722
		2m/s F	**311.837**	135.081	458.68	867.587
	Full-bore rupture of 6inches discharge line	**4m/s C**	No result	No result	No result	No result
		2m/s F	No result	No result	No result	No result
	Fixed duration release	**4m/s C**	No result	No result	No result	No result
		2m/s F	No result	No result	No result	No result

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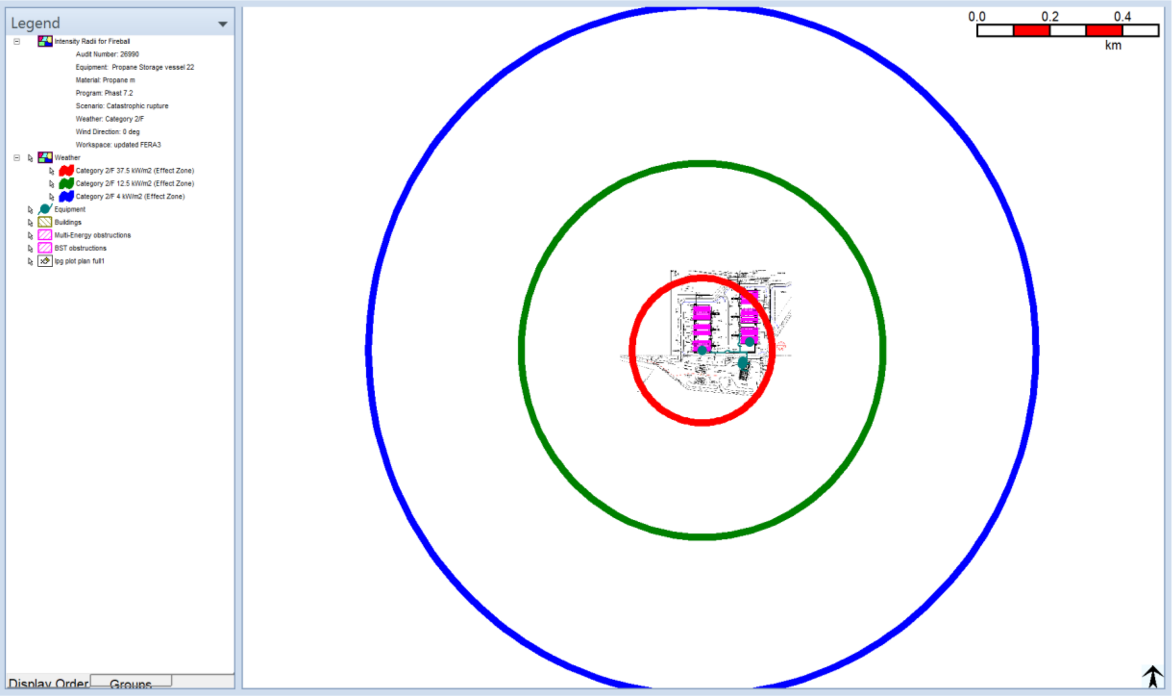
DOI URL: https://doi.org/10.52589/AJSTE-W7J0KWOC

Table 26: Hazard Distance due to Fireball for Propane Pressure Vessel #22

PROPANE PRESSURE VESSEL #22						
S/no	**Failure case**	**Weather category**	**Fireball diameter [m]**	**Consequence Downwind Distance (m)**		
				37.5 kW/m²	**12.5 kW/m²**	**4 kW/m²**
	Catastrophic Failure	**4m/s C**	299.1	185.439	487.611	900.275
		2m/s F	299.1	191.986	495.767	914.854
	Full-bore rupture of 6inches discharge line	**4m/s C**	No result	No result	No result	No result
		2m/s F	No result	No result	No result	No result
	Fixed duration release	**4m/s C**	No result	No result	No result	No result
		2m/s F	No result	No result	No result	No result



Audit Number: 26990
Equipment: Propane Storage vessel 22
Material: Propane m
Program: Phast 7.2
Scenario: Catastrophic rupture
Weather: Category 2/F
Wind Direction: 0 deg
Workspace: updated FERA3

Fig 13: Zone of Thermal Radiation Intensity Levels due to Fireball from Catastrophic Failure of Propane Pressure Vessel #22.

Table 27: Failure Cases and Consequences

S/no	Failure cases	Pressure vessel	Consequences
	Catastrophic rupture cases	LPG pressure vessel #18	**Dispersion, Explosion and Fireball**
		Propane Pressure vessel #22	**Dispersion, Explosion and Fireball**
	Full-bore rupture of 6inches discharge line cases	LPG pressure vessel #18	**Dispersion, Explosion and Jet fire**
		Propane Pressure vessel #22	**Dispersion, Explosion and Jet fire**
	Fixed duration release cases	LPG pressure vessel #18	**Dispersion, Explosion and Jet fire**
		Propane Pressure vessel #22	**Dispersion, Explosion and Jet fire**

The Maximum Credible Event (MCE) From Failure Cases

The failure cases that produce the greatest impact/consequence both to occupied buildings and its occupants were selected as the maximum credible event (MCE) and can be seen in Table 29.

Table 28: Maximum Credible Events from all Major Scenario cases

S/no.	Failure scenario	Consequence	Consequence level	Impact distance
1	Fixed duration release of LPG vessel #18 at 2/F weather category	Dispersion and flash fire	8,522.46ppm (LFL)	894.885m
2	Fixed duration release of Propane vessel #22 at 2/F weather category	Jet fire thermal radiation	37.5 kW/m^2	180.72m
3	Catastrophic failure of the Propane pressure vessel #22 at 2/F weather category	Fireball thermal radiation	37.5 kW/m^2	191.986m
4	Catastrophic rupture case of LPG vessel #18 at 2/F weather category	Explosion overpressure	0.7bar	166.959m

Impact of Occupied Buildings due to Maximum Credible Events

The occupied buildings in the vicinity of the LPG and Propane storage and dispensing facility can be potentially affected by the hazardous outcomes depending on the consequence distances.

The maximum dispersion is due to the Fixed duration release case of LPG Vessel #18 at a weather category of 2/F, which gives a maximum LFL fraction hazard distance of 894.885m

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at a concentration of 8,522.46 ppm. Based on the modelling, the flash fire envelope covers the dispersion distance thus all occupied buildings within the facility will be affected but at a shorter duration than a fireball as shown in Figures 14 and 15. Jet fire due to fixed duration release of Propane vessel #22 at 2/F weather category produces a flame length of 137.305 m and thermal radiation of 37.5 kW/m^2 at 180.72m hazard distance. This will affect all occupied buildings (Dispatch office, Control room, Weighbridge operator cabin, Security cabin, Drivers waiting room and Loading bay cabin) within the facility. This is shown in Figure 16.

Fireball due to catastrophic rupture of propane vessel #22 at 2/F weather category has fireball diameter of 299.1 m and thermal radiation of 37.5 kW/m^2 at 191.986m, as shown in Figure 17 and can reach all occupied buildings (Dispatch office, Control room, Weighbridge operator cabin, Security cabin, Drivers waiting room and Loading bay cabin) within the facility but at a short duration. Explosion due to catastrophic rupture of LPG vessel #18 at 2/F weather category produces an overpressure effect of 0.7barg at 166.959m hazard distance as seen in Figure 18 and can affect all occupied buildings (Dispatch office, Control room, Weighbridge operator cabin, Drivers waiting room and Loading bay cabin) within the facility except Security cabin and Dispatch cabin. The failures and accompanying consequences are shown in Figure 27.

Table 29: Maximum Credible Events and Building Structures

S/no.	Failure scenario	Consequence	Consequence level	Impact distance	Affected occupied buildings
1	Fixed duration release of LPG vessel #18 at 2/F weather category	Dispersion and flash fire	8,522.46ppm (LFL)	894.885m	All occupied buildings within the facility will be affected
2	Fixed duration release of Propane vessel #22 at 2/F weather category	Jet fire thermal radiation	37.5 kW/m^2	180.72m	All occupied buildings within the facility will be affected
3	Catastrophic failure of the Propane pressure vessel #22 at 2/F weather category	Fireball thermal radiation	37.5 kW/m^2	191.986m	All occupied buildings within the facility will be affected
4	Catastrophic rupture case of LPG vessel #18 at 2/F weather category	Explosion overpressure	0.7barg	166.959m	All occupied buildings except the Security cabin and Dispatch cabin

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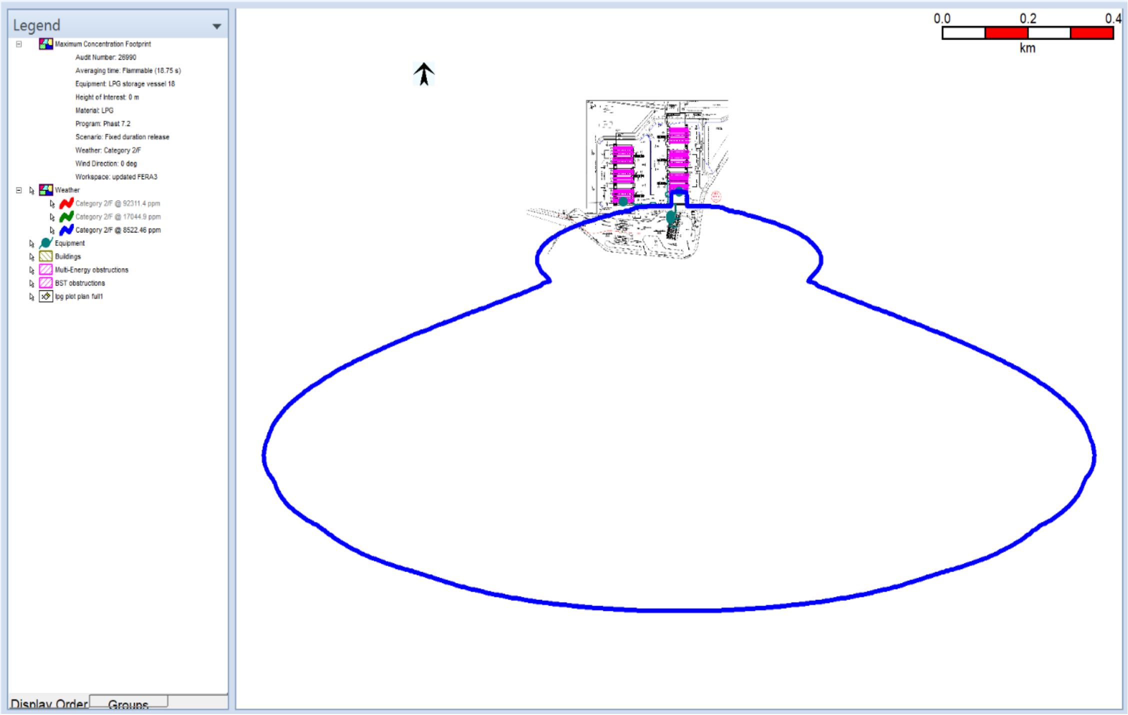
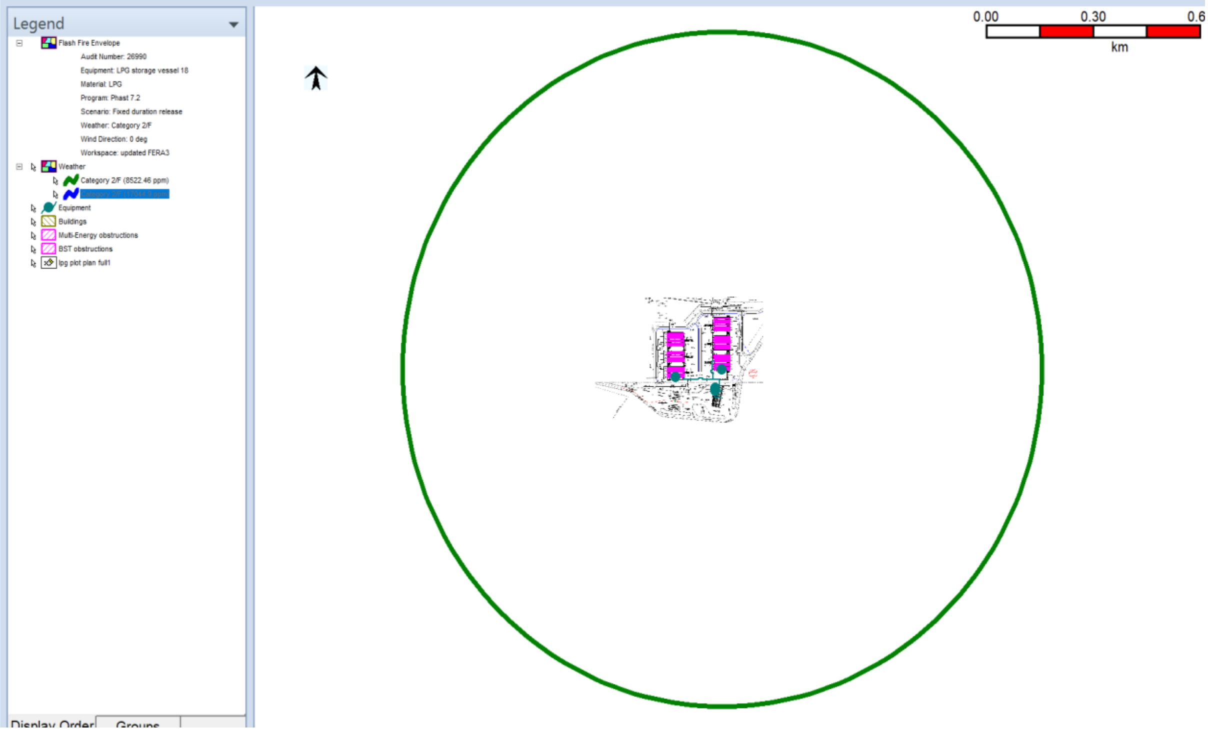


Maximum Concentration Footprint
Audit Number: 26990
Averaging time: Flammable (18.75 s)
Equipment: LPG storage vessel 18
Height of Interest: 0 m
Material: LPG
Program: Phast 7.2
Scenario: Fixed duration release
Weather: Category 2/F
Wind Direction: 0 deg
Workspace: updated FERA3
Weather
Category 2/F @ 92311.4 ppm
Category 2/F @ 17044.9 ppm
Category 2/F @ 8522.46 ppm
Equipment
Buildings
Multi-Energy obstructions
BST obstructions
lpg plot plan full1

Fig 14: GIS showing maximum cloud concentration footprint at a concentration of 8522.46ppmat 2/F weather condition due to fixed duration release of LPG Vessel #18



Flash Fire Envelope
Audit Number: 26990
Equipment: LPG storage vessel 18
Material: LPG
Program: Phast 7.2
Scenario: Fixed duration release
Weather: Category 2/F
Wind Direction: 0 deg
Workspace: updated FERA3
Weather
Category 2/F (8522.46 ppm)
Category 2/F (17044.9 ppm)
Equipment
Buildings
Multi-Energy obstructions
BST obstructions
lpg plot plan full1

Fig 15: Impacted Zone of Flash Fire Envelope due to Fixed Duration Release of LPG Vessel #18 at 2/F Weather Category

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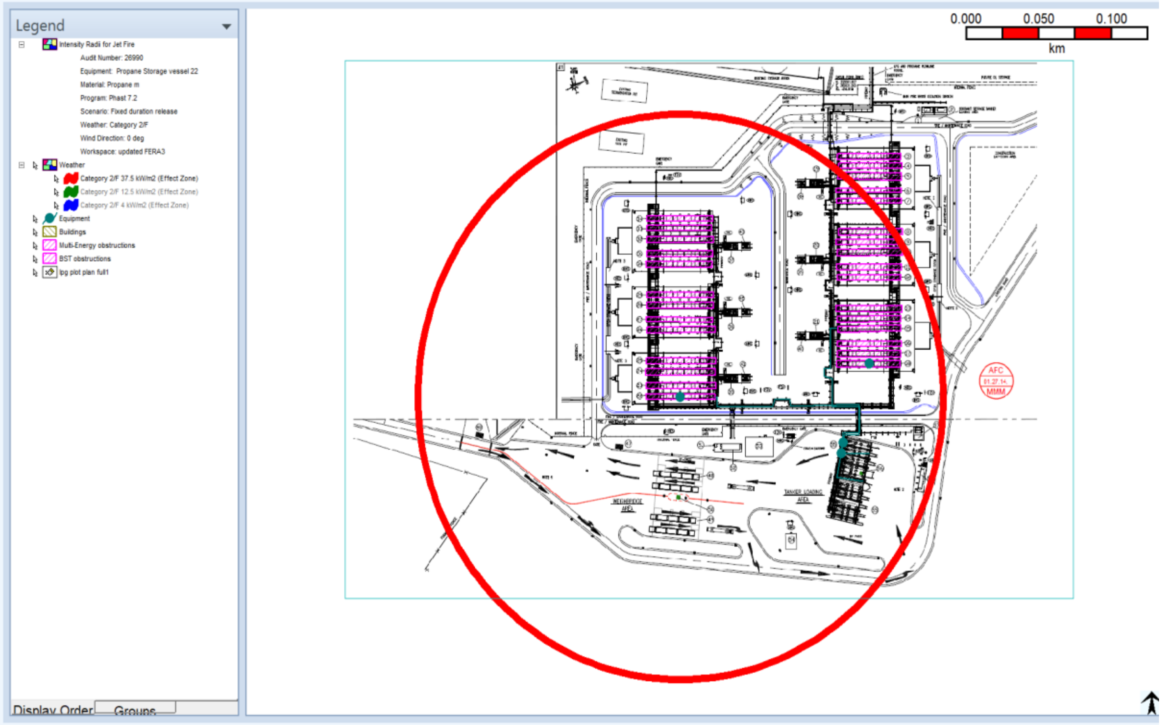


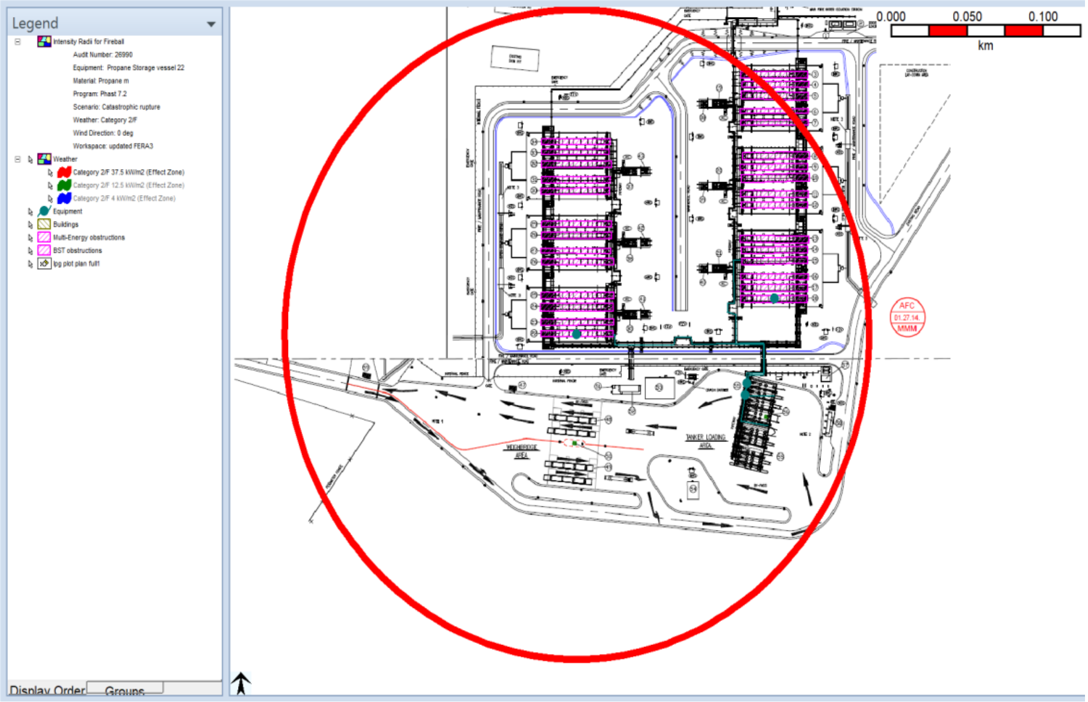
Legend

Intensity Radii for Jet Fire
Audit Number: 26990
Equipment: Propane Storage vessel 22
Material: Propane m
Program: Phast 7.2
Scenario: Fixed duration release
Weather: Category 2/F
Wind Direction: 0 deg
Workspace: updated FERA3

Weather
🟥 Category 2/F 37.5 kW/m2 (Effect Zone)
🟩 Category 2/F 12.5 kW/m2 (Effect Zone)
🟦 Category 2/F 4 kW/m2 (Effect Zone)

Equipment
Buildings
Multi-Energy obstructions
BST obstructions
lpg plot plan full1

Fig 16: Impacted Zone of Thermal Radiation Intensity of 37.5 kW/m^2 due to Jet Fire from Fixed Duration Release of Propane Vessel #22 at 2/F Weather Category



Legend

Intensity Radii for Fireball
Audit Number: 26990
Equipment: Propane Storage vessel 22
Material: Propane m
Program: Phast 7.2
Scenario: Catastrophic rupture
Weather: Category 2/F
Wind Direction: 0 deg
Workspace: updated FERA3

Weather
🟥 Category 2/F 37.5 kW/m2 (Effect Zone)
🟩 Category 2/F 12.5 kW/m2 (Effect Zone)
🟦 Category 2/F 4 kW/m2 (Effect Zone)

Equipment
Buildings
Multi-Energy obstructions
BST obstructions
lpg plot plan full1

Fig 17: Impacted Zone of Thermal Radiation Intensity of 37.5 KW/m^2 due to Fireball from Catastrophic Failure of the Propane Pressure Vessel #22 at 2/F Weather Category

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Late Explosion Worst Case Radii
Audit Number: 26990
Equipment: LPG storage vessel 18
Material: LPG
Program: Phast 7.2
Scenario: Catastrophic rupture
Weather: Category 2/F
Wind Direction: 0 deg
Workspace: updated FERA3

Fig 18: Impacted Zone of Explosion Overpressure Contour of 0.7bar due to Catastrophic Rupture case of LPG vessel #18 at 2/F Weather Category

IMPLICATION TO RESEARCH AND PRACTICE

The implications arising from this work include among several things,

1. It will enable the company or facility under consideration to evaluate the situation of the occupied buildings within it and whether they are at safe distances from any incidence of fire or explosion that may occur.
2. Aid in carrying out fire and gas mapping study of the LPG Storage and loading facility for the purpose of providing credible detector coordinates to enable early detection, warning and response with respect to gas leakage and fire breakout.
3. It will enable design and civil engineers to decide on what modifications/adjustments may need to be put in place to prevent or mitigate the devastating impact of an explosion on the occupied buildings.
4. It will increase the confidence level of plant operators and field personnel regarding their personnel safety.
5. It will assist in satisfying the requirements of recognised and generally accepted good engineering practices (RAGAGEP)

CONCLUSION

In line with the aim of this study, a consequence analysis was carried out using the PHAST simulation software. Based on the hypothetical event scenarios evaluated and results obtained, it can be concluded that the thermal radiation intensity of 37.5 kW/m^2 due to Jet fire from the Fixed duration release of Propane vessel #22 at 2/F weather category has the greatest consequence when compared to results from flash fire and fireball as they are only short-lived. This implies that all the occupied buildings within the facility that are in the vicinity/effect zone of the thermal radiation contour will suffer structural integrity damage if not designed to withstand such a thermal load. Furthermore, occupants of the buildings will inevitably be exposed to intolerable temperatures indoors and evacuation will be impracticable. Any personnel outdoor are most likely to suffer from 100% lethality.

Also, the explosion overpressure effect with the greatest consequence of 0.7barg was due to the catastrophic rupture of LPG vessel #18 at 2/F weather category. This overpressure effect will impact all the occupied buildings with the overpressure effect contour except that of the security cabin and the dispatch office. This implies that all occupied buildings (non-blast) within this overpressure effect contour will experience total destruction and Probable 100% fatalities of occupants.

Based on the above, it is crucial that the building citing evaluation be considered at the design stage when the facility layout plan is being developed so as to reduce the severe impact to occupied buildings from Maximum Credible Events. All portable occupied buildings (portacabins) within the maximum credible event consequence zone would need to be replaced with blast building capable of withstanding the least overpressure of 0.7barg or have a blast wall that is capable of withstanding a minimum overpressure of 0.7barg installed between the portable buildings. Also, to prevent an explosion due to BLEVE at the LPG and Propane storage facility, mounded storage bullets will be required. In addition to the use of fixed fire protection systems like water deluge for cooling of the LPG and Propane vessels to prevent BLEVE from occurring due to flame impingement from the jet fire of adjacent vessels, the use of diesel/AGO operated vehicles/trucks equipped with spark arresters within the LPG Storage and loading facility would be sacrosanct. Appropriate safety instrumented system (SIS) should always be considered to prevent or control releases e.g. Fire and gas/emergency shutdown systems. The SIS system should be based upon enforcement of the prescribed maintenance/testing programs in order to achieve a frequency reduction credit.

FUTURE RESEARCH

Future research would apply the Risk-based approach in which a wide variety of scenarios is taken into consideration and where the frequency of occurrence is determined for each scenario. In this approach, the frequency of the initial release and the Probability distribution of the quantity and location of the release, in addition to the Probability of ignition for both explosion and fire hazards will be taken into account along with the Probability of the atmospheric parameters which include wind direction, atmospheric stability etc.

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