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# Quantitative Health, Safety and Economic Risk Assessment of LPG Refilling Stations in Abia, Bayelsa and Delta State under BLEVE Scenarios

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***Abstract- Liquefied Petroleum Gas (LPG) refilling stations are increasingly established across Abia, Bayelsa and Delta States to meet rising domestic and industrial energy demands. However, the potential occurrence of Boiling Liquid Expanding Vapour Explosion (BLEVE) presents significant health, safety and economic risks, particularly in densely populated areas. This study presents a quantitative risk assessment of selected LPG refilling stations across Abia, Bayelsa and Delta States using fireball modelling and probit analysis to estimate thermal radiation impacts, fatality probability, injury levels and economic loss.Key parameters evaluated include fireball radius, duration, lift height, LPG capacity, mass, surface emissive power, heat flux, thermal dose and projected fragment distance. Results show that fireball radii ranged from 41.6 m to 616.9 m, while fireball duration varied between 6.5 s and 56.7 s depending on LPG capacity. Larger installations such as IM1 (2000 m³ equivalent capacity) generated fireball lift heights exceeding 1200 m with high fatality probit values (>3.8). In nearly all cases, the distance from fireball centre to target object exceeded the measured object distance (X > D), indicating substantial thermal radiation impact and potential economic damage. Fragment effects were generally insignificant due to short projected fragment distances relative to object distance. The findings demonstrate that thermal radiation from BLEVE poses severe life safety and asset risks, particularly for high-capacity installations located near populated or commercial structures. The study underscores the need for stricter siting regulations, improved setback distances, and enhanced emergency preparedness planning for LPG infrastructure in Nigeria.***

***Index Terms- Liquefied Petroleum Gas; BLEVE; Fireball modelling; Thermal radiation; Probit analysis; Quantitative risk assessment; Process safety; Nigeria***

## I. INTRODUCTION

### 1.1 Background

Liquefied Petroleum Gas (LPG) has emerged as one of the fastest-growing energy sources in Nigeria over the past decade, driven by its relative affordability, portability, ease of storage, and lower carbon emissions compared to traditional fuels such as firewood, charcoal, and kerosene. As concerns over deforestation, indoor air pollution, and climate change intensify, LPG has been widely promoted by government agencies and energy stakeholders as a cleaner and more sustainable cooking alternative. National policies encouraging a transition to clean household energy, combined with private sector investment in downstream gas infrastructure, have significantly expanded LPG availability across both urban and semi-urban regions. In Southern Nigeria—particularly in Edo, Imo, Ondo, Delta, Bayelsa, Rivers, and Abia States—urban expansion, rising population density, and increased commercial activities have stimulated rapid proliferation of LPG storage and refilling stations [1-4].

This expansion has improved access to cleaner cooking fuel and supported economic activities such as food services, small-scale industries, and transportation. However, the accelerated development of LPG infrastructure has also introduced heightened safety concerns. In many instances, refilling stations are established within densely populated neighborhoods where residential buildings, schools, markets, healthcare facilities, and major roadways exist in close proximity to pressurized storage tanks. Such siting practices increase the potential exposure of large populations to accidental releases and major fire events [5-9].

Despite its environmental and economic advantages, LPG presents significant hazards because it is stored under pressure in liquid form. Under normal operating conditions, LPG remains stable within engineered containment systems. However, when containment integrity is compromised—due to mechanical failure, corrosion, poor maintenance, external fire exposure, impact damage, or over-pressurization—the consequences can be catastrophic. One of the most severe accident scenarios associated with pressurized hydrocarbon storage is the Boiling Liquid Expanding Vapour Explosion (BLEVE). A BLEVE occurs when a vessel containing superheated liquid ruptures suddenly, leading to rapid depressurization and instantaneous flash vaporization of the liquid contents. The sudden phase transition generates a powerful explosion accompanied by the formation of a large fireball [10-14].

The physical effects of a BLEVE are multidimensional and often devastating. Immediate vessel rupture may result in intense blast overpressure capable of damaging nearby structures. The expanding vapor cloud can ignite, producing a fireball that emits high levels of thermal radiation over a considerable radius. This thermal radiation can cause severe burn injuries, ignite secondary fires, and compromise structural integrity of adjacent buildings. In addition, fragments of the ruptured vessel may be projected over significant distances, posing further injury and impact hazards. The combined effects—blast, heat, and projectiles—create a complex hazard environment that can result in multiple fatalities, critical injuries, long-term health consequences, infrastructure destruction, business interruption, and substantial economic loss [15-17].

In developing regions, including many parts of Southern Nigeria, rapid urbanization frequently outpaces regulatory planning and land-use control. Informal development patterns and high land demand often lead to hazardous facilities being sited without adequate separation distances from vulnerable receptors. In some cases, setback requirements may exist within national or local guidelines but are weakly enforced. Additionally, limited application of advanced hazard modelling tools during licensing and approval processes reduces the ability of authorities to accurately predict impact zones associated with worst-case scenarios. Emergency response capacity may also be constrained by traffic congestion, limited firefighting resources, and inadequate public awareness of evacuation procedures [18-23].

These contextual factors significantly amplify the potential societal consequences of LPG-related accidents. As storage capacities increase to meet growing demand, the magnitude of possible fireball events and thermal radiation footprints also increases. Without systematic evaluation, communities and regulators may underestimate the scale of potential impact [24-26].

Consequently, a structured Quantitative Risk Assessment (QRA) approach is essential to evaluate both the likelihood and consequences of BLEVE scenarios in rapidly urbanizing environments. QRA provides a scientific basis for estimating fireball dimensions, radiation intensity, fatality probability, and economic loss, while integrating failure frequency data to determine individual and societal risk levels. Such analysis supports evidence-based decision-making, informs siting criteria, strengthens regulatory standards, and enhances public safety planning. In the context of expanding LPG infrastructure in Southern Nigeria, the application of QRA is not only technically appropriate but critically necessary for sustainable and safe energy development [27-30].

1.2 Nature of BLEVE Hazards

i. A BLEVE typically occurs when:
ii. A pressurized vessel containing LPG is exposed to external fire.
iii. The liquid inside boils due to heat input.
iv. Internal pressure rises beyond vessel strength.
v. Catastrophic rupture occurs.

The primary hazard mechanisms include:
vi. Thermal radiation from fireball
vii. Overpressure shockwave
viii. Missile fragments from vessel rupture
ix. Secondary fires

Thermal radiation is often the dominant life-threatening effect. The severity of injury depends on heat flux intensity and exposure duration, typically evaluated using thermal dose models and probit equations.

1.3 Fireball Modelling Parameters

When a BLEVE occurs, a fireball forms with characteristics dependent on LPG mass. Empirical correlations are commonly used to determine:

Fireball radius (R)
Fireball duration (t)
Fireball lift height (H)
Surface emissive power (SEP)
Heat flux (q)
Thermal dose (k)

Thermal dose is commonly expressed as:

$$k = q^{4/3} x\, t \qquad (1)$$

Probit models are then applied to estimate fatality probability:

$$Y = a + b ln\,(k) \qquad (2)$$

Where:
Y = Probit value
k = thermal dose
a, b = empirical constants

A probit value of 5 corresponds approximately to 50% fatality probability. Values between 3 and 4 indicate lower but significant injury/fatality risk.

1.4 Problem Statement

Many LPG refilling stations in Southern Nigeria are installed within short distances (10–45 m) from target objects such as buildings or populated areas. However, the potential impact radius of a BLEVE fireball may exceed 150 m in medium installations and over 600 m in high-capacity facilities.

There is limited publicly available quantitative assessment of:

- Expected fireball size for existing LPG capacities
- Fatality probabilities
- Thermal radiation exposure
- Economic damage potential

Without such analysis, regulatory setback distances may be inadequate.

1.5 Aim and Objectives

This study aims to quantitatively evaluate health, safety and economic impacts of BLEVE scenarios at selected LPG refilling stations in Southern Nigeria.
Specific objectives include:

- Determination of fireball characteristics (radius, duration, lift height).
- Calculation of heat flux and thermal dose.
- Estimation of fatality and injury probabilities using probit models.
- Assessment of damage potential to nearby target objects.
- Evaluation of economic implications of thermal damage.

1.6 Study Coverage

Stations analysed include:

i. Abia (AB1)
ii. Bayelsa (BA1–BA6)
iii. Delta (DT1–DT2)

Capacities range from small installations (5–50 units) to large storage systems (up to 5000–20000 equivalent units).

1.7 Significance of the Study

This research provides:

- A scientific basis for LPG station siting regulations.
- Evidence for enforcing minimum separation distances.
- Guidance for emergency response planning.
- Quantitative justification for insurance and economic loss estimation.
- Policy recommendations for urban energy infrastructure development.

Given Nigeria's expanding LPG adoption policy, such analysis is essential for sustainable and safe implementation.

## II. METHODOLOGY

Study Area and Data Collection

LPG refilling stations across Abia, Bayelsa, Delta, Edo, Imo, Ondo and Rivers States were analysed. Data collected include:

i. LPG storage capacity (V)
ii. Estimated LPG mass (M)
iii. Measured distance to nearest target object (D)
iv. Station identification code
v. Capacities ranged from small installations (5–50 units equivalent) to very large storage systems (2000–5000 units).

QRA Framework

A full Quantitative Risk Assessment (QRA) was conducted to estimate both the likelihood and consequences of BLEVE scenarios at selected LPG refilling stations. The QRA methodology followed internationally recognized frameworks including CCPS [3], TNO Purple Book [7], and HSE risk criteria guidelines.

Risk was defined as:

$$\text{Risk} = \text{Frequency x Consequence}$$

The QRA comprised:

1. Hazard identification
2. Scenario selection
3. Frequency analysis
4. Consequence modelling (fireball, radiation, probit)
5. Individual risk estimation
6. Societal risk evaluation
7. Risk acceptability comparison

Evaluation of Failure Rate (EOFR)[1]

The evaluation of the failure rate of the LPG refilling stations studied can be determined using the mathematical formula stated below

$$(EOFR)^1 = \frac{1}{E^1{}_{MTBF}} = \frac{1}{S^1/N^1} = \frac{N^1}{S^1} \qquad (4)$$

For various units of the plant, we have

$$(EOFR)^1 = \left(\frac{1}{E^1{}_{MTBF}}\right) = \left(\frac{N^1}{S^1}\right)_{Tunit} \qquad (5)$$

Evaluation of Total Failure Rate (EOTFR)[1]

The evaluation of the total failure rate of the units can be expressed mathematical as:

$$(EOFR)^1 = (EOFR)^1_{Tunit\,A} + (EOFR)^1_{Tunit\,B} + (EOFR)^1_{Tunit\,C} + (EOFR)^1_{Tunit\,D} \qquad (6)$$

Calculations For AB1

$V = 60\,m^3$

D = 12m

$R_b = c_9\ m^{0.325}$

$c_9 = 3.24$

$t = c_{10} \text{ x } m^{0.26}$

$c_{10} = 0.852$

$t = 0.852 \text{ x } 31020^{0.26} = 12.53s$

M= 517 x 60 = 31020kg

$R_b = 3.24 \text{ x} 28.82 = 93.3$ m

$H_{BLEVE}$ = 186.6 m = Lift-off height of fireball

$X = \sqrt{12^{2+H_{BLEVE}{}^2}}$ = Distance from the center of the fireball to the object

$X = \sqrt{34963.56} = 186.98$

x =X-Rb=93.3m

$\text{Fview} = \frac{93.3^2}{186.6^2} = 0.25$

$$SEP = \frac{\Delta Hc\,x\,m\,x\,Fs}{4\pi x R_{fb}{}^2\,x\,t} = \frac{46.013\,x\,10^6\ \ x31020\ x0.246}{\pi x4\ x93.3^2\ x12.53} =$$

2561397.71 $J/m^2 s$

q = 2561397.71 x 0.25 x 0.7335 = 469696.17 $J/m^2 s$

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k =437993330.2 kw/$m^2$ 4/3 s = Thermal dose

$M_l$ = 0.80 x 60/0.001752 = 0.8 x Volume of sphere x $v_{fl}$ =
$M_l$= 0.80x60x0.001752= 0.0084095kg
$M_g$ = 0.20 x 60/0.029076 = 20/100 x volume of sphere x $v_{g1}$ =
$M_g$ = 0.20x60x0.029076= 0.3489kg
$M_f$ = 0.0084+ 0.348/2= 0.1782
$E_{av}$ = $W_{av}$ x M = Explosion energy
$E_{avl}$ = $W_{avl}$ x $M_l$ = -100.55 x$10^3$ x 0.0084095= -845 MJ
$E_{avg}$ = $W_{avg}$ x $M_g$ = 13.72 x$10^3$ x 0.3489=4786.90 MJ
$E_{avtotal}$ = $E_{avl}$ + $E_{avg}$ = 3941 MJ
Effective Blast energy 2 x 3941 MJ
R= 12x 0.101x$10^6$/3941 x2 = 153.76= 5.35

$$d=\sqrt[3]{\frac{Vx6}{\pi}}$$

d = 4.84

$C_A$ $A_D$ = 0.615 x $\frac{\pi}{4}$ $d^2$ = 11.31

$$R=\frac{P_a\ C_D A_D R_i}{M_f}$$

$$R_i=\frac{5.35\ x 0.1782}{1.20\ x 11.31}=0.07\text{m}$$

Calculations For BA1

$V=100m^3$ = Volume of storage tank
D = 10m = Distance to target object
$R_b = c_9\ m^{0.325}$ = Radius of fireball
$c_9$ = 3.24
t = $c_{10}$ x $m^{0.26}$ = Time of BLEVE
$c_{10}$ = 0.852
t = 0.852 x $51700^{0.26}$= 14.32s
M= 517 x 100 = 51700kg = Mass of LPG
$R_b$ = 3.24 x34.03= 110.26 m
$H_{BLEVE}$ = 220.5m

$$X=\sqrt{10^{2+H_{BLEVE}^2}}$$

$X=\sqrt{48500}$ = 220.2
x = 109.9

$$\text{Fview}=\frac{110^2}{220.2^2}=0.249$$

$$SEP=\frac{\Delta Hc\,x\,m\,x\,Fs}{4\pi x R_{fb}^2\,x\,t}=\frac{46.013\,x10^6\ \ x51700\,x0.246}{\pi x4\,x110.2^2\,x14.32}=$$

203109.3 J/$m^2$ s
q = 203109.3 x 0.249 x 0.7335 = 37096 J/$m^2$ s

k =1194551.8 kw/$m^2$ 4/3 s

$M_l$ = 0.80 x 100x0.001752 = 0.8 x Volume of sphere x $v_{fl}$ =
$M_l$= 0.80x100x0.001752= 0.1405kg = Fractional Mass of Liquid LPG
$M_g$ = 0.20 x 100/0.029076 = 20/100 x volume of sphere x $v_{g1}$ =
$M_g$ = 0.20x100x0.029076= 0.581kg = Fractional Mass of gas LPG
$M_f$ = 0.1405+0.581/2= 0.360= Mass of fragment on the explosion
$E_{av}$ = $W_{av}$ x M = Explosion energy
$E_{avl}$ = $W_{avl}$ x $M_l$ = -100.55 x$10^3$ x 0.1405= -14127.2 MJ = Explosion energy for saturated liquid
$E_{avg}$ = $W_{avg}$ x $M_g$ = 13.72 x$10^3$ x 0.581=7971.32 MJ = Explosion energy for saturated vapour
$E_{avtotal}$ = $E_{avl}$ + $E_{avg}$ = -6155 MJ= Total explosion energy
Effective Blast energy 2 x 6155= 12311.36 MJ
R= 10x 0.101x$10^6$/12311.36 = 153.76= 4.34

$d=\sqrt[3]{\frac{Vx6}{\pi}}$= diameter of LPG storage tank

d = 5.74

$C_D$ $A_D$ = 0.615 x $\frac{\pi}{4}$ $d^2$ = 15.96= Drag and lift fragments (tumbling)
$C_D$ = drag coefficient
$A_D$ = Exposed area in a plane perpendicular to the trajectory

$R=\frac{P_a\ C_D A_D R_i}{M_f}$ = Scaled maximal range

$R_i=\frac{4.34\ x 0.360}{1.20\ x 15.96}$= 0.0815m = Maximal range to target

Calculations For BA2

$V=10m^3$ = Volume of storage tank

D = 25m = Distance to target object

$R_b = c_9 \ m^{0.325}$ = Radius of fireball

$c_9 = 3.24$

t = $c_{10}$ x $m^{0.26}$ = Time of BLEVE

$c_{10} = 0.852$

t = 0.852 x $5170^{0.26}$= 7.8s

M= 517 x 10 = 5170kg = Mass of LPG

$R_b$ = 52.1 m

$H_{BLEVE}$ = 104.2m

$$X = \sqrt{25^{2+H_{BLEVE}^2}}$$

X= 107.2 m

x = 55.1

Fview= $\frac{55.1^2}{107.2^2}$ = 0.249

$$SEP = \frac{\Delta Hc\, x\, m\, x\, Fs}{4\pi x R_{fb}^2\, x\, t} = \frac{46.013\, x10^6\ \ x5170\, x0.246}{\pi x4\, x52.2^2\, x14.32} =$$

2173872 J/m$^2$

q = 2173872 x 0.249 x 0.7335 = 3986338 J/m$^2$ s

k =1314509 kw/m$^2$ 4/3 s

$M_l$ = 0.80 x 10x0.001752 = 0.8 x Volume of sphere x $v_{f1}$ =

$M_{l=}$ 0.80x10x0.001752= 0.01405kg = Fractional Mass of Liquid LPG

$M_g$ = 0.20 x 10/0.029076 = 20/100 x volume of sphere x $v_{g1}$ =

$M_g$ = 0.20x10x0.029076= 0.0581kg = Fractional Mass of gas LPG

$M_f$ = 0.1405+0.581/2= 0/036084= Mass of fragment on the explosion

$E_{av}$ = $W_{av}$ x M = Explosion energy

$E_{avl}$ = $W_{avl}$ x $M_l$ = -100.55 x10$^3$ x 0.= -14127.2 MJ = Explosion energy for saturated liquid

$E_{avg}$ = $W_{avg}$ x $M_g$ = 13.72 x10$^3$ x 0.581=7971.32 MJ = Explosion energy for saturated vapour

$E_{avtotal}$ = $E_{avl}$ + $E_{avg}$ = -6155 MJ= Total explosion energy

Effective Blast energy 2 x 6155= 12311.36 MJ

R= 10x 0.101x10$^6$/12311.36 = 153.76= 4.34

$$d = \sqrt[3]{\frac{Vx6}{\pi}}$$ = diameter of LPG storage tank

d = 5.74

$C_D$ $A_D$ = 0.615 x $\frac{\pi}{4}$ d$^2$ = 15.96= Drag and lift fragments (tumbling)

$C_D$ = drag coefficient

$A_D$ = Exposed area in a plane perpendicular to the trajectory

$$R = \frac{P_a\ C_D A_D R_i}{M_f}$$ = Scaled maximal range

$$R_t = \frac{4.34\, x0.360}{1.20\, x15.96}$$ = 0.0815m = Maximal range to target

Calculations For BA3

$V = 15$ = Volume of storage tank

D = 4000m = Distance to target object

$R_b = c_9 \ m^{0.325}$ = Radius of fireball

$c_9 = 3.24$

t = $c_{10}$ x $m^{0.26}$ = Time of BLEVE

$c_{10} = 0.852$

t = 0.852 x $7755^{0.26}$= 8.74s

M= 517 x 15 = 7755kg = Mass of LPG

$R_b$ = 39 m

$H_{BLEVE}$ = 119m

$$X = \sqrt{4000^{2+H_{BLEVE}^2}}$$

X= 4001.7 m

x = 394.2m

Fview= $\frac{394.2^2}{4001.7^2}$ = 0.249

$$SEP = \frac{\Delta Hc\, x\, m\, x\, Fs}{4\pi x R_{fb}^2\, x\, t} = \frac{46.013\, x10^6\ \ x7755\, x0.246}{\pi x4\, x39^2\, x14.32} =$$

2213872 J/m$^2$

q = 2213872 x 0.249 x 0.7335 = 4186338 J/m$^2$ s

k =1312509 kw/m$^2$ 4/3 s

$M_l$ = 0.80 x 15x0.001752 = 0.8 x Volume of sphere x $v_{f1}$ =

$M_{l=}$ 0.80x15x0.001752= 0.021kg = Fractional Mass of Liquid LPG

$M_g$ = 0.20 x 15/0.029076 = 20/100 x volume of sphere x $v_{g1}$ =

$M_g$ = 0.20x15x0.029076= 0.08721kg = Fractional Mass of gas LPG

$M_f$ = 0.021+0.08721/2= 0.05411= Mass of fragment on the explosion

$E_{av} = W_{av}$ x M = Explosion energy

$E_{avl} = W_{avl}$ x $M_l$ = -100.55 x$10^3$ x 0.021= -2111,55 MJ = Explosion energy for saturated liquid

$E_{avg} = W_{avg}$ x $M_g$ = 13.72 x$10^3$ x 0.08721=62243,3 MJ = Explosion energy for saturated vapour

$E_{avtotal} = E_{avl} + E_{avg}$ = 60132.52 MJ= Total explosion energy

Effective Blast energy 2 x 60132.55= 120265 MJ

R= 10x 0.101x$10^6$/120265 = = 60.15

$d=\sqrt[3]{\frac{15x6}{\pi}}$= diameter of LPG storage tank

d = 3.05

$C_D$ $A_D$ = 0.615 x $\frac{\pi}{4}$ $d^2$ = 4.521= Drag and lift fragments (tumbling)

$C_D$ = drag coefficient

$A_D$ = Exposed area in a plane perpendicular to the trajectory

$$R=\frac{P_a\ C_D A_D R_i}{M_f}$$ = Scaled maximal range

$R_i = \frac{4.34\ x 0.360}{1.20\ x 15.96}$ = 0.864m = Maximal range to target

Calculations For BA4

$V=40$ = Volume of storage tank

D = 1000m = Distance to target object

$R_b = c_9\ m^{0.325}$ = Radius of fireball

$c_9$ = 3.24

t = $c_{10}$ x $m^{0.26}$ = Time of BLEVE

$c_{10}$ = 0.852

t = 0.852 x20680= 11.284s

M= 517 x 40 = 20680kg = Mass of LPG

$R_b$ = 81.80m

$H_{BLEVE}$ = 163.7m

$$X=\sqrt{40^{2+H_{BLEVE}}{}^2}$$

X= 1013 m

x = 931.1m

Fview= $\frac{931.1^2}{1013.3^2}$ = 0.25

$SEP= \frac{\Delta Hc\, x\, m\, x\, Fs}{4\pi x R_{fb}{}^2\, x\, t} = \frac{46.013\ x 10^6\ \ x 20680\ x 0.246}{\pi x4\ x 81.80\ x 14.32}$ = 225466 J/$m^2$

q = 225466 x 0.249 x 0.7335 = 45160 J/$m^2$ s

k =1551780 kw/$m^2$ 4/3 s

$M_l$ = 0.80 x 40x0.001752 = 0.8 x Volume of sphere x $v_{fl}$ =

$M_l$= 0.80x40x0.001752= 0.05560kg = Fractional Mass of Liquid LPG

$M_g$ = 0.20 x 40/0.029076 = 20/100 x volume of sphere x $v_{gl}$ =

$M_g$ = 0.20x40x0.029076= 0.2326kg = Fractional Mass of gas LPG

$M_f$ = 0.021+0.08721/2= 0.05411= Mass of fragment on the explosion

$E_{av} = W_{av}$ x M = Explosion energy

$E_{avl} = W_{avl}$ x $M_l$ = -100.55 x$10^3$ x 0.0556= -5662 MJ = Explosion energy for saturated liquid

$E_{avg} = W_{avg}$ x $M_g$ = 13.72 x$10^3$ x 0.2326=3191.3 MJ = Explosion energy for saturated vapour

$E_{avtotal} = E_{avl} + E_{avg}$ = 308.2 MJ= Total explosion energy

Effective Blast energy 2 x 308= 617 MJ

R= 10x 0.101x$10^6$/4942 = = 27.33

$d=\sqrt[3]{\frac{40x6}{\pi}}$= diameter of LPG storage tank

d = 4.24

$C_D$ $A_D$ = 0.615 x $\frac{\pi}{4}$ $d^2$ = 4.551= Drag and lift fragments (tumbling)

$C_D$ = drag coefficient

$A_D$ = Exposed area in a plane perpendicular to the trajectory

$$R=\frac{P_a\ C_D A_D R_i}{M_f}$$ = Scaled maximal range

$R_i = \frac{27.33\ x 0.1442}{1.20\ x 18.694}$ = 0.5444m = Maximal range to target

## III. RESULTS AND DISCUSSION

LPG Refilling Station Location

The volume and distance LPG refilling station to target were obtained across states were obtained to

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calculate possible potential health, safety and economic loss in an event of a BLEVE. Data used for calculation is presented in Table 1.

Table 1: LPG stations and Potential Targets

| Code | Locations | LPG Volume in $m^3$ | Distance to target Objects in m |
|---|---|---|---|
| AB 1 | Abia | 60 | 12 |
| BA 1 | Bayelsa | 100 | 10 |
| BA 2 | Bayelsa | 10 | 25 |
| BA 3 | Bayelsa | 15 | 4000 |
| BA 4 | Bayelsa | 40 | 1000 |
| BA 5 | Bayelsa | 5 | 10 |
| BA 6 | Bayelsa | 30 | 15 |
| DT 1 | Delta | 30 | 12 |
| DT 2 | Delta | 40 | 15 |

LPG Health, Safety and Economic Calculation from BLEVE
For Abia State (AB1)

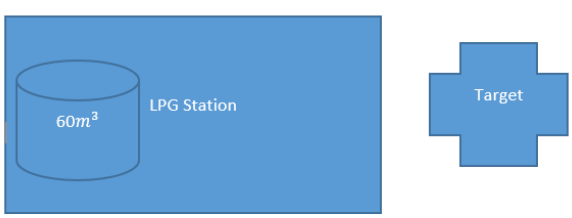


Figure 1: Liquefied Petroleum Gas Safety and Economic model

Calculation for harm effects and economic loss due BLEVE resulting from LPG station is presented in Appendix D.

From Table 1, in an event of BLEVE for LPG at this station, there is potential fatality, injuries due to high exposure to thermal dose and damage to target objects if, $R_f$is greater than D. The percentage of population can suffer fatality and injuries can be determined from the probit

The value target object is equal to economic loss.
Table 2. LPG stations analysis for Abia (AB1)

| Data | Values |
|---|---|
| Radius of fireball, $R_b$ | 93.23 m |
| Duration of fireball ,t | 12,53 s |
| Lift Height of fireball, $H_{Bleve}$ | 186.4 m |
| LPG measured capacity, V | 60 $m^3$ |
| Measured distance to target object, D | 12 m |
| Distance from Centre fireball to target object, X | 186.8 m |
| Length of radiation from fireball surface, x | 93.60 m |
| Surface emissive power, SEP | 256 x $10^4$ $J/_{m^2}$ $s$ |
| Mass, M | 31020 kg |
| Heat Flux, q | 4.6 x $10^4$ $J/_{m^2}$ $s$ |
| Thermal Dose, k | 1.6 x $10^6$ $(kw/_{m^2})^{\frac{4}{3}}$ s |
| BLEVE projected distance to target, $R_f$ | 0.07 m |
| Probit Fatality, $Y_d$ | 3.68 |
| Probit injury Protective, $Y_p$ | 1.717 |
| Probit injury Unprotected, $Y_{un}$ | 1.45 |

From Table 2, in an event of BLEVE for LPG at this station, there is potential fatality, injuries due high exposure to thermal dose, damage from fireball to the target objects because X is greater than D and no damage to target objects due to fragment effect because,"R" _"f" is less than D for AB1. The percentage of population that can suffer fatality and injuries can be determined from the probit, this value can be checked on probit table which is not provided in this work

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The value of damage from fireball and fragment is equal to economic loss. From the calculation, this fireball is expected to travel a distance 186.8 m in 12.53 s which will completely impact on the target object.

Table 3: LPG stations analysis for Bayelsa (BA1)

| Data | Values |
|---|---|
| Radius of fireball, $R_b$ | 110 m |
| Duration of fireball ,t | 14.3 s |
| Lift Height of fireball, $H_{Bleve}$ | 220.5 m |
| LPG measured capacity, V | 100 $m^3$ |
| Measured distance to target object, D | 10 m |
| Distance from Centre fireball to target object, X | 220.2 m |
| Length of radiation from fireball surface, x | 109.2 m |
| Surface emissive power, SEP | 540x$10^4$ $J/m^2\ s$ |
| Mass, M | 51700 kg |
| Heat Flux, q | 4.8 x $10^4$ $J/m^2\ s$ |
| Thermal Dose, k | 1.7 x $10^6$ $(kw/m^2)^{\frac{4}{3}}$ s |
| BLEVE projected distance to target, $R_f$ | 0.0815 m |
| Probit Fatality, $Y_d$ | 3.734 |
| Probit injury Protective, $Y_p$ | 1.700 |
| Probit injury Unprotected, $Y_{un}$ | 1.500 |

From Table 3, in an event of BLEVE for LPG at this station, there is potential fatality, injuries due high exposure to thermal dose, damage from fireball to the target objects because X is greater than D and no damage to target objects due to fragment effect because, $R_f$ is less than D for BA1. The percentage of population that can suffer fatality and injuries can be determined. from the probit, this value can be checked on probit table which is not provided in this work.

The value of damage from fireball and fragment is equal to economic loss. From the calculation, this fireball is expected to travel a distance 220.2 m in 14.3 s which will completely impact on the target object.

Table 4 LPG stations analysis for Bayelsa (BA2)

| Data | Values |
|---|---|
| Radius of fireball, $R_b$ | |
| Duration of fireball ,t | 7.8 s |
| Lift Height of fireball, $H_{Bleve}$ | 104.3 m |
| LPG measured capacity, V | 10 $m^3$ |
| Measured distance to target object, D | 25 m |
| Distance from Centre fireball to target object, X | 107.2 m |
| Length of radiation from fireball surface, x | 55.1 m |
| Surface emissive power, SEP | 202.2x$10^4$ $J/m^2\ s$ |
| Mass, M | 51700 kg |
| Heat Flux, q | 3.7 x $10^4$ $J/m^2\ s$ |
| Thermal Dose, k | 1.2 x $10^6$ $(kw/m^2)^{\frac{4}{3}}$ s |
| BLEVE projected distance to target, $R_f$ | 0.159 m |
| Probit Fatality, $Y_d$ | 3.4943 |
| Probit injury Protective, $Y_p$ | 1.521 |
| Probit injury Unprotected, $Y_{un}$ | 1.261 |

From Table 4, in an event of BLEVE for LPG at this station, there is potential fatality, injuries due high exposure to thermal dose, damage from fireball to the target objects because X is greater than D and no damage to target objects due to fragment effect because,"R" _"f" is less than D for BA2. The percentage of population that can suffer fatality and injuries can be determined from the probit, this value can be checked on probit table which is not provided in this work

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The value of damage from fireball and fragment is equal to economic loss. From the calculation, this fireball is expected to travel a distance 107.2 m in 7.8 s which will completely impact on the target object.

Table 5 LPG stations analysis for Bayelsa (BA3)

| Data | Values |
|---|---|
| Radius of fireball, $R_b$ | 59 m |
| Duration of fireball ,t | 8.74.3 s |
| Lift Height of fireball, $H_{Bleve}$ | 119 m |
| LPG measured capacity, V | 15 $m^3$ |
| Measured distance to target object, D | 4000 m |
| Distance from Centre fireball to target object, X | 4001.7 m |
| Length of radiation from fireball surface, x | 3942 m |
| Surface emissive power, SEP | 22 x $10^4$ $J/_{m^2}$ $s$ |
| Mass, M | 7755 kg |
| Heat Flux, q | 0.036x$10^4$ $J/_{m^2}$ $s$ |
| Thermal Dose, k | 0.000120x$10^6$ ( $kw/_{m^2}$ )$^{\frac{4}{3}}$ s |
| BLEVE projected distance to target, $R_f$ | 0.864 m |
| Probit Fatality, $Y_d$ | 1.157 |
| Probit injury Protective, $Y_p$ | 0.8979 |
| Probit injury Unprotected, $Y_{un}$ | 1.0759 |

From Table 5, in an event of BLEVE for LPG at this station, there is potential fatality, injuries due high exposure to thermal dose, damage from fireball to the target objects because X is greater than D and no damage to target objects due to fragment effect because,"R" _"f" is less than D for BA3. The percentage of population that can suffer fatality and injuries can be determined from the probit, this value can be checked on probit table which is not provided in this work

The value of damage from fireball and fragment is equal to economic loss. From the calculation, this fireball is expected to travel a distance 4001.7 m in 8.74 s which will completely impact on the target object.

Table 6 LPG stations analysis for Bayelsa (BA4)

| Data | Values |
|---|---|
| Radius of fireball, $R_b$ | 81.8 m |
| Duration of fireball ,t | 11.28 s |
| Lift Height of fireball, $H_{Bleve}$ | 163.7 m |
| LPG measured capacity, V | 40 $m^3$ |
| Measured distance to target object, D | 1000 m |
| Distance from Centre fireball to target object, X | 1013.2 m |
| Length of radiation from fireball surface, x | 9312 m |
| Surface emissive power, SEP | 59.7x $10^4$ $J/_{m^2}$ $s$ |
| Mass, M | 20680 kg |
| Heat Flux, q | 0.11x $10^4$ $J/_{m^2}$ $s$ |
| Thermal Dose, k | 1.18x$10^6$ ( $kw/_{m^2}$ )$^{\frac{4}{3}}$ s |
| BLEVE projected distance to target, $R_f$ | 0.544 m |
| Probit Fatality, $Y_d$ | 2.403 |
| Probit injury Protective, $Y_p$ | 0.392 |
| Probit injury Unprotected, $Y_{un}$ | 0.170 |

From Table 6, in an event of BLEVE for LPG at this station, there is potential fatality, injuries due high exposure to thermal dose, damage from fireball to the target objects because X is greater than D and no damage to target objects due to fragment effect because,"R" _"f" is less than D for BA4. The percentage of population that can suffer fatality and injuries can be determined from the probit, this value can be checked on probit table which is not provided in this work

The value of damage from fireball and fragment is equal to economic loss. From the calculation, this fireball is expected to travel a distance 1013.3 m in 11.28 s which will completely impact on the target object.

Table 7: LPG stations analysis for Bayelsa (BA5)

| Data | Values |
|---|---|
| Radius of fireball, $R_b$ | 41.6 m |
| Duration of fireball ,t | 6.5 s |
| Lift Height of fireball, $H_{Bleve}$ | 83.2 m |
| LPG measured capacity, V | 5 $m^3$ |
| Measured distance to target object, D | 10 m |
| Distance from Centre fireball to target object, X | 83. m |
| Length of radiation from fireball surface, x | 42.1 m |
| Surface emissive power, SEP | 20 x $10^4$ $J/_{m^2}$ $s$ |
| Mass, M | 2585 kg |
| Heat Flux, q | 3.6 x $10^4$ $J/_{m^2}$ $s$ |
| Thermal Dose, k | 1.47x$10^6$ ( $kw/_{m^2}$ )$\frac{4}{3}$ s |
| BLEVE projected distance to target, $R_f$ | 0.117 m |
| Probit Fatality, $Y_d$ | 3.444 |
| Probit injury Protective, $Y_p$ | 1.465 |
| Probit injury Unprotected, $Y_{un}$ | 1.207 |

From Table 7, in an event of BLEVE for LPG at this station, there is potential fatality, injuries due high exposure to thermal dose, damage from fireball to the target objects because X is greater than D and no damage to target objects due to fragment effect because,"R" _"f" is less than D for BA5. The percentage of population that can suffer fatality and injuries can be determined from the probit, this value can be checked on probit table which is not provided in this work

The value of damage from fireball and fragment is equal to economic loss. From the calculation, this fireball is expected to travel a distance 83 m in 6.5 s which will completely impact on the target object.

Table 8: LPG stations analysis for Bayelsa (BA6)

| Data | Values |
|---|---|
| Radius of fireball, $R_b$ | 74.4 m |
| Duration of fireball ,t | 10.4 s |
| Lift Height of fireball, $H_{Bleve}$ | 149 m |
| LPG measured capacity, V | 30 $m^3$ |
| Measured distance to target object, D | 15 m |
| Distance from Centre fireball to target object, X | 149.5 m |
| Length of radiation from fireball surface, x | 75.3 m |
| Surface emissive power, SEP | 23 x $10^4$ $J/_{m^2}$ $s$ |
| Mass, M | 15510 kg |
| Heat Flux, q | 4.35x $10^4$ $J/_{m^2}$ $s$ |
| Thermal Dose, k | 1.48x$10^6$ ( $kw/_{m^2}$ )$\frac{4}{3}$ s |
| BLEVE projected distance to target, $R_f$ | 0.134.2 m |
| Probit Fatality, $Y_d$ | 3.614 |
| Probit injury Protective, $Y_p$ | 1.646 |
| Probit injury Unprotected, $Y_{un}$ | 1.381 |

From Table 8, in an event of BLEVE for LPG at this station, there is potential fatality, injuries due high exposure to thermal dose, damage from fireball to the target objects because X is greater than D and no damage to target objects due to fragment effect because,"R" _"f" is less than D for BA6. The percentage of population that can suffer fatality and injuries can be determined from the probit, this value can be checked on probit table which is not provided in this work

The value of damage from fireball and fragment is equal to economic loss. From the calculation, this fireball is expected to travel a distance 149.5 m in 10.4 s which will completely impact on the target object.

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Table 9: LPG stations analysis for Delta (DT1)

| Data | Values |
|---|---|
| Radius of fireball, $R_b$ | 74.4 m |
| Duration of fireball ,t | 10.4 s |
| Lift Height of fireball, $H_{Bleve}$ | 149.1 m |
| LPG measured capacity, V | 30 $m^3$ |
| Measured distance to target object, D | 12 m |
| Distance from Centre fireball to target object, X | 149. m |
| Length of radiation from fireball surface, x | 75. m |
| Surface emissive power, SEP | 23.9 x $10^4$ $J/m^2$ $s$ |
| Mass, M | 15510 kg |
| Heat Flux, q | 4.37x $10^4$ $J/m^2$ $s$ |
| Thermal Dose, k | 1.53x$10^6$ ( $kw/m^2$ )$^{\frac{4}{3}}$ s |
| BLEVE projected distance to target, $R_f$ | 0.124 m |
| Probit Fatality, $Y_d$ | 3.617 |
| Probit injury Protective, $Y_p$ | 1.648 |
| Probit injury Unprotected, $Y_{un}$ | 1.384 |

From Table 9, in an event of BLEVE for LPG at this station, there is potential fatality, injuries due high exposure to thermal dose, damage from fireball to the target objects because X is greater than D and no damage to target objects due to fragment effect because,"R" _"f" is less than D for DT1. The percentage of population that can suffer fatality and injuries can be determined from the probit, this value can be checked on probit table which is not provided in this work

The value of damage from fireball and fragment is equal to economic loss. From the calculation, this fireball is expected to travel a distance 149.1 m in 10.4 s which will completely impact on the target object.

Table 10: LPG stations analysis for Delta (DT2)

| Data | Values |
|---|---|
| Radius of fireball, $R_b$ | 81.8 m |
| Duration of fireball ,t | 11.2 s |
| Lift Height of fireball, $H_{Bleve}$ | 163.7 m |
| LPG measured capacity, V | 40 $m^3$ |
| Measured distance to target object, D | 15 m |
| Distance from Centre fireball to target object, X | 164. m |
| Length of radiation from fireball surface, x | 82. m |
| Surface emissive power, SEP | 24.6 x $10^4$ $J/m^2$ $s$ |
| Mass, M | 20680 kg |
| Heat Flux, q | 4.4 x $10^4$ $J/m^2$ $s$ |
| Thermal Dose, k | 1.58 x $10^6$ ( $kw/m^2$ )$^{\frac{4}{3}}$ s |
| BLEVE projected distance to target, $R_f$ | 0.134 m |
| Probit Fatality, $Y_d$ | 3.624 |
| Probit injury Protective, $Y_p$ | 1.675 |
| Probit injury Unprotected, $Y_{un}$ | 1.409 |

From Table 10, in an event of BLEVE for LPG at this station, there is potential fatality, injuries due high exposure to thermal dose, damage from fireball to the target objects because X is greater than D and no damage to target objects due to fragment effect because,"R" _"f" is less than D for DT2. The percentage of population that can suffer fatality and injuries can be determined from the probit, this value can be checked on probit table which is not provided in this work

The value of damage from fireball and fragment is equal to economic loss. From the calculation, this fireball is expected to travel a distance 164 m in 11 s which will completely impact on the target object.

## IV. DISCUSSION

The results confirm that thermal radiation is the dominant hazard mechanism in LPG BLEVE scenarios. High-capacity installations produce extensive hazard zones, exceeding common urban setback distances.

Small installations may still pose severe local hazards when placed within 10 m of buildings. Current siting practices in some states appear inconsistent with consequence modelling results.

Risk-based regulatory enforcement, mandatory quantitative risk assessment prior to licensing, and strict compliance monitoring are strongly recommended.

## V. CONCLUSION

This study demonstrates that BLEVE incidents at LPG refilling stations in Southern Nigeria present substantial thermal radiation hazards capable of causing fatalities, severe injuries and significant economic loss.

Key findings include:

i. Fireball radii ranged from 41.6 m (small installations) to 616.9 m (large installations).
ii. High-capacity facilities (e.g., IM1, IM3) produce extremely large lift heights (>1000 m) and high fatality probit values (>3.8).
iii. In most stations, X > D, indicating that target objects fall within severe thermal radiation zones.
iv. Fragment impact was negligible compared to fireball thermal effects.
v. Economic losses correlate directly with fireball radiation exposure.
vi. The results highlight the urgent need for:
vii. Stricter enforcement of setback distances.
viii. Risk-based zoning policies.
ix. Improved safety audits and inspection.
x. Mandatory quantitative risk assessment before licensing.

## REFERENCES

[1] Lees FP. Lees' Loss Prevention in the Process Industries. 4th ed. Oxford: Butterworth-Heinemann; 2012.

[2] Mannan S, editor. Lees' Process Safety Essentials: Hazard Identification, Assessment and Control. Oxford: Butterworth-Heinemann; 2014.

[3] CCPS (Center for Chemical Process Safety). Guidelines for Chemical Process Quantitative Risk Analysis. 2nd ed. New York: AIChE; 2000.

[4] CCPS. Guidelines for Consequence Analysis of Chemical Releases. New York: AIChE; 2010.

[5] Crowl DA, Louvar JF. Chemical Process Safety: Fundamentals with Applications. 3rd ed. Upper Saddle River: Prentice Hall; 2011.

[6] TNO. Methods for the Calculation of Physical Effects (Yellow Book). 3rd ed. The Hague: Netherlands Organization for Applied Scientific Research; 2005.

[7] TNO. Guidelines for Quantitative Risk Assessment (Purple Book). 3rd ed. The Hague; 2005.

[8] Mudan KS. Thermal radiation hazards from hydrocarbon pool fires. Prog Energy Combust Sci. 1984;10:59–80.

[9] Roberts AF. The analysis of BLEVE incidents. J Hazard Mater. 1981;4:87–98.

[10] Birk AM. Fireball sizing and thermal radiation estimation methods for LPG BLEVEs. J Loss Prev Process Ind. 1995;8(5):303–312.

[11] Hemmatian B, Planas-Cuchi E, Casal J. Analysis of LPG BLEVE incidents and fireball behaviour. J Hazard Mater. 2013;260:299–309.

[12] Planas-Cuchi E, Gasulla N, Casal J. BLEVE of LPG tanks: Prediction of fireball geometry and thermal radiation. Process Saf Environ Prot. 2004;82(B4):323–331.

[13] Casal J. Evaluation of the Effects and Consequences of Major Accidents in

Industrial Plants. 2nd ed. Amsterdam: Elsevier; 2018.

[14] Abbasi T, Abbasi SA. The boiling liquid expanding vapour explosion (BLEVE): Mechanism, consequence assessment, management. J Hazard Mater. 2007;141:489–519.

[15] Landucci G, Argenti F, Tugnoli A, Cozzani V. Quantitative assessment of fireball impact from LPG BLEVEs. Reliab Eng Syst Saf. 2009;94:192–200.

[16] Bagster DF, Pitblado RM. The estimation of fatality rates in thermal radiation accidents. Trans IChemE. 1991;69:77–85.

[17] Eisenberg NA, Lynch CJ, Breeding RJ. Probit analysis for estimating fatalities from thermal radiation. J Fire Prot Eng. 1975;7:5–15.

[18] HSE (Health and Safety Executive). Failure Rate and Event Data for Use within Risk Assessments. London: HSE; 2012.

[19] NFPA 58. Liquefied Petroleum Gas Code. National Fire Protection Association; Latest ed.

[20] API 521. Pressure-Relieving and Depressuring Systems. American Petroleum Institute; Latest ed.

[21] Perry RH, Green DW. Perry’s Chemical Engineers’ Handbook. 8th ed. McGraw-Hill; 2008.

[22] Pietersen CM. Analysis of LPG fireball radiation hazards. J Hazard Mater. 1985;11:59–72.

[23] Darbra RM, Palacios A, Casal J. Domino effect in chemical accidents: Main features and accident sequences. J Hazard Mater. 2010;183:565–573.

[24] Cozzani V, Tugnoli A, Salzano E. The development of an inherent safety approach to LNG and LPG installations. J Loss Prev Process Ind. 2009;22:407–417.

[25] Van den Bosch CJH, Weterings R. Methods for the Calculation of Physical Effects Due to Releases of Hazardous Materials. CPR 14E; TNO; 2005.

[26] Landucci G, Tugnoli A, Cozzani V. Influence of tank size on BLEVE consequences. Process Saf Environ Prot. 2010;88:1–10.

[27] Haddon-Cave M. Large-scale fireball experiments and thermal radiation modelling. Fire Saf J. 1982;5:123–134.

[28] AIChE. Layer of Protection Analysis (LOPA): Simplified Process Risk Assessment. 2nd ed.; 2001.

[29] Khan FI, Abbasi SA. Major accidents in process industries and analysis of causes and consequences. J Loss Prev Process Ind. 1999;12:361–378.

[30] Ogundipe KE, Olaniran OJ. Urban siting of hazardous facilities and risk exposure in developing countries. Saf Sci. 2012;50:2059–2066.