Boiling Liquid Expanding Vapor Explosion (BLEVE)
Abstract

This study investigates Boiling Liquid Expanding Vapor Explosion (BLEVE). BLEVE is one of the major risks in the storage and transportation of Liquefied Petroleum Gas (LPG) and other hazardous materials. Liquefied Petroleum Gas (LPG) is stored partly in liquid state, as the remainder of the container above the liquid filled with a gaseous vapor. In most cases, BLEVE is used to refer to combination of BLEVE and fireball, that is, if the accidents involve mechanical and thermal effects simultaneously. The combination of fireball and BLEVE can be summarized in terms of three effects which include thermal radiation, pressure wave and flying fragments.

The objective of this study is to identify and raise awareness and hazard communication (HAZCOM) brought about by BLEVE as well as to recommend safety precautions in cases of BLEVE. Various case studies involving BLEVE have been included in this study in order to help in achieving the laid down objectives. Case Study 1 was from experiments investigating occurrences of BLEVE under different conditions whereas Case Study 2 involved actual BLEVE explosions accident.

The results have revealed that most of the BLEVE explosions happened due to leakage of Liquefied Petroleum Gas (LPG) leakage resulting from lack of awareness of potential dangers in addition to underestimation of safety precaution.
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Chapter 1: Introduction

Liquefied Petroleum Gas’ (LPG) demand has been on the rise, especially in the commercial and residential sectors of developed and developing countries. It is expected that the use of cleaner gaseous and liquid fuels will continue to rise with increase in populations and the demand for energy is also expected to increase world wide. The Liquefied Petroleum Gas (LPG) is stored in the form of liquid under pressure, although it vaporizes into a gas upon the release of the pressure. The Liquefied Petroleum Gas (LPG) is generally composed of butane, propane or some combination of such organic gases. The expanded uses of Liquefied Petroleum Gas (LPG) increase the potential for leaks in the Liquefied Petroleum Gas (LPG) containers as well as an increase in the potential for fire. The Liquefied Petroleum Gas (LPG) containers include portable storage tanks, tank trucks, storage tanks in commercial installations, and railroad tank cars. The Liquefied Petroleum Gas (LPG) are used in industrial or domestic heating, as refrigerants, in cooking or hot water systems, in tar posts, in torches, at construction sites in salamanders, among other uses. Moreover, they are used as a motor fuel albeit on a limited scale.

Boiling Liquid Expanding Vapor Explosion (BLEVE) is one of the major risks in the storage and transportation of Liquefied Petroleum Gas (LPG) and other hazardous materials. A BLEVE had been introduced some decades ago after various catastrophic damages had came about as a result of pressure waves originating from boiling and vaporization of Pressure Liquefied Gases (PLG) along depressurization. The storage vessel fragments at high speed may come out of explosion center with high velocity to bring about serious damage to industrial facilities, properties, and accidents with fatalities to operators in industries. This is an example of explosion which may take place when a vessel with liquid under pressure is ruptured. Explosions of this nature are often extremely hazardous. A BLEVE comes about when a vessel with liquid beyond its atmospheric boiling point ruptures.
The Liquefied Petroleum Gas (LPG) is stored partly in liquid state, as the remainder of the container above the liquid filled with a gaseous vapor. However, there are situations in which a BLEVE can occur with non-flammable substance which are extremely cold, such as liquid helium or liquid nitrogen or other cryogens or refrigerants. Thus, BLEVE can not often be categorized as a type of chemical explosion. On the other hand, if the Liquefied Petroleum Gas (LPG) is flammable, then it may be the case that the BLEVE takes place before the ignition of the resulting cloud of substance, resulting in the formation of a fireball and, in some cases, a fuel-car explosion, commonly referred to as a vapor cloud explosion (VCE). A large area is usually contaminated if the materials are toxic.

In most cases, BLEVE is used to refer to combination of BLEVE and fireball, that is, if the accidents involve mechanical and thermal effects simultaneously. The substances that can lead to BLEVE, including butane, propane, chorine and vinyl chloride, among others, are quite common in the industries and in various installations such as tanks and tank cars in which they can occur. Although action of fire on a container is the frequent cause of BLEVE, there are other different causes such as runaway reactions as well as collisions.

1.1 Description of BLEVE

When a tank which contains liquid under pressure is exposed to heat, such as from the thermal radiation from a fire, there will be increase in pressure inside the tank. After a while, the wall of the container will no longer be able to contain the high stress, making the walls to collapse (the steel which is often used to construct most Liquefied Petroleum Gas (LPG) containers may fail at the pressures of approximately 15 atmospheres, when the walls’ temperature reaches about 650 degrees Celsius). This often takes place in the upper section of the container in which the walls are not in contact with the liquid to bring about the cooling effect.
making the temperature of the walls to increase and consequently decrease the mechanical resistance of the wall (Abbasi and Abbasi, 2007).

On the other hand, the wall in contact with the liquid will maintain a much lower temperature because it transfers its heat to the liquid. Should a safety valve open, the boiling liquid is expected to have a stronger cooling action brought about by the heat of evaporation. Upon failure brought about by the instantaneous depressurization, the liquid’s temperature becomes greater than the one corresponding to the new pressure. This liquid in this unstable condition is referred to as superheated water. According to Chen et al. (2007), it is normal for liquids to withstand a small amount of superheating, and in some experimental conditions can be pushed far beyond the boiling point at atmospheric-pressure. However, different liquids have different limits to superheat, commonly referred to as the superheat temperature limit. When the liquid’s temperature at the moment of depressurization is higher than the superheat temperature limit, there will be an instantaneous violent flash of a fraction of superheated liquid vapor and liquid explosion, consequently releasing a biphasic liquid/vapor mixture. This phenomenon takes place very fast (within 1 ms). The significant increase in the volume of the liquid upon its vaporization, 250 times in case of propane and 1,750 times in the case of water, together with the expansion of the already existing vapor results to a strong wave of pressure revealed by the explosion and the bursting of the container in addition to breaking of the container into many pieces. Van Den Berg et al. (2004) revealed that when the container breaks, there is a slight drop in pressure followed by a rise of pressure to a maximum; a local explosion results when the initial depressurization brings the liquid/vapor near the break to a superheated state. The missiles and the pressure wave will only be the effects of explosion if the fluid involved is not combustible. Such is an occurrence when a water steam (steam boiler) explodes.
On the other hand, if the substance is combustible (such as fuel like liquefied petroleum gas) as is always the case in the process industry, the liquid/gas mixture will most likely ignite when released by the explosion, resulting in a fireball having a shape almost similar to hemisphere, initially at the ground level. Thermal radiation plays an important role in this first stage which only lasts a couple of seconds (Chen et al., 2007). The entire mass of fuel only burns at its periphery due to lack of air inside the mass due to the fact that the mixture is outside the limits of flammability. Moreover, not all the fuel initially within the tank takes part in this fire. As time goes, air is entrained into the fireball by the turbulence of the fire. At the same time, the thermal radiation vaporizes the droplets of the liquid while also heating the mixture. Consequently, the entire mass increases in volume turbulently to make a spherical shape which rises to leave a wake of variable diameter. The resulting fireballs may be quite large, bringing about a very strong thermal radiation. The combination of fireball and BLEVE can be summarized in terms of following effects:

i. Thermal radiation

ii. Pressure wave

iii. Flying fragments

The manner in which these effects occur also vary: projectiles are actuated by directional or punctual mode whereas thermal radiation and blast occur by covering a given surface. However, it is not possible to establish the precise time at which the explosion may occur. It was believed about two decades ago that once the emergency began, such as from the moment the fire begins to impinge on the container, there was a particular duration of time that should elapse before the explosion. As such, it was possible that various measures can be put in place to prevent the explosion such as refrigeration of the tank with hoses. However, as more actual
accidents were being investigated and results documented, it was revealed that the time before explosion could be extraordinarily short. For example, there was only 69 seconds between the first fire causing explosion and the first BLEVE in an accident which took place in Mexico City (Reinke and Yadigaroglu, 2001). There are various factors to which the instant at which a BLEVE can take place when a container is exposed to fire and they include:

i. Thermal flux from fire, which depends on the distance between the tank and the fire as well as whether there is flame impingement and the manner of the flame (whether it is torching, pool fire, among others)

ii. Diameter of the tank

iii. The level of fill of the tank

iv. Release capacity of the safety valves

v. Availability of protective layer of a particular thickness for isolating the material.

1.2 Objectives of the study

1.2.1 General objective

To identify and raise awareness and hazard communication (HAZCOM) brought about by BLEVE

1.2.2 Specific objectives

i. To investigate BLEVE

ii. To recommend safety precautions in cases of BLEVE
Chapter 2: Literature review

Boiling liquid expanding vapor explosion (BLEVE) is among the most severe accidents that can take place in an industrial area or when transporting hazardous materials.

2.1 Definition of Risk Management Concepts

Risk management entails the identification, analysis as well as economic control of the risks that can be threat to assets such as property, human, reputation, among others.

Hazard is a rare or an extreme event human-made or natural environment that has adverse effect on property, human life or activity in a way that can cause a disaster.

Risk is the probability of hazard and consequence that may bring about accident. Risk also entails the expected losses such as damage to properties, injuries, disruption of social and economic activities or livelihood, and lose of life due to a specific hazard.

Explosion is the sudden and usually violent release of energy accompanied with generation of high temperature and loud sharp sound. Explosion can be categorized as fire explosion, Vapor Cloud Explosion (VCE), Chemical Explosion and Mechanical Explosions.

2.2.1 Fire explosion

Fire explosions often cause injuries and deaths, and those managing fire explosion need to prepare adequately for making special efforts should they occur. There is need to investigate cases of fire explosion involving serious injuries just like fire explosions that has immediate fatalities due to the fact that fire explosion injuries may lead to death even days or weeks after the explosion. As shown in figure 1 below, explosion releases energy that can either result in pressure discontinuity or blast wave.
2.2.3 **Vapor Cloud Explosion (VCE)**

A Vapor Cloud Explosion (VCE) comes about as a result of ignition of a cloud of flammable gas, vapor or mist and is associated with flame speeds that are sufficiently high to produce over pressure. In situations that the vapor involved is flammable, the resulting cloud of flammable gas released in the atmosphere is most likely to ignite soon after the occurrence of BLEVE to form a fireball. The occurrence of combustion is so rapid that there is no generation of pressurized gases, making it to be considered as a gas fire instead of an explosion. A vapor cloud explosion can either be regarded as unconfined or confined explosion. Unconfined explosion involves the explosion of a mixture of vapor and air in the open air and is the widely used term. On the other hand, confined explosion involves explosion of flammable mixture of vapor and air within a closed system such as a vessel or a building.
2.2.3 Chemical Explosion
This is an explosion in which high pressure is generated as a result of exothermic reactions whereby there is fundamental change in the chemical nature of the fuel. Such chemical reactions that take place in explosion often spread (propagated) in a reaction front distant to the point of initiation. Although chemical explosions are commonly propagated by reactions involving vapors, gases, or dusts mixed with air, they can also involve explosive mixtures of fuels and oxidizer or solid combustibles. Combustions of that nature are referred to as propagation reaction due to the fact that due to the fact that they take place progressively within the fuel (reactant) with a distinct flame front separating un-reacted and reacted fuel.

2.2.4 Mechanical Explosions
These are the explosions whereby a high pressure gas results in a purely physical reaction. Such physical reactions do not bring about any change in the fundamental chemical nature of the fuel in the tank. A purely mechanical explosion involves the rupturing of the tank or cylinder for storing the gas under high pressure which results in the releasing of the gas stored under high-pressure like compressed oxygen, carbon dioxide or air.

2.2.5 Effects of explosions
There are four major groups in which the effects of explosions may be categorized into and they include thermal effect, shrapnel effect, seismic effect and blast pressure wave effect.

2.2.5.1 Blast Pressure Front Effect
A large amount of gas is usually produced by explosion of a material. The gases undergo expansion at a high speed after which they ascend from the point of origin. The gases together with the air that they displace produce a pressure front that is mainly the cause of damage and injuries brought about by the explosions (Elatabani, 2010).
In case the BLEVE takes place in the open, the strength of the blast at a distance of 4 fireball radii is approximately 40 mbar pressure which can break window glass and even knock down a member of rescue team (Abbasi and Abbasi, 2007). On the other hand, if BLEVE happen near some structures or other objects then the blast wave could be big enough to collapse a building as well as to propel objects over a large distance. Combustion of flammable cloud can also bring about a blast wave. This usually occurs when a flammable material is released and mixes with air within an enclosed structure. When the mixture is ignited, a powerful explosion with severe blast may result. Such a threat is quite difficult to quantify and its effect can be far reaching in case the released flammable gas is not ignited to form a fireball because severe explosion can result from its late ignition.

2.2.5.2 Shrapnel effect

In some cases, the vessel, the container or the structure restricting the blast pressure fronts can be ruptured, making them to be broken into pieces that are thrown far away distances. The broken pieces are referred to as missiles or shrapnel. They usually bring about personal injury and great damage to properties, usually far off distances from the source of explosion. The shrapnel can cause additional explosions by severing electric utility lines, storage containers, flammable fuel lines as well as fuel gas. Various factors such as the size of the tank, temperature of the liquid, level of fill, as well as position with respect to the main axis of the tank may cause the projectiles not to reach the 4-6 fireball radii. Figure 2 illustrates projectiles thrown by BLEVE. It is evident that the projectiles were thrown randomly in different directions. Actual pieces of the tank are labeled primary projectiles whereas the nearby objects that were displaced due to the energy of BLEVE have been labeled secondary projectiles.
2.2.5.3 **Thermal Effect**

Combustion explosions give out amounts of energy that cause the heating of combustion gases and ambient air, making their temperature to be high (Casal et al., n.d.). This energy which has been given out can ignite combustibles which are nearby or cause burn injuries to those standing nearby. The secondary fire may also cause additional injury and damage from the explosion as well as making investigation process and rescue mission complicated. In most cases, it is not easy to determine whether it is the fire or the explosion which took place first. Great quantities of heat are always produced by all chemical explosions. The duration of the high temperatures and the nature of the explosive fuels dictate the thermal damage caused. Deflagrating explosions takes longer period of time, although they produce lower temperatures whereas detonating explosions occur within limited time but produces very high temperatures. Firebrands and fireballs are some of the thermal effects of explosion, especially when flammable vapors are involved in BLEVE.
The momentary ball of flame which occurs during or after the explosion is what is referred to as the fireballs (Abbasi and Abbasi, 2007). The fireballs may be accompanied with thermal radiation of high intensity albeit in short duration. On the other hand, the burning or hot fragments propelled during the explosive event are referred to as the firebrands. These are some of the events which might start fires away from the central point of the explosion.

2.2.5.4 Seismic Effect
Seismic effect comes about due to expansion of blast pressure wave and the falling damaged portions of huge structures transmit earth tremor or significant localized seismic through the ground (Abbasi and Abbasi, 2007). The seismic effects may result in secondary damage to structures, tanks, cables, pipelines as well as utility services found underground. The seismic effects are often not significant in the case of small explosions.

2.3 Occurrence of BLEVE
Occurrence of BLEVE does not depend on the cause of the container failure. There container must be under pressure for BLEVE to occur, the pressure must be greater than the strength of the container, and the container must be made weak in some way such as through fire, impact or corrosion. According to Abbasi and Abbasi (2007), other ways of weakening of the container which have be the failing of container due to flame impingement. There is need to take into consideration the important and dangerous dimensions of both ignition and fireballs the liquefied gas released because of a BLEVE is flammable. Pinhasi et al. (2007) mentioned that the notion that BLEVE are just restricted to liquefied gases which are flammable is a fallacy. He explained that BLEVE can occur with different types of liquefied gases, including nonflammable gases.

The size of BLEVE depends on the size as well as the weight of the container in addition to the quantity of the remaining liquid inside the container during BLEVE. It is always the case
that a bigger BLEVE results from a bigger container. Most of the liquefied gases BLEVEs that are induced by flame usually occur when the liquid remaining inside the container covers approximately a half to three quarters of the entire container. The vaporization of the remaining liquid usually results in the destruction of the container which forms rockets that are usually thrown far off distances. Reports have indicated that such projectiles have caused death as far as 800 feet from the container involved in BLEVE (Reid, 1979; Van Den Berg et al., 2005; Chen et al., 2007). Moreover, there may not be complete vaporization of the material inside the container during BLEVE, and such material may also be propelled great distances from the container. According to Reinke and Yadigaroglu (2001), it is appropriate for the personnel to be at a distance that is four times the radius of the fireball for a particular size tank. For example, a safe distance of about 100 meters is appropriate for a container whose capacity is 1,000 liters. A distance of at least 100 meters has been recommended for any size of container impinged by fire.

2.3.1 Conditions for the occurrence of BLEVE

Various conditions must be in place for BLEVE to occur:

-Presence of a liquid

Glass and vapor alone cannot BLEVE, a liquid is necessary. However, it is not necessary for the liquid to be liquid to be flammable. Inflammable liquids such as water can BLEVE, albeit without the formation of fire.

-The liquid need to be inside a container closed tightly

BLEVE can occur in a vented container if the vent is either damaged or is not adequate for the pressure inside the container.

-the confined liquid’s temperature must be greater than its boiling point at atmospheric pressure
The pressure on the surface of the liquid is directly proportional to the temperature needed for the liquid to boil. The vapor pressure increase when a tightly closed container with the liquid is heated. The increase in vapor pressure is associated with an elevated boiling point of the liquid. The temperature is normally brought above the boiling point due to the occurrence of fire and heat is not always necessary. However, there are liquids whose boiling points are extremely low at atmospheric pressure. Such liquids already have temperature above their boiling point at normal atmospheric pressure.

-structural failure of the container

It is necessary for the container to have structural failure which may come about due to various reasons such as metal fatigue, mechanical damage by corrosion or collision, and damage or inadequacy of valve. The most common cause of structural failure of the container is the direct flame impingement. Container failure usually takes place in the metal around the vapor space. It is quite difficult to heat metal in contact with the liquid due to the fact that liquid is generally excellent absorbers and conductors of heat, but vapors are not.

2.3.2 Superheating and depressurization

Although the explosion of a container having a pressurized flammable liquid will most likely result in a fireball, such an explosion may not necessarily be considered to be BLEVE. According to Abbasi and Abbasi (2007), such an explosion may be qualified as BLEVE if these two conditions are met: significant superheating of the liquid and instantaneous depressurization.

Significant superheating of the liquid is a condition that is fulfilled by most liquefied gases exposed to attack by fire (such as Liquefied Petroleum Gas (LPG), ammonia, and chlorine, among others). However, the condition may also be fulfilled by other liquids in tightly enclosed containers and can exhibit anomalous heating, such as when exposed to fire.
On the other hand, instantaneous depressurization is a phenomenon that is often associated with the type of failure of the container. The liquid may be made to superheat due to sudden drop in pressure within the container upon failure. However, the flashing may be explosive if there is significant superheating of the liquid.

Upon the meeting of these two conditions, an instantaneous evaporation of the contents occurs together with the formation of numerous boiling nuclei in all the mass of the liquid (commonly referred to as homogenous nucleation). Under these conditions, the explosion is quite violent due to the extraordinary velocity at which the volume increases. Such a phenomenon is the one that is demonstrated by BLEVE explosion.

2.3.3 Temperature and Superheating Limit Locus

Different authors have recommended various procedures for establishing the superheat temperature limit as well as the superheating limit locus that can be used in the determination of the conditions under which a BLEVE can take place for different substances. One of the major contributors was Reid (1976, 1979). The theoretical superheating limiting conditions for the existence of spontaneous homogeneous nucleation in each mass of the liquid can be obtained from the tangent line of the vapor pressure against temperature curve at the critical point. Reid (1979) explained that the tangent represents the limit whereby the liquid can be heated before the occurrence of spontaneous nucleation with a vapor explosion as illustrated in figure 3.
Antoine equation can be used to establish the relationship between the vapor pressure and temperature as shown below (Casal et al., n.d.):

\[
\ln P = -\frac{A}{T} + B \quad (1)
\]

The derivative pressure is differentiated with respect to temperature to obtain the tangent to the saturation curve at the critical point:

\[
\frac{dP}{dT} = \frac{AP}{T^2} \quad (2)
\]

The expression in equation 2 is applied to critical point to yield (Casal et al., n.d.):

\[
\frac{dP_c}{dT_c} = \frac{P_c A}{T_c^2} = \tan \alpha \quad (3)
\]
The expression in equation 3 gives the gradient (slope) of the line tangent to the saturation curve at the critical point. The expression below shows the equation of the straight line (Casal et al., n.d.):

\[ P = t g \alpha \cdot T + b \]  \hspace{1cm} (4)

2.4 Warning signs of BLEVE

There are various warnings signs that should be looked out for in case of BLEVE emergency, they include: discoloration of container (usually the color changes to cherry red), metal shell producing pinging sound, bulge or bubble of container, steam emanating from the surface of the tank, shrill sound due to pressure, and tear in the surface of the tank.

2.5 Mechanism of BLEVE

There exist very few mechanisms of BLEVE and they are reliant on very limited experimental data. The steps of BLEVE are summarized as follows:

i. Failure of the vessel. There are various causes for vessel failure and they include vessel corrosion, heating, overloading, and external hitting, among other causes.

ii. Phase transition. The liquefied gas stored in a vessel usually experience instantaneous depressurization due to failure of the vessel. The pressurized liquid/vapor mixture is in a saturated thermodynamic state and its temperature is higher than its boiling point in the initial stages. However, with decrease in the original pressure to the atmospheric pressure, the liquid/vapor mixture gets superheated in few milliseconds.

iii. It is possible for the pressurized liquid to endure being in a superheated state when the temperature within the vessel is significantly lower than the liquid’s superheat limit temperature (SLT). On the other hand, fast bubble nucleation starts within the vessel in case the temperature is significantly above the superheat limit temperature.
(SLT), resulting in the violent splashing of the liquid/vapor mixture from the vessel into the environment.

iv. Explosion from depressurization and bubble nucleation. The intense phase in superheated state is accompanied by the boiling of the liquid. This causes bubble nucleation. Moreover, the expansion of vapor caused by the initial vapor stored in the vessel and the vaporization of the liquid will bring about BLEVE explosion.

v. Formation of blast wave. A powerful blast is formed by the increase in total volume of the expanding vapor. The blast wave can bring damage to nearby facilities.

vi. Rupture of the vessel. The vessel usually ruptures because of the powerful blast wave. The pieces and fragments of the ruptured vessel fly outwards like rocket missiles in every direction.

vii. Fireball or toxic fluid dispersion. The vessel fragments and the blast wave are the only effects of the explosion.

2.6 Estimating the Effects of BLEVE

There are various factors that can be used to estimate the effects of BLEVE. This paper discusses four methods that can be used in estimating the effects of BLEVE and they include thermal radiation, mechanical energy released in the explosion, missiles, and pressure wave.

2.6.1 Thermal Radiation

When a flammable substance is involved in a BLEVE explosion, it is common for a fireball to follow as well as to release intense thermal radiation. The release of thermal energy usually takes a very short time (less than 40 seconds), although the time depends on the mass of substance contained in the tank. Thermal radiation often takes place from the initial moment by strong radiation, consequently eliminating the possibility of the persons found near the scene of escaping as they are likely to suffer the effects of the blast. The effects of the fireball may be
predicted by evaluating parameters such as thermal radiation at any distance, diameter of the tank, and the duration. Various researchers have proposed correlations for predicting the duration and diameter of fireball whose source is a particular mass of fuel (Le Métayera, 2005). The following expression has been commonly adopted (Casal et al., n.d.):

\[ D = a \times M^b \]  \hspace{1cm} (5)

\[ t = c \times M^e \]  \hspace{1cm} (6)

Where \( D \) is the diameter of the fireball, \( t \) is the duration, \( M \) is the mass and \( a, b, c, \) and \( e \) are empirical and semi-empirical constants. Table 1 below shows a comparative study which was carried out by using the two expressions given above (equation 5 and equation 6).

<table>
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<th>Author</th>
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<th>( c )</th>
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<tr>
<td>High</td>
<td>(Lihou and Maunde, 1982)</td>
<td>6.20</td>
<td>0.320</td>
<td>0.490</td>
<td>0.320</td>
</tr>
<tr>
<td>HSCCb</td>
<td>(Lihou and Maunde, 1982)</td>
<td>6.45</td>
<td>0.333</td>
<td>5.530</td>
<td>0.333</td>
</tr>
<tr>
<td>API</td>
<td>(Kayes, 1985)</td>
<td>5.33</td>
<td>0.327</td>
<td>1.089</td>
<td>0.327</td>
</tr>
</tbody>
</table>

*aSafety and Reliability Directorate.*

*bHot shell cold core model.*

*c\( M \) is used as \( \log_{10} M \)

Table 1: estimating fireball duration and diameter (Satyanarayana et al., 1991).

All these equations can be used to estimate the diameter and duration of fireball. It is not easy to determine which of these equations is the best for making the estimations. However,
previous comparative analyses have revealed that the duration and the diameter of the fireball can be predicted by adopting the correlations given below (Casal et al., n.d.):

\[ D = 6.14M^{0.325} \]  \hspace{1cm} (7)

\[ t = 0.41M^{0.340} \]  \hspace{1cm} (8)

where the units are m, kg, and s for D, M and t respectively.

It should also be noted that there are just but a few experimental data available for backing up the comparative analysis given above (Le Métayera et al., 2005). Moreover, these data are not always accurate, although they are obtained from actual accidents involving large fireballs as the films are either bad or incomplete. The difficulties experienced in experiments conducted on a large scale make the studies involving fireball accidents happening time to time in the transportation of certain materials as well as in the industries quite complicated.

Although, the correlations allows for the estimation of the size of the fireball, it is worth noting that the fireball’s size and position change continuously, consequently changing the thermal radiation. It has been revealed by available films of BLEVE accidents that the growth of fireball is occurs quickly up to its optimum diameter before remaining constant for a short duration of time and then dissipate. The solid body model shown in equation 9 is often used in the estimation of the thermal radiation by a surface at a specific distance (Casal et al., n.d.):

\[ I = \tau \times F \times E_p \]  \hspace{1cm} (9)

Where \( I \) is the thermal radiation, \( \tau \) is the atmospheric transmissivity, \( F \) is the view power and \( E_p \) is the emissive power. It is, therefore, necessary to know the value of the atmospheric transmissivity, the view power, the emissive power as well as the distance between the target and...
the flame. The distance can be determined by estimating the height of the location of the fireball. The height varies with the substance as it is a function of specific volume as well as the fuel’s latent heat of vaporization. Various correlations have been suggested for the estimation of this height; equation 10 shows the simplest of these correlations (Casal et al., n.d.):

$$H = 0.75D$$  \hspace{1cm} (10)

Where $H$ is the height of the location of the center of the fireball measured in meters (m) and $D$ is the diameter of the fireball calculated using equation 7.

The atmospheric transmissivity can be estimated by adopting equation 11 below (Casal et al., n.d.):

$$\tau = 2.02(P_wX)^{-0.09}$$  \hspace{1cm} (11)

Where $x$ is the surface receiving the radiation, $P_w$ is the pressure.

The maximum view factor corresponds to the sphere and the plane orthogonal to its radius. Calculating the maximum view factor is quite simple because of the geometrical simplicity of the system and is given by the equation 12 below (Casal et al., n.d.):

$$F = \frac{D^2}{4r^2}$$  \hspace{1cm} (12)

Where $r$ is the distance between the center of the fireball and the surface receiving the radiation and $D$ is the diameter of the fireball calculated using equation 7.

Finally, the emissive power is calculated using equation 13 given below (Casal et al., n.d.):
\[ E_p = \frac{\eta M H_c}{\pi D^2 t} \]  

(13)

Where \( H_c \) is the heat of combustion (kJkg\(^{-1}\)), \( D \) is the diameter of the fireball calculated using equation 7, \( t \) is the time duration of the fireball calculated in equation 8 and \( \eta \) is used in the estimation of the energy emitted as thermal radiation (its maximum value is limited to 0.4) and is calculated using equation 14 below (Casal et al., n.d.):

\[ \eta = 0.27 P_0^{0.32} \]  

(14)

Where \( P_0 \) is the relative pressure within the container just before the explosion and is measure in MPa.

2.6.2 Mechanical Energy Released During Explosion

The mechanical energy contained within a container is released when the container bursts during a BLEVE explosion (it should not be forgotten that the units of pressure is energy per unit volume). The content of the vessel increases in volume instantly due to the expansion of the vapor within the container at the moment of explosion and the vapor from the superheated liquid. During the BLEVE explosion, the energy released is distributed as follows:

- As the energy of the pressure wave
- For heating the environment
- As the kinetic energy of the projectiles
- As the potential energy of the fragments

The relative distribution of the released energy changes with respect to the specific conditions of the explosion. It is quite difficult to determine the accurate quantity of energy that will contribute to the pressure wave (Le Métayera et al., 2005). Furthermore, type of failure
(whether ductile or fragile) is another important aspect of the conditions for explosion. It is a common for fissures to form as the walls of the tank start to thin due to plastic creep when the wall is heated and stressed. When the effect is focused in one location, such as in the case of a jet fire, the growth of the fissures may stop as the fissures enter thicker and stronger materials (Abbasi and Abbasi, 2007). In some cases, the fissures may bring about instantaneous depressurization as well as a significant flashing effect within the liquid. Consequently, there may be pressure recovery which may initiate in a crack resulting in the bursting of the tank as well as BLEVE.

On the other hand, widespread thermal effect (such as in the case of a pool of fire) is associated with continuous growth of the fissure which causes the bursting of the tank and finally BLEVE (Chan et al., 2007). The mode of the failure dictates the propagation speed. The crack speed propagated by the wall thickness which has been reduced by the plastic creep is different from the one that has been propagated by shear failure through thicker material (). The crack velocity has an upper limit which is related to the density and yield strength of the material (). The actual propagating velocity, which can attain velocities of 200ms\(^{-1}\), is usually less than the limiting velocity.

The energy released by the vapor initially in the vessel is given by equation 15 as shown below (Casal et al., n.d.):

\[
E_v = m(u_1 - u_2)
\]  

(15)

Where \(E_v\) represents the energy released as vapor expands (kJ)

\(m\) represents mass of the vapor inside the vessel during failure (kg)
\( u_1 \) is the vapor’s internal energy during the bursting of the vessel (kJkg\(^{-1}\))

\( u_2 \) is the vapor’s energy after the expansion to atmospheric pressure (kJkg\(^{-1}\)).

Suppose the expansion isentropic and the vapor behaves like an ideal gas, the energy equation becomes (Casal et al., n.d.):

\[
E_v = 10^2 \left( \frac{PV}{\gamma - 1} \right) \left( 1 - \left( \frac{P_a}{P} \right)^{(\gamma-1)/\gamma} \right)
\]

(16)

Where \( E_v \) represents the energy released as vapor expands (kJ)

\( P_a \) is the atmospheric pressure (bar)

\( \gamma \) is ratio of specific heats

\( V \) is the initial volume of vapor (m\(^3\))

\( P \) is the pressure in the container just before the explosion (bar)

2.6.3 Pressure Wave

The pressure wave resulting from an explosion can be determined by using the equivalent TNT mass. Although this method is quite simple, it has some inaccuracies since the energy released in the BLEVE explosion of a vessel has a lower velocity compared to that released in a TNT explosion. The other source of inaccuracy is due to the fact that the volume of the vessel is significantly larger than in the case of equivalent amount of a conventional explosive.

One of the inaccuracies is eliminated by correcting the distance between the explosion center and the place of the pressure wave because the initial volume occupied by the energy
emitted during the explosion is significantly larger than the one that can be occupied by an equivalent mass of TNT. The scaled distance, \( d_n \), is used in making the correction. The scaled distance, \( d_n \), uses the principle that when two charges of different sizes but of the similar geometry and same explosive detonate in the same atmosphere, there will be generation of similar pressure waves at the same scaled distance, \( d_n \). The same principle is applicable in the case of two different explosives by considering the fact that these two types of explosion having similar overpressure will produce in same effects.

The scaled distance is directly proportional to the real distance and inversely proportional to the cube root of TNT mass as shown in equation 17 (Casal et al., n.d.):

\[
d_n = \frac{d}{(\beta W_{TNT})^{1/3}}
\]  

(17)

Where \( d_n \) is the scaled distance (m kg\(^{-1/3}\))

\( d \) is the real distance from used in estimating the over pressure (m)

\( \beta \) is the fraction of the emitted energy converted in pressure wave

The value of the scaled distance, \( d_n \), graph in figure 4 can then be used in estimating the overpressure by using the graph shown in figure 4 below:
2.6.4 Missiles

It is difficult to quantify the projectiles from BLEVEs due to their random behavior. The explosion throws fragments which have restricted and directional action, although its radius of destructive effects is larger than that of the pressure wave as well as the thermal effect of the fireball. A domino effect may result if tanks and equipment are destroyed by the fragments. A velocity ranging between 4 to 12 ms\(^{-1}\) is needed by a fragment to penetrate a similar tank, although a fragment in a BLEVE explosion can attain a maximum velocity ranging from 150 to 200 ms\(^{-1}\). The two types of projectiles from BLEVE that are found in conventional expansion of containers include the primary projectiles and the secondary projectiles. Primary projectiles consist of pieces of the container whereas the secondary projectiles are generated from objects such as bricks, pipes, and bars, among other nearby objects accelerated by the explosion. The
number of primary projectiles is dependent on the shape of the vessel, the type of vessel failure, as well as the severity of the explosion.

It is common for a BLEVE to involve ductile failure, meaning that the cracks propagate at low velocity and without branching. A fragile failure usually results in a few fragments, and the number of projectiles will be as low as ranging from 2 to 15 (Ermakov et al., 2009). According to Le Métayera (2005), a fragile failure will typically have less than 5 projectiles. When cylindrical tanks are involved, the initial cracks follow an axial direction before changing and following a circumference, such as along a welding. This results in the breaking of the vessel into two pieces: the front section of the vessel and the backside (or the bottom) of the tank. Previous results of analyses of various BLEVE cases involving cylindrical tanks were summarized in the table below:

<table>
<thead>
<tr>
<th></th>
<th>With projectiles</th>
<th>Without projectiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Due to fire</td>
<td>89</td>
<td>24</td>
</tr>
<tr>
<td>Without any fire</td>
<td>17</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 2: Number of projectiles in BLEVE (Casal et al., n.d.)

There can be three projectiles resulting from cylindrical tanks. In some cases, there can be two types of failure if three fragments are involved. The vessel can be divided into the central body and two bottoms, or it can first be divided into a bottom and the rest of the vessel (two fragments) before the rest of the vessel is further divided through imaginary line that may be viewed as the separation of the vapor and the liquid as illustrated in figure 5. The bottom part often breaks by the welding or it can break at a distance of about 10 percent of the entire length of the vessel in case there is no welding.
The projectiles from cylindrical tanks can attain a distance that is greater than the one attained by fragments from spherical vessels. In order to predict the range of cylindrical tank projectiles, especially the tube fragments, the expressions given below have been suggested (Casal et al., n.d.):

\[
  l = 90M^{0.33}; \quad \text{for tanks whose capacity} \ < 5m^3 \quad (18)
\]

\[
  l = 465M^{0.1}; \quad \text{for tanks whose capacity} \ > 5m^3 \quad (19)
\]

Where \( l \) is the range of the projectiles (m) and \( M \) is the mass of the substance in the vessel (kg).

The difference between the two expressions comes about because of the reduced relative effect of drag with increase in the size of the tank (Chen et al., 2007). This is because increase in the capacity beyond 5m³ results in the increase in the length of the tank instead of increase in the diameter of the tank. The two expressions were obtained by making the assumption that the tank is containing liquefied petroleum gas (LPG) and 80% full at the time of failure, and that the fragments under consideration were launched at an optimum angle, that is, 45° to the horizontal. However, the actual ranges of most fragments will be less than those predicted by equations (18) and (19).
2.7 Prevention Measures

Emergency cases that may lead to a BLEVE fireball type of accident are quite challenging to improvise sufficient actions for controlling the situation. It is dangerous to have a plan that will require the presence of people due to the fact that it is not possible to anticipate when explosion might occur. It is appropriate for preventive actions to be taken before hand ( ). The risk of a BLEVE may be minimized considerably to levels which are tolerable if various measures such as the ones listed below are taken at the same time.

2.7.1 Sloping ground

It is appropriate to design the installation in such a way that any leak of the liquefied petroleum gas (LPG) could be removed immediately from the section in which there is a tank that need protection. The ground should be sufficiently smooth and there should be a minimum slope of 1.5 percent (2.5 percent is appropriate). There should be a drainage system in place that leads to a tank or a trench that is distant enough to avoid any contact between them and the flames. Furthermore, the case of the wind should be taken into consideration by ensuring that the flames can make an inclination of $45^\circ$ and a sufficient drag as well as being able to cover a distance which doubles the diameter of the trench (Abbasi and Abbasi, 2007).

2.7.2 Thermal insulation

It is appropriate to blanket the walls of the tank with a fireproof material which is of sufficiently low thermal conductivity. This will ensure that heating of the vessel which causes pressure increase in case of fire will be delayed significantly. Moreover, in case of long emergency, the heat flow of the system will be significantly reduced by the thermal insulation, making it possible to prevent explosion by using the safety valve. It should be noted that fireproofing relies a lot on the efficient operation of the safety valve. However, the valves are not
designed in such a way that they can be able to solve such types of fire emergencies on their own due to the fact that their cross-section may be excessive. Fireproofing can only guarantee protection for a limited time (about five hours). According to Ermakov et al. (2009), thermal insulators are the most appropriate devices for road or railway tanks.

It may be necessary to install other protective systems such as cooling vessel in order to complement thermal insulation. It should be ensured that structural elements such as the legs of the vessel are insulated in order to prevent the vessel from falling in case of excessive heating. Installation of thermal insulation should be carried out in such a way that its effectiveness can be guaranteed during fire emergency and also to allow for the periodical inspection of surface of the tank and other structural elements.

2.7.3 Cooling with water

The use of water sprinklers in the protection of vessels which have been exposed to the direct action of fire is a common practice which has been proven to be reliable over the years (). It is recommended that water should be used from the first moments, with the wall to be cooled totally covered with a layer of a particular thickness, especially the sections that are directly in contact with the flame. The needed rate of flow of water has to be kept constant. However, there are situations in which the action of firefighters and the inevitable increase in the consumption of water have resulted in significant reduction in the pressure in the network, leading to reduction in the rate of flow of water to a minimum value which is dependent on the circumstances. However, in order to have the tank that has been engulfed in fire protected, the rate of flow of water will depend on the circumstances.

Chen et al. (2007) stated that if the safety is designed correctly and working normally, the rate of flow of water should not be lower than $8 \text{ l m}^{-2} \text{ min}^{-1}$. Other researchers have stated that the rate of flow of water below $10 \text{ l m}^{-2} \text{ min}^{-1}$ in case of direct contact with fire is dangerous. As such,
a rate of flow of water of 15 l m\(^{-2}\) min\(^{-1}\) has been generally accepted by most researchers (). It has further been recommended that water need to be applied before the wall of the tank reaches a temperature of 80°C. Smaller rates of flow can be used in case there is only thermal radiation and no flame impingement.

In case the flame impingement is on the wall, the type of the flame dictates the thermal flux (the thermal flux is about 100 kW m\(^{-2}\) in the case of a pool of fire whereas the thermal flux can reach 350 kW m\(^{-2}\) for a flame which is highly turbulent). If such situations occur in the zone of the wall that is above the surface of the liquid then rates of flow can be greater than 25 l m\(^{-2}\) min\(^{-1}\) may suffice.

It should also be ensured that all the safety elements, such as valves and pies, among others, have been designed in such a way that they can resist the action of fire as well as the high temperatures that are common during emergencies; if not, such elements might may collapse in the initial stages of emergency, especially if they are directly exposed to the flames.

**2.7.4 Pressure reduction**

Reducing the pressure ensures that the walls of the vessel will experience less force, consequently reducing the risk of explosion in case there is increase in temperature. It has generally been recommended that the installed devices should be able to minimize the pressure to about 7 bar (relative) or to half the design pressure in a quarter of an hour (15 minutes). However, the time can be longer in case the vessel is thermally insulated and the ground is slope. The depressurization can make it necessary to have in place a remote control valve instead of the safety valve. Care should be taken because there are some situations in which a strong depressurization may bring about extremely low temperatures which may result in fragile conditions in the steel.
2.7.5 Mounding or Burying

Some researchers have suggested total or partial burying of the vessel (). Burying protects the vessel against thermal radiation for a large period of time in addition to offering protection against missiles impacts. However, corrosion of the walls of the tank is one of the major disadvantages of adopting this measure.

2.7.6 Water Barriers

This relatively new system is applied by having in place a set of sprayers to generate curtains of fine spray of water. Such curtains absorb the vapor released from the leak before dispersing them into the atmosphere, consequently minimizing the risk of ignition.

2.7.7 Protection for Mechanical Impacts

It is appropriate to protect tanks containing materials which have been superheated from impact from moving vehicles, cranes or other equipment.

2.7.8 Avoiding Overflow

Overflow is one of the incidents that have caused a lot of BLEVEs. However, installation of various adequate devices such as safety valves and level controls has ensured it can be avoided, making it to be less common nowadays (Abbasi and Abbasi, 2007).

2.7.9 Minimum Separation Distances

Various regulations have been put in place to establish the minimum distances between vessels. Minimum separation distances are important in cases of thermal radiation, especially when avoiding direct contact between the flames from one vessel to the walls of another vessel. However, the minimum separation distances do not guarantee protection in case of explosion due to projectiles and blasts.
2.7.10 Actuation on Initiating Mechanisms
Various systems have been suggested to help in avoiding homogeneous nucleation such as installation of aluminum mesh within the tank as well as the addition of nuclei for initiating boiling. Although these systems have been adopted for specific applications, they are still under investigation.

2.8 Precaution Measures to be taken During Emergencies
It is advisable to approach the leak or fire from upwind whenever possible. It is necessary to keep nozzle as low as possible and to aim it upwards in order to disperse the flaming vapors or gases. Multiple lines should be used as required by the situation.

\[\text{Figure 7: dispersing the flaming vapors or gases upwards (Elatabani, 2010)}\]

Everyone should be cleared from the vapor cloud area. The areas in the vapor cloud’s path should be evacuated immediately. It is necessary to shut off all sources of ignition simultaneously. It should not be forgotten that the Liquefied Petroleum Gas (LPG) is denser than air.
Everyone who is not actually engaged in the operation should be kept at least 1000 feet from the rear and the front of the tank as well as at least 500 feet from the tank’s sides.

It is appropriate to call for the assistance of the possible, if they are not already present in the scene, in order to establish and maintain the zone of safety. It may also be appropriate to call for help of Fire Department Units if necessary.

2.8.1 Handling a leak with a fire

It is necessary to stop the leak before extinguishing the fire, unless the condition is extremely unusual.
A heavy fog stream should be used in protecting the member as the member is shutting off the valve in case the only valve that can stop the gas flow is exposed to flame or heat or is involved in the fire. The flashback which may have the member entrapped in the flames need to be prevented by proceeding slowly with the operation. It is necessary for the involved members to wear protective fire clothing as well as masks.
Large quantity of water should be supplied on tank surfaces which are exposed to heat from auto exposure or from any other source of fire. It is appropriate to approach the tank from its sides while applying water to all the valves and piping as well as all the exposed surfaces.

*Figure 12: supplying large quantity of water to protect the tank (Elatabani, 2010)*

Operating personnel, chauffeurs or any other qualified officer with the knowledge of how to stop the flow of the gas or with any pertinent information that may be helpful in the operation should be consulted. In case it is not possible to shut off the flow of the gas or if the escaping gas is on fire, it is advisable to apply large quantity of water on the piping and the tank so as to permit controlled burning in order to allow the contents of the tank to be consumed by fire without risking the tank or pipe failure. It should be ensured that the fire is not extinguished.
Figure 13: using large quantities of water to control the fire (Elatabani, 2010)

The fire extinguishers that are appropriate for the Liquefied Petroleum Gas (LPG) fires include the portable dry chemical extinguishers and carbon dioxide extinguishers. They need to be applied in the base of the fire as shown below.

Figure 14: using fire extinguishers (Elatabani, 2010)

Tank failure is common in the vapor area of the tank under fire conditions when water cannot be supplied sufficiently to prevent the softening or weakening of the metal to a point where the failure of the metal occurs.
Before the occurrence of the tank failure, there may be an increase in the volume of fire and/or the rise in the level of noise brought about by the rise in pressure inside the tank. This is sometimes accompanied by either bubble or blister being formed on the shell of the tank. It is advisable to withdraw operating force to safe area should any of these symptoms be present.

In ordinary circumstances, the tank involved in fire should not be moved; neither should there be an attempt of moving it because little can be saved when trying to minimize the hazard. However, should the condition in place make it necessary to move the tank, then the movement...
should be executed by putting the tank in upright position. It is not advisable to drag it in such a way that the valves and the piping may be damaged further. Furthermore, care should be taken to avoid damage to the valves and pipes when attempting to turn the tank upright, when removing the tank to some remote location or when facilitating product withdrawal. It is necessary to remove portable Liquefied Petroleum Gas (LPG) cylinders that are exposed to serious fire to a safe location.

![Figure 17: portable LPG cylinders removed to safe location (Elatabani, 2010)](image)

2.8.2 Liquefied Petroleum Gas (LPG) Leak without Fire

In case the Liquefied Petroleum Gas (LPG) which is escaping is not on fire, it is necessary to close all the valves which can stop the gas from flowing. As such, small lines like the copper tubing may be flattened to stop the flow of the gas. If there is a vehicle involved in the transportation of Liquefied Petroleum Gas (LPG), it is necessary to consult the driver. However, plant personnel should be consulted on how to shut off leaks if storage facility is involved.
Water spray can sufficiently be used to disperse Liquefied Petroleum Gas (LPG) vapor. As such, water should be used as soon as possible to direct the spray stream to cut off the normal path of vapor and to disperse the vapor to a location which is safe. It is not advisable for members holding the hose to enter the vapor cloud. They should be as close to the ground as possible behind the spray for them to be protected from radiant heat should the vapor be ignited unexpectedly.

It may be necessary to use heavy streams of water from a safe distance in case the water spray has not been effective in dispersing the Liquefied Petroleum Gas (LPG) vapor.
Chapter 3: Methodology

3.1 Research Purpose

This study is based on the findings various cases of BLEVE accident whose records have been used to determine the extent of the damage brought about by BLEVE explosion and determine the consequences on people and structures. According to Zikmund (2000, 50), research study can be carried on a particular phenomenon by describing, exploring or explaining the phenomenon. This study utilizes descriptive research method. According to Robson (2002, 59), descriptive research method is carried out in order to portray accurate profile of events, situations or persons. On the other hand, the purpose of this research is exploratory since it gives greater understanding of the mitigation strategies and measures for BLEVE (Robson, 2002).

There are two major approaches that a researcher can employ in collecting information – quantitative and qualitative approaches (Creswell, 2003). In this study, a qualitative approach has been adopted instead of the quantitative approach. This is due to the fact that quantitative approach is employed by a researcher that seeks to measure variables, verify existing theories or
question them whereas qualitative approach is employed by a researcher that seeks to understand meanings and phenomenon, evaluate ideas or experience, determine the relationship between two items or understand human behavior and factors that cause such behavior (Creswell, 2003).

This research study also seeks to investigate the response of rescue personnel in case of BLEVE emergency, therefore, it evaluates human behavior to a given extent, and explores a particular phenomenon, that is BLEVE explosion, and as such, qualitative research methodology is the most appropriate (Creswell, 2003). Advantages of qualitative research over a quantitative approach include:

- Provision of depth and detail: The information collected through qualitative research such as interviews looks deeper by taking into account attitudes, behavior as well as feelings as opposed to quantitative research whose dataset is narrower and sometimes superficial.

- Creates openness: By allowing people to expand their answers to interview questions, the respondent may open a new topic that may prove relevant to the subject matter.

- Does not promote pre-judgments.

According to Churchill and Dawn (2002, 274-275), the genres of qualitative research are becoming more important modes of inquiry not only for social sciences but also for applied fields such as social work, education, regional planning, nursing, community development, and management. The purposes for developing methods of opinion qualitative research is to enable researchers understand people as well as their perception. In addition, qualitative methods enable researchers to have a better understanding of the social as well as cultural contexts within which
people live. Furthermore, the researcher is also enabled by the qualitative research to have a first
hand experience and to perceive the context whereby actions and decisions occur.

A key motivation for the adoption of qualitative research is the ability of those involved
to talk about their experiences and perceptions, and this is one of the important things that
differentiate human beings from other creatures. This makes it possible for a researcher to find
out the thought of fellow human beings, since knowing what a human being is thinking is more
important than just being able to explain their actions.

Kisber (2010, 13) felt that qualitative researchers are obliged to satisfy the following
issues when carrying out their work:

i. **Transparency**

Transparency is the benchmark for carrying out a research as well as in presenting and
publicising findings. In other words, a qualitative research needs to be clear, explicit and open
with regard to the methods and procedure used.

ii. **Validity**

Validity of a qualitative research entails the trustworthiness of a qualitative study. Saunders et al.
(2003) explained, “Validity is concerned with whether the findings are really about what they
appear to be about.”

iii. **Access and consent**

The respondents to be interviewed in the qualitative research should be reachable either face to
face or through phone or mail. The respondents should also give their consent for participation in
the study.

iv. **Generalizability**
Generalizability of qualitative research is the particularizability in qualitative work as explained below.

v. Reflexivity

Reflexivity in qualitative research is the process of reflection on the research. A process of continuous reflection is necessary when carrying out interviews.

vi. Voice

In a qualitative research, voice refers to various, and usually conflicting, interpretive positions that need to be taken into consideration when representing data.

According to Rubin and Babbie (2009, 230), some of the recognizable strengths and weaknesses that characterize qualitative approaches to inquiry are as given below:

i. Depth of Understanding

Qualitative research is quite effective for studying attitudes as well as behaviours which are difficult to describe, and also for the study of social processes over a given period of time as explained by Grove (2005, 23). Thus, this method permits deep level of understanding, which is its key strength. Qualitative research methods can seldom be challenged to be “superficial”, a challenge that is common in quantitative research.

ii. Flexibility

Another major advantage associated with qualitative research is its flexibility. A researcher using qualitative research method may modify his/her research design at any time. Moreover, the researcher is always prepared to carry out a qualitative research when the occasion arises; whereas it is not easy for a researcher to initiate an experiment or a survey. Flexibility will help in adjusting the questions asked to the interviewees with respect to the answers they give to the questions.
iii. **Subjectivity**

Although the measurements of qualitative research are in-depth, they are usually quite personal. For instance, if a researcher may make a report that members of a particular club are conservative, it should be known that such a judgment is inevitably related to the researcher’s politics. When compared to quantitative research, such subjectivity of most qualitative research methods may be considered as either advantage or disadvantage. Subjectivity enables each of the interviewees to be asked questions that are relevant to them.

iv. **Generalizability**

Generalization is regarded as one of the major goals of science. Social scientists often study particular situations as well as events in order to generally learn about social life. Generalizability is one of the problems for qualitative research.

3.2 Data Collection Method

A major interest of researchers is to collect data that concerns the phenomena that they are interested in conducting a research study on. Data are the objects that can be used for making inference or reckoning. Some authors have defined the difference between data and information by stating that information is the knowledge that results from organization of data into useful form. Collins and Hussey (2009) explained that data can either be qualitative or quantitative, and that quantitative data is in numerical form whereas the qualitative data is in non-numeric form.

3.2.1 Primary and Secondary Data

Differentiation between primary and secondary sources of data is crucial in social research. Primary sources are data which are unpublished; that is, the researcher has directly
collected them from the target individuals or organization. The primary data are collected from fieldwork, interviews, and unpublished documents like minutes of meetings. On the other hand, secondary data are any data which a researcher has gathered from sources which had been published before. These are the data collected from previously published books, journal articles, and newspaper articles. Primary data has a greater weight than secondary data due to the fact that primary data adds credibility as well as richness to qualitative manuscripts. Primary data that has been collected by the researcher represent part of the added value that a researcher brings to the table. Case study has been adopted in this research study.

Chapter 4: Case Studies

4.1 Case study 1

The focus of this case study has been placed on the investigation conducted as a joint project (STEP-CT90-098) on the consequences of JIVE (Jet-fire Interaction with Vessels containing pressurized liquids). Investigation was conducted with a view to finding out the thermal response of propane tanks that have been subjected to attack by jet-fire as well as to assess how effective the mitigation techniques are.

Four field experiments were carried out to investigate the response of thermal of 4.5 tonne water capacity horizontal propane tank that had been filled partially to a jet fire. The jet fire was made up of an ignited, horizontal flashing liquid propane jet whose flow rate was approximately 1.5 kgs\(^{-1}\) from a nozzle with a diameter hole of 12.7mm. The nozzle’s position was 4.5 meters from the front surface and 100 cm (one meter) below the axial center of the tanks.
The exposures of the vessel were 200kWm\(^2\) which is double the exposure of hydrocarbon pool fire that engulfs a vessel fully.

Standard tanks of diameter 1.2 meters, capacity of 4,546 litres was used as well as 3,864 litre of propane (85 percent fill) and the Liquefied Petroleum Gas vessel whose length was 4 meters with semi-ellipsoidal end caps. The length of the center barrel was 3.276 meters and was constructed by the use of double rolled and longitudinally butt welded plates. The thickness of the walls was about 7.1mm and was made up of carbon low alloy steel. Pressure relief valves of standard size (1½" NTP ASME/BS 500 3090) were fitted in the tanks. External thermocouple walls were fitted into all the vessels. Thermocouples of diameter 1.5mm were used in measuring the interior temperatures, liquid, and vapor, at different levels. Remote calibrated pressure transducers were used in measuring the pressures of the liquid and vapor. Remote computer data acquisition system was used in monitoring all the transducers. About 5 cameras were used as separate videos and infra red thermal imaging were used for making recordings of the fireballs formed.

Commercial grade propane was used for the tank contents as well as for the jet fire fuel. Four vessels whose volume percent were 20%, 41%, 60% and 85% were examined under the jet fire attack from 0.9MPa sub-cooled liquid propane which had been ignited. Both video records and HSL documents provided detail and used to archive the obtained data. Additional analysis of tank remnants such as physical, micro and macro metallurgical examinations were undertaken as well as thermo-hydraulic and extensive video analyses of data were conducted.

4.1.1 Findings and Discussion
All the vessels failed catastrophically within 5 minutes and resulted in both BLEVEs and fireballs.
Examination of the thermo-hydraulic data revealed that decrease in the fill level led to increase in the time to first vent (85% fill reported multiple vents), decrease in the rate of pressure increase before vent, decrease in the rate of pressure increase after multiple venting, and diminishing in the pressure at failure (see table 3). The change in liquid wetted wall with the level of fill can be used in explaining most of the behavior shown in table 3.

<table>
<thead>
<tr>
<th>Tank (fill %)</th>
<th>C (20)</th>
<th>A (41)</th>
<th>B (60)</th>
<th>D (85)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Valve operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) cycles</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(b) (P/T)_{initial} (barg °C)</td>
<td>7.9/19</td>
<td>8.4/20</td>
<td>7.7/20</td>
<td>8.7/18</td>
</tr>
<tr>
<td>(c) P_{open} (barg)</td>
<td>18.6</td>
<td>18.8</td>
<td>18.1</td>
<td>18.3</td>
</tr>
<tr>
<td>(d) P_{close}</td>
<td>17.2</td>
<td>16.5</td>
<td>14.1</td>
<td>13.9</td>
</tr>
<tr>
<td>2. Pressurization (dP/dt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) before valve open</td>
<td>0.095</td>
<td>0.092</td>
<td>0.106</td>
<td>0.15</td>
</tr>
<tr>
<td>(b) after valve open</td>
<td>-ve</td>
<td>0.035</td>
<td>0.047</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3: Thermo-hydraulic Response of JIVE Vessels

All the vessel failures occurred in the same duration of time (251 ± 28 seconds).

Furthermore, the maximum and mean vapor wall temperatures were also comparable (810 ± 74E and 611 ± 90EC) as shown in table 4. The temperatures of the vapor wall metal were extremely variable owing to the jet fire impact. It was possible for temperatures to drop as low as 150°C locally (less than 500 mm) from the initial site of rapture. This may affect the strength of the metal and any over-pressure crack formed may bring about the arrest in the cooler, stronger, thicker and tougher wall during the unloading of the vessel due to the initial local vapor depressurization before the double phase re-pressurization.
Table 4: IVE Vessel Thermal Response at Failure (Venart, n.d.)

Table 5 shows the sizes of the initial ruptures that were formed in each of the four trials. Estimation of the sizes of the openings was carried out from the remnants of the tank and they were considered as the measure of the feather edge ruptures up to the point of initiation of fast fracture as $45^\circ$ shear lips in addition to little plastic contraction.

Table 5: Initial crack size, stress intensity factor and failure stress; JIVE Tanks (Venart, n.d.)

Table 6 summarizes characteristics of the resulting fireballs in the four tanks under consideration, including the duration, size, height, and Surface Emissive Powers (SEP) of the fireballs.
Table 6: Fireball height, duration, size, and Surface Emissive Powers (SEP) (Venart, n.d.)

<table>
<thead>
<tr>
<th>Tank (fill %)</th>
<th>Mass (kg)</th>
<th>SEP (kW/m²)</th>
<th>Duration (s)</th>
<th>Diameter (m)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mean</td>
<td>max</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (20)</td>
<td>279</td>
<td>410</td>
<td>640</td>
<td>3.5</td>
<td>45</td>
</tr>
<tr>
<td>A (41)</td>
<td>710</td>
<td>278*</td>
<td>484*</td>
<td>5.5</td>
<td>45</td>
</tr>
<tr>
<td>B (60)</td>
<td>1272</td>
<td>365</td>
<td>550</td>
<td>6.5</td>
<td>55</td>
</tr>
<tr>
<td>D (85)</td>
<td>1708</td>
<td>350</td>
<td>580</td>
<td>7</td>
<td>45</td>
</tr>
</tbody>
</table>

*British Gas Measurements

4.2 case study 2

This case study concerns the accident involving LPG in New Mexico in November 19, 1984. The accident involved a major fire and multiple catastrophic explosions at a storage and distribution terminal of Liquefied Petroleum Gas (LPG). The accident not only led to total destruction of terminal but also led to the death of about 600 people, caused injury to about 7,000 people, and evacuation of 200,000 people. A seismometer which was 20 km away from the terminal detected the blasts. A total of nine explosions were recorded on a Richter Scale, the largest explosion being 0.5.

The cause of the accident has not yet been definitely established due to the magnitude of the damage. However, some evidence show that a large quantity of Liquefied Petroleum Gas (LPG) appeared to have leaked from a tank or a pipeline, spilling in an enclosed wall, before forming a flammable cloud which cloud of vapor which ignited. The flash fire and explosions resulting from the ignition impacted other Liquefied Petroleum Gas (LPG) tanks, pipes and storage spheres, releasing additional Liquefied Petroleum Gas (LPG) and exposing nearby tanks to fire. Most of the explosions were of BLEVE type. The BLEVE explosions were caused by the Liquefied Petroleum Gas (LPG) vessel failure due to exposure to heat or flames from the fire.
A report made after the accident indicated that there had been various problems with bypassed or inoperative safety devices, inaccurate instruments, a missing relief valve, as well as poor house keeping.

The following risk mitigation measures were suggested to be put in place to avoid such accidents:

i. It should be ensured that the fixed water spray fire protection systems are available and in good working condition. Such systems provide important protection against BLEVE.

ii. Fire fighting procedures should be understood with a view to protecting emergency fire rescue personnel.

iii. Any problem with protective safety systems need to be reported immediately and follow up must be made to ensure that the problems are fixed.

iv. The worst events that can happen in the plant should be known as well as the systems that have been put in place for ensuring that such events do not occur and that responsibility is taken for the verification that the systems are working properly.
Conclusion

A coherent and plausible has been presented by the analyses and interpretation of the Jet-fire Interaction with Vessels containing pressurized liquids (JIVE) tank failure data. The tank failures can be best explained by the resulting fracture which is arrested and then re-initiated before becoming critical. There also has to be some physical reasons that can be used in explaining the crack re-initiation that transitioned to fast fracture as observed in all the experiments in the case study.

After arresting the cracks in a ductile material, significant additional energy is required for re-initiation. Liquid fill influence on the time delay appears to be a function of heat transfer as well as the distance to the surface of the boiling Liquefied Petroleum Gas (LPG). Some of the observations made in the case study contradict earlier literature on liquid superheat, making it necessary to design further experiments that will be in line with BLEVE and fireball models.
References


Understanding BLEVEs. Centre d’Estudis del Risc Tecnolo`gic (CERTEC), Universitat Polite`cnica de Catalunya—Institut d’Estudis Catalans, Barcelona, Catalonia, Spain, pp 7-19.


Venart, J. E. S. (n.d.) Boiling liquid expanding vapor explosions (BLEVE); possible failure mechanisms and their consequences