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Blast overpressures from medium scale BLEVE tests

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Abstract

The measured blast overpressures from recent tests involving boiling liquid expanding vapour explosions (BLEVE) has been studied. The blast data came from tests where 0.4 and 2 m^3 ASME code propane tanks were exposed to torch and pool fires. In total almost 60 tanks were tested, and of these nearly 20 resulted in catastrophic failures and BLEVEs. Both single and two-step BLEVEs were observed in these tests. This paper presents an analysis of the blast overpressures created by these BLEVEs. In addition, the blast overpressures from a recent full scale fire test of a rail tank car is included in the analysis.

The results suggest that the liquid energy content did not contribute to the shock overpressures in the near or far field. The liquid flashing and expansion does produce a local overpressure by dynamic pressure effects but it does not appear to produce a shock wave. The shock overpressures could be estimated from the vapour energy alone for all the tests considered. This was true for liquid temperatures at failure that were below, at and above the atmospheric superheat limit for propane. Data suggests that the two step type BLEVE produces the strongest overpressure. The authors give their ideas for this observation.

The results shown here add some limited evidence to support previous researchers claims that the liquid flashing process is too slow to generate a shock. It suggests that liquid temperatures at or above the Tsl do not change this. The expansion of the flashing liquid contributes to other hazards such as projectiles, and close in dynamic pressure effects. Of course BLEVE releases in enclosed spaces such as tunnels or buildings have different hazards.

Keywords: BLEVE; Blast overpressure; Shock

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1. Introduction

If a tank containing a pressure liquefied gas (PLG) ruptures there are two possible outcomes:

(i) Partial failure with finite rupture and transient single or two phase jet release
(ii) Complete rupture with total loss of containment (TLOC) and BLEVE

BLEVE stands for, boiling liquid expanding vapour explosion. Reid (1979) suggested that for a BLEVE to take place, the sudden pressure drop must take the liquid to the superheat limit spinodal Carey (1992) so that homogeneous nucleation takes place in the bulk liquid. If the definition of a BLEVE requires homogeneous nucleation then it is possible there has never been a real BLEVE. If we define a BLEVE as simply a "boiling liquid expanding vapour explosion" then we do not need homogeneous nucleation. We have observed many explosions from the TLOC of propane pressure vessels. We do not think any of them involved bulk homogeneous nucleation.

In this paper we will use the following definition of a BLEVE:

A BLEVE is the explosive release of expanding vapour and boiling liquid when a container holding a PLG fails catastrophically.

A key word here is catastrophic failure. In this case catastrophic failure means the tank is fully opened to release its contents nearly instantaneously. The BLEVE does not cause the tank rupture. The BLEVE results from the sudden opening of the vessel. In most cases this means the tank is flattened on the ground after the BLEVE and parts (e.g., tank end caps) may be thrown over large distances.

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A BLEVE generates hazards including shock overpressures, high velocity expanding vapour and flashing liquid, projectiles and release of the contained PLG. If the PLG is flammable then there is a fire or explosion hazard. If the material is toxic then there is an exposure hazard.

A TLOC of a PLG vessel can take place for a number of reasons including: flawed materials, fatigue, corrosion, poor manufacture, thermal stresses, pressure stresses and reduction in material strength due to high wall temperatures. Any one of these could result in a TLOC. However, in most accidents it is a combination of several of the above factors that add up to cause the failure of a vessel.

A BLEVE is a physical explosion that follows the sudden loss of containment of a PLG. When a PLG experiences a sudden pressure drop (due to loss of containment) the bulk of the liquid is sent into a state of superheat. If the degree of superheat is large it causes rapid and violent flashing of the liquid. Generally speaking, a large degree of superheat requires a very rapid pressure drop.

Researchers have shown that BLEVEs can take place without reaching the superheat limit. However, it has been shown (see for example Barbone, Frost, Makis, & Nerenberg, 1994) that the flashing response to the sudden pressure drop will be most powerful if the atmospheric superheat limit is reached. In real world pressure vessels with rough internal surfaces and with liquid with impurities and pre-nucleation of bubbles, reaching the superheat limit is very unlikely. Heterogenous nucleation starts well before the superheat limit is reached.

There is coupling between the tank failure and the fluid properties. When a vessel begins to rupture the growing fissure acts like a relief valve and this triggers outward flow and a pressure drop in the vessel. This leads to liquid flashing and a pressure transient in the vessel. Birk and Cunningham (1994) presented a BLEVE map based on fire tests of 400 L propane tanks. This map showed that the strength of the tank and the liquid fill level and temperature determine if a tank will BLEVE or not. For tanks severely weakened (e.g., by fire or by severe corrosion) a BLEVE can take place with the propane at ambient temperature. In these cases the vapour space energy may be sufficient to drive the tank to catastrophic failure. However, as the tank strength increases, the liquid energy must play a more important role in the tank failure process. With high liquid fills and temperature, any rupture that forms results in strong flashing of the liquid. This flashing causes pressure recovery in the tank and this can drive the tank to catastrophic failure and BLEVE.

This paper is about estimating overpressures generated by BLEVEs. In a recent paper, van den Berg, van der Voort, Weerheijm, & Versloot, (2006) looked at numerically calculating BLEVE overpressures assuming near-instantaneous releases of liquid. They did this by solving the Euler equations in various domains. This is very valuable. We need these detailed analytical tools. However, we also need simple calculation procedures to estimate BLEVE hazards. This paper is about simple analysis techniques.

The literature presents techniques to estimate BLEVE overpressures as a function of the PLG properties, the vessel size, and the distance to the target. Many of them use the liquid energy to predict the BLEVE overpressure. However, evidence in several references (see for example AIChE Centre for Chemical Process Safety, 1994; Baker, Cox, Westine, Kulesz, & Strehlow, 1983) point to the fact that the shock overpressure from BLEVEs is relatively low and that data suggest that the liquid phase change does not generate a shock. For this reason most published methods grossly overestimate the BLEVE overpressure, especially in the near field.

2. Sequence of events

Let us consider a case where a pressure vessel is partially filled with a PLG and its vapour. For the liquid to be a PLG it must be stored at an elevated pressure at ambient temperature. This means the liquid is at a temperature above its normal atmospheric boiling point.

If a small hole forms in the vapour space wall of this tank then vapour will escape. This causes a small pressure drop which sends the liquid into a small degree of superheat which then causes some of the liquid to flash to vapour. This will take place near the liquid surface at the tank wall where there are nucleation sites for boiling. The newly generated vapour will act to maintain the pressure in the vessel. The generation of vapour takes heat energy from the liquid. Overtime the venting and boiling process cools the liquid and the pressure and temperature in the vessel will decrease.

If the hole is large then the vapour mass flow thought the hole will be large and the pressure drop will be greater and more rapid, resulting in more superheat, and stronger flashing. With strong flashing the liquid height will swell significantly due to the vapour bubbles rising through the liquid. The flow out of the vessel will probably entrain liquid droplets (i.e., two-phase flow) thus increasing the mass flow and thrust forces.

If the vessel opens fully and rapidly, then the vapour space energy will be released suddenly and a shock wave will be produced. This shock will move out into the surroundings at supersonic speed. The sudden loss of the vapour space will send the liquid deep into a state of superheat. The liquid will respond with a powerful flashing response. This is a BLEVE. The question is, does the liquid phase change produce a shock? Is the liquid phase change an explosion? This is still a question.

3. Single and two-step BLEVEs

BLEVEs have been observed (Birk, Cunningham, Ostic, & Hiscoke, 1997) where the tank failure process is very rapid. One moment the tank is there, and next moment it is gone. In regular video this means the tank is there in one frame and in the next frame it is gone. In high speed video (say 500 frames/s) the tank rupture process is better resolved. The hole starts as a pin hole and it grows to traverse the length of the vessel in short order. In such a rupture the fissure traverses the entire tank length at speeds greater than 200 m/s (Birk et al., 1997). The crack travels faster than the speed of sound in the vapour space. For a 2 m long tank the event is over in 10 ms. This is usually called a rapid or single-step BLEVE.

BLEVEs from slow ruptures have also been observed (Birk, VanderSteen, Davison, Cunningham, & Mirzazadeh, 2003). In these two-step BLEVEs the process starts with a small fissure and then this fissure stops growing. On a 2000 L tank the fissure may stop when it is 5 or 10 cm long. The powerful two-phase flow out of the fissure causes a pressure drop in the tank that drives the liquid into superheat. The resulting boiling response causes a pressure transient in the tank. This transient may involve pressure recovery. We have tried to measure if there is pressure overshoot but have not been successful. There is just too much violent action taking place at this instant to measure these details with confidence. This pressure transient combined with possible flow-induced cooling at the crack tips (Venart, 2000) makes the crack unstable and causes the crack to start to grow again. At some point the crack length reaches a critical length and the crack growth rate accelerates and the tank is opened fully. This leads to a TLOC and BLEVE. This process can take seconds for the crack to travel the full length of the tank. We have observed times on the order of 2 s on a 2000 L tank for this slow failure. The average crack speed can be on the order of 1 m/s, but of course in the final phase the crack is once again growing at upwards of 200 m/s.

Once the tank is fully open, the vapour space releases a shock. Fully open means the tank open area is of the order of the tank cross-section. The liquid must flash to vapour to do work on the surroundings. It must flash very rapidly to produce its own shock. It is believed the liquid responds too slowly to produce a shock of its own. We have never seen a blast overpressure plot from a real pressure vessel BLEVE where a shock can be attributed only to the liquid expansion.

It is the opinion of the authors that the two-step kind of BLEVE tends to lead to the largest blast overpressures. Limited evidence of this will be shown later in this paper. As noted above, the flashing starts before the tank is fully open and the shock is released. Flashing begins while the vessel is starting to open up. For this reason it is expected that the initial shock strength can be estimated by assuming the energy for the shock comes only from the vapour space energy at the time of full opening of the vessel. This can be approximated from the vapour space energy just before failure of the vessel. The initial shock overpressure can be estimated from the well known shock tube equations (see for example Baker et al., 1983). The decay of pressure with distance in the far field can also be estimated from well established scaling laws (Baker et al., 1983).

Data suggests the violent liquid flashing following the vapour space shock is not fast enough to produce its own shock. As will be shown later, this appears to be true even if the liquid temperature exceeds the atmospheric superheat limit temperature Tsl. However, there may be a great deal of thermal energy stored in the liquid and therefore one does have to consider where it all goes. The flashing will cause violent two-phase jetting which can cause projectile effects, tub-rocket effects, and close in pressure loading of objects. The duration of this loading may be very long compared to shock loading effects. The jetting and pressure loading is very local, and directional in nature. For BLEVEs that are in the open, the flash vaporization may not have much effect other than producing projectiles. However, in enclosed spaces such as chemical plants or tunnels, the flash vaporization may do considerable damage.

Why should a two-step BLEVE produce a stronger blast? With a very rapid single step type failure it is the vapour space energy that opens the tank and then whatever energy is left over goes into producing a shock. In such a rapid failure the liquid has not had time to get involved with the opening of the vessel. In a two-step BLEVE the tank failure is so slow the liquid has time to assist in the failure process. The flashing liquid replenishes the vapour space energy during the process. At the instant the tank opens fully, there is simply more vapour energy to produce the shock. As one would expect, the exact energy available is difficult to estimate because the work done on the tank wall is difficult to calculate. However, this tells us the upper limit on the energy put into the shock wave is 100% of the vapour isentropic expansion energy at the tank failure pressure and the vapour condition at the saturation state.

3.1. *The two-step BLEVE*

The definition of an explosion is, a sudden energy release that causes a loud noise Baker et al. (1983). This noise is a pressure shock. A BLEVE makes such a noise. During our testing of 400 and 2000 L propane tanks we were able to observe the noise from a position 370 m from the tank side. In many cases we also measured the blast overpressure at 10 and 20 m from the cylindrical tank sides and ends.

In most BLEVEs we heard a loud, low frequency boom noise when the tank failed catastrophically. But in a few cases, the two-step BLEVE cases, there was a very different, high frequency crack noise, like that from a whip or a nearby lightning strike. When this happened we assumed that this case must be a much stronger shock.

We know that a shock gets thicker as it travels due to dissipation of energy. A thick shock will give a lower frequency bang noise. This is like the noise from a far away lightning strike. The further away you are, the lower the frequency of the noise. We also know the shock overpressure gets smaller with distance. So a low-frequency boom suggests a lower overpressure.

The following sequence of figures shows the early stages of a two-step BLEVE of a 2000 L ASME Code propane tank. The tank was heated by fire. The tank failed at the top due to high temperature in the vapour space wall. The high temperatures resulted in plastic deformation of the wall. At some point a small fissure formed to start the two-step BLEVE process. In this type of BLEVE the wall fails in an axial fissure but the crack stops growing. The crack releases a two-phase liquid and vapour jet. The resulting pressure transient and flow through the fracture causes the fracture to restart to take the tank to catastrophic failure and BLEVE. The details of this restart process is still being studied. Based on the authors BLEVE testing experience it is believed about 10–20% of fire inducted BLEVEs are of this two-step type. The two-step BLEVE appears to give the strongest blast overpressure.

In Fig. 1 we see a lobe of flame rising from the top of the tank. This is a jet of propane escaping from a small axial fissure on the tank top. This is the beginning of the rupture. In the next frame, Fig. 2, we see the lobe of flame increasing in size. The fissure length is still quite short, indicated by the width of the jet at the tank top. In the next frame, Fig. 3 we see that things are changing. The jet is much larger and we see the hint of a mist covering the entire top of the tank. The fissure has grown to the full length of the tank. The crack has turned and gone circumferential at the head welds. The tank is unzipped but it has not opened yet. The unzipped tank is still pressurized. The tanks walls have mass and therefore a finite time is needed to accelerate the tank parts to open the tank. Some time between this frame and the next, Fig. 4, the tank opens up. The cylinder section is opened and flattened on the ground and the tank ends are torn free. At some point in this process the tank opens sufficiently to release shocks. We cannot see a shock in Fig. 4, because it is buried in the cloud that has been formed by the release before the shock is released. In the next frame, Fig. 5, the tank has failed catastrophically and released its contents. We see the released cloud and we see a shock has overrun the cloud. The opaque white cloud shows the outer edge of the expanding flashing liquid.

Fig. 1. Failure of 2000 L ASME code propane tank (wall begins to fail at top with initial two-phase jet release, jet is burning, $t = 0$ ms).

Fig. 2. Failure of 2000 L ASME code propane tank (two-phase jet release continues, $t = 17$ ms).

Fig. 3. Failure of 2000 L ASME code propane tank (two-phase jet release continues, fracture growing rapidly, $t = 34$ ms).

Fig. 4. Failure of 2000 L ASME code propane tank (wall fails catastrophically with BLEVE, shock and cloud coincident, $t = 50$ ms).

Fig. 5. Failure of a 2000 L ASME code propane tank (shock is visible and overtakes cloud release, $t = 67$ ms).

This is as far as the flashing liquid goes because it has used up its energy to push the atmosphere out of the way. This cloud ignited to produce a fireball about 45 m in diameter. This shows how local the liquid flashing effects are in this test.

The position of the shock wave can be seen from the fine mist produced by the passing of the shock. The shock is further out than the flashing liquid and is moving at supersonic speed. Assuming the shock is coincident with the cloud front in Fig. 4 we can estimate the shock average speed from the distance traveled in the next frame. This turns out to be about 350 m/s or just above sonic speed in air. Of course a shock must be supersonic, but a weak shock travels at just above sonic speed.

In this case we measured an overpressure at 10 m from the tank side of about 15 kPa. This gives (from normal shock tables for air, see for example White, 1986) a pressure ratio of 1.15 and a shock Mach number of about 1.09 or 370 m/s. This means our shock speed estimate is good based on the video frame and it also means we did not miss a much stronger and faster shock.

We know from the shock tube equation (see for example Baker et al., 1983) that the initial overpressure generated by the failure of the tank could have been as high as 300 kPa. This gives a pressure ratio of about 4 for the shock front right at the tank wall. This overpressure indicates a normal shock with a speed of $M = 1.9$ or about 650 m/s.

This sequence was captured by a standard hi. 8 mm camcorder. The time between frames is approximately 17 ms. Therefore this event was a relatively short two-step BLEVE lasting about 67 ms. This gives an average crack speed of about 22 m/s. This is an order of magnitude slower than the 200 m/s that is typical of a single-step failure. We have observed similar two-step BLEVEs lasting 2 s from the point where the rupture begins to where the tank fails catastrophically.

As can be seen from the sequence the liquid and vapour cloud release starts before the shock is released. The expanding propane cloud quickly loses momentum from the process of pushing the atmosphere out of the way and then the shock overtakes it. It is believed that the shock is produced by the release of the tank vapour space as will be explained in the following sections.

3.2. Blast overpressure predictions

When estimating overpressure effects from BLEVEs we must consider close in effects and far field effects. Very close to the tank we expect both a shock wave and a high velocity flow from the flashing liquid and expanding vapour. Far away from the tank we expect only the shock wave which is propagating through the local air. This shock wave will have a blast wind of air behind it.

From the figures shown earlier, we saw the propane cloud does not go very far. For the 2000 L tank the propane cloud has a diameter of about 15 m. Therefore the main loading from this is very local. The flashing liquid does work by accelerating tank fragments and by pushing the atmosphere out of the way.

For the far reaching overpressure effects it is necessary to identify the source of the energy for the shock wave. For a BLEVE this means establishing whether the shock is produced by the liquid or the vapour. We know the energy in the vapour is available immediately to do work on the surroundings. For the liquid to do work on the surroundings it must first change phase into a vapour. This phase change process takes time and this process may be too slow to produce a shock wave (see for example Baker et al., 1983).

The thermo-mechanical energy available is usually calculated from the change in internal energy of the stored substance (liquid or vapour) as it is expanded isentropically (adiabatically and reversibly) from the containment pressure to atmospheric pressure.

$$E = m(u_1 - u_{2s}),$$

where u_1 is the internal energy of initial contents, u_{2s} the internal energy of contents after isentropic expansion from initial pressure to atmospheric pressure and m the mass of contents.

This equation can be applied to the vapour and liquid energies separately or they can be combined.

The hemispherical shock wave moves out from the source at supersonic velocity and as it moves out its strength decreases. One method to estimate the decay of the shock overpressure with distance uses the TNT equivalence approach. This method is based on experiments for high explosives and applies for symmetrical explosions far away from bounding surfaces.

With the TNT method, the propane thermo-mechanical energy is converted to an equivalent TNT mass and then this is used to estimate the shock overpressure based on empirical correlations for TNT explosions (see for example Kinney & Graham, 1985). This method produces conservative estimates of shock overpressures from propane BLEVEs since the energy release process for BLEVEs is much slower than that from high explosives. However, this approach can give overly conservative predictions in the near field.

The TNT equivalence calculation requires that the energy released by the BLEVE be converted into a TNT equivalent. The mechanical energy available in 1 kg of liquid propane at 55 °C is approximately 63 kJ/kg. For saturated vapour at 55 °C, the energy available is 124 kJ/kg. This assumes isentropic expansion of the liquid or vapour to atmospheric pressure. The explosion energy in 1 kg of TNT is 4680 kJ/kg. This would suggest that propane liquid has only 1.3% the explosive potential of the equivalent mass of TNT. A compressed gas release of propane would have about 2.7%. It must be stressed that these percentages are for the release of stored thermal energy, not chemical energy (i.e., they do not include the explosive potential if propane burns or detonates).

The overpressure vs. distance for the far field can by calculated using the following empirical relation from Kinney and Graham (1985) for high explosives:

$$\frac{p}{P_a} = \frac{808\left[1 + \left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{1 + \left(\frac{Z}{0.048}\right)^2}\sqrt{1 + \left(\frac{Z}{0.32}\right)^2}\sqrt{1 + \left(\frac{Z}{1.35}\right)^2}},$$

where p is the explosion overpressure, P_a the ambient pressure, and Z the TNT-scaled distance $= r/m^{0.333}$ where m is the TNT mass (kg) and r the range to target (m).

The form of these blast waves can be complex because of the non-spherical shape of the vessel and the reflections with the ground and other objects. In this case the release of energy is just above ground level and this causes an enhancement of the blast wave. First, the ground reduces the expansion volume by half and this effectively doubles the energy of the explosion. Secondly, the ground also reflects the incident wave and this reflected pressure wave can have a magnitude as much as two times the overpressure of the incident wave. Thirdly, the cylindrical tank causes the blast to be stronger from the sides than from the ends because of the way the tank opens.

The TNT method can be used for the far field. To determine if the target is in the far field we need to use the energy-scaled distance. If the target is in the near field then the overpressure will be highly directional in nature (due to the cylindrical shape of the vessel, and due to how the vessel opens up) and the overpressure will be different than would be the case if the source of the explosion was from TNT (high explosive). For far field cases, the blast becomes less directional and the overpressure is reasonably predicted using the TNT equivalent method. For distance scaling the energy-scaled distance is usually presented as

$$\bar{R} = r\left[\frac{P_o}{E}\right]^{1/3},$$

where $\bar{R}$ is the energy-scaled distance = Rbar, r is the range to target (m), P_o the ambient pressure (kPa), and E the energy in fluid available during isentropic expansion to atmospheric pressure (kJ).

The following summarizes the various factors as suggested in the CCPS guidelines AIChE Centre for Chemical Process Safety (1994) for the bursts of cylindrical vessels.

Ground effect	Multiply energy by 2 for all Rbar
Ground reflection	Multiply overpressure by 1.1 for scaled Rbar >1
Cylindrical tank	Multiply pressure by 1.6 (for $1.6<$Rbar<3.5) Multiply pressure by 1.4 (for Rbar $>$ 3.5)

These factors are approximate because the local blast effect depends on the details of how the tank opens up. In our tests we saw local side pressures that were double the end pressures. The ends are somewhat protected from the blast by the slow moving end caps. The above factors for the tank cylindrical shape are approximate and likely to decay towards unity at large Rbar.

For the near field the TNT approach gives overly conservative estimates of the overpressure. In this case the near field is for scaled distance Rbar<2. This is because in the near field high explosives give much higher overpressures than bursting propane tanks.

For Rbar >2, this is the far field and the blast can be estimated from data for high explosives such as TNT. For the near field we need to calculate the initial shock overpressure at the tank wall. This is done using the well known shock tube equation (see for example Baker et al., 1983)

$$\frac{p_1}{P_0} = \frac{p_{so}}{P_o}\left[1 - \frac{(k_1-1)\left(\frac{a_o}{a_1}\right)\left(\frac{p_{so}}{P_o}-1\right)}{\sqrt{2k_o\left(2k_o + \left((k_o+1)\left(\frac{p_{so}}{P_o}-1\right)\right)\right)}}\right]^{\left(\frac{-2k_1}{k_1-1}\right)},$$

where P_1 is the pressure in vessel, P_o the ambient pressure = 101.3 kPa, p_{so} the air shock overpressure, a_1 the sound speed in vessel vapour = 270 m/s, a_o the sound speed in ambient air = 340 m/s, k_1 the ratio of specific heats for vapour = 1.1, and k_o the ratio of specific heats for air = 1.4.

For a propane tank failing at a pressure around 2 MPa the pressure on the high-pressure side of the shock p_{so} is approximately 0.4 MPa absolute. This is of course much lower than the pressure from a high explosive and therefore a different decay curve is needed. Fig. 6 shows the appropriate decay curve for this case from Baker et al. (1983).

The decay of the overpressure is shown as a function of the scaled distance Rbar. In a BLEVE event the liquid energy may be ten times the vapour energy but after the cube root this reduces to a factor of about 2. This means at a given distance from the explosion, the Rbar based on the

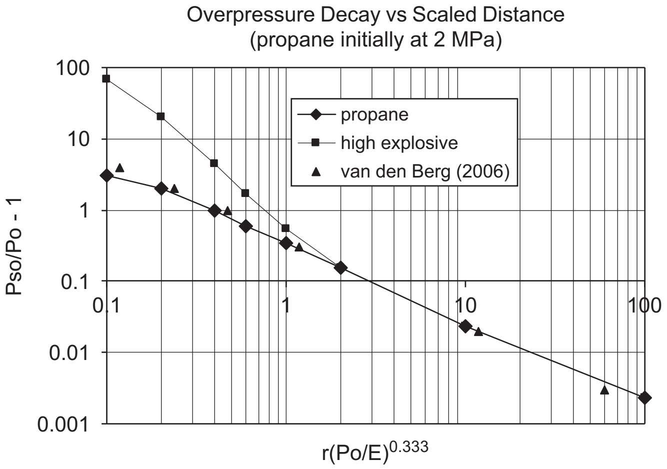

Fig. 6. Overpressure decay curve for propane tank BLEVE (data from AIChE Centre for Chemical Process Safety, 1994).

liquid energy will be about half of that for the vapour. Then if Rbar = 2 for the vapour we expect Rbar = 1 for the liquid energy. This results in a considerably higher overpressure from the liquid.

The decay curve for the propane release is shown in Fig. 6. The figure also includes a numerical solution for the blast decay from van den Berg et al. (2006). The numerical prediction agrees very well with the traditional decay curve for the high explosive in the far field and the shock tube solution in the near field.

3.3. *Blast from vapour and liquid*

3.3.1. *Source of shocks*

When a gas-filled vessel ruptures the resulting blast wave has two characteristic peaks (i.e., a leading shock, followed by a negative pressure phase, followed by a second shock). The negative pressure phase and the second shock are explained by some (see for example Baker et al., 1983) as being due to an overexpansion followed by a recompression of the released gas.

Some references suggest that both the vapour and the superheated liquid will produce a shock wave while some references suggest that the flashing process is too slow to form a shock that propagates into the surrounding atmosphere. In the testing by Johnson and Pritchard (1991) they concluded that they could not identify whether the shock was produced by the liquid or the vapour. We have never been able to see a shock by the liquid in our testing. If the flashing liquid cannot form a shock then the energy released by the liquid will only be involved with projectile acceleration and close in dynamic pressure loading of structures. This of course can cause considerable hazard and damage in the near field. However this also means the liquid will have no overpressure effect in the far field.

Blast data from BLEVE experiments typically produce the classic two-shock waveform as seen from gas vessel ruptures. Fig. 7 shows typical blast data from a 2000 L tank during a two-step BLEVE.

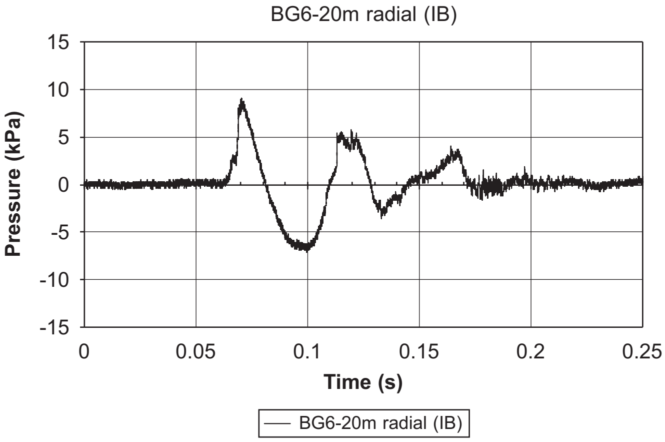

Fig. 7. Blast wave at 20 m from side of a 2000 L propane tank BLEVE.

As can be seen from the figure there is an initial shock followed by a second shock and then there is a third wave of pressure rise that is not really a shock. The second shock is not the liquid expansion. It is the normal second shock from the exploding vapour space. The third pressure rise may be the wind produced by the flashing expanding liquid doing work on the atmosphere to push it out of the way. If it is, the pressure from this is less than the shocks produced by the vapour space. For the pressure rise indicated, it suggests a wind speed of 80–100 m/s. The data from these tests did not show any separate shock that could be attributed to the liquid expansion. Note that the physical expansion of the liquid ends at around 6–7 m (see Fig. 5) for this size tank and the nearest blast gage was at 10 m.

In the CCPS guidelines book AIChE Centre for Chemical Process Safety (1994) a blast wave plot is shown from a butane BLEVE and the first pressure spike generated by the tank contents was labeled as the liquid shock. It is not clear how this was established. The reference that the pressure plot came from Johnson and Pritchard (1991) concluded that is was not possible to determine if the blast was generated by the vapour or liquid. They did conclude that an overpressure predicted based on the liquid energy greatly overestimated the overpressure observed.

The CCPS AIChE Centre for Chemical Process Safety (1994) suggest that in many accidents, most of the far field blast effect is produced by the vapour expansion. They also suggest that the liquid must be at or above the atmospheric superheat limit for the liquid to flash explosively and produce a significant overpressure. In the example shown in Fig. 7 the liquid was slightly above the Tsl. One may still argue that the scale of the tank was too small to produce a shock from the flashing liquid.

3.3.2. *Expansion of boiling liquid*

The velocity of the expanding vapour and flashing liquid will decrease rapidly with distance as it does work by pushing the atmosphere back. This work is $P_o V$ where P_o is the ambient pressure and V the final volume of the release. Therefore the damaging effects of the flashing liquid will only be seen close to the source (except of course if fragments are sent a large distance).

The worst of the damage by the flash vaporization will be limited to a space approximated by the volume of a hemispheric bubble of radius r_b that is formed when all of the energy in the flashed mass goes into pushing the atmosphere out of the way, i.e.

$$r_b = \left[\frac{3\pi E}{2p_o}\right]^{1/3}.$$

This is very small in comparison to the volume affected by the propagation of a shock wave. Recall that a shock is not the interface between the surrounding air and the source gas that produces the shock. The actual interface between these gases is well behind the shock and in fact, its effects do not travel nearly as far as the shock does. This is clearly seen in Fig. 5.

Fig. 8 shows the overall expansion of propane following an isentropic expansion from saturation conditions to atmospheric pressure. As the temperature goes up the expansion factor goes up. As can be seen this radius is quite small and it approximates the size of the zone affected by the flash vapourization seen in Fig. 5.

For Figs. 1–5 shown earlier the fill and liquid temperature were approximately 65% and 57 °C, respectively. This suggests a hemisphere radius of 5.8 m. This agrees well with the image of Fig. 5. It is expected that the drag loading by the expanding cloud in this volume could be considerable. The velocity of the vapour and liquid droplets in this cloud can be hundreds of m/s. If all the expansion energy goes into the kinetic energy of a homogeneous two-phase flow the theoretical velocity is of the order of 400 m/s. Of course it would never reach this velocity because the atmosphere is holding it back. The cloud shape as seen in Fig. 5 is more a cylinder because of the initial jet release from the top of the failing tank.

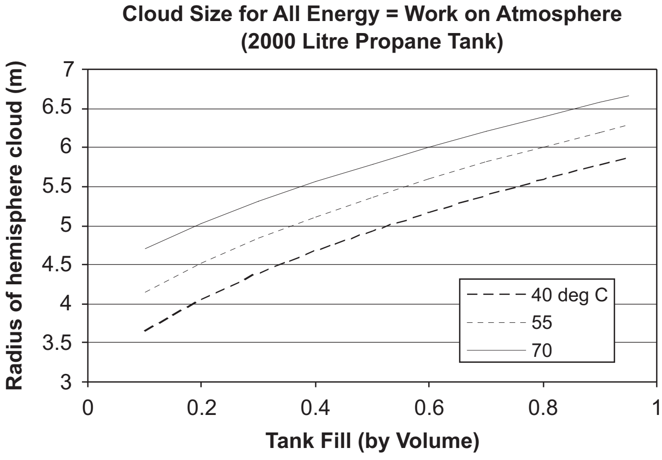

Fig. 8. Radius of hemisphere cloud from liquid expansion (for 2000 L tank).

4. BLEVE blast data

This paper deals with the overpressures generated by the release of pressurized vapour and the expanding flashing liquid when a container holding a PLG fails catastrophically. This paper will not be considering any overpressures generated by the combustion of a released quantity of a flammable PLG. In our test programs, we never saw a blast wave from the combustion for scales from a few kg of propane to 800 kg.

There is little data available for the overpressures generated by BLEVE type events. Most of the data that does exist suggests that the overpressure from the release of a PLG is relatively small. Usually the damage from overpressures is less than the damage from the combustion of the released flammable PLG. However, there is still some debate as to whether special, extremely energetic BLEVEs can take place resulting in a significantly larger blast threat. The effect of release scale may also play a factor. Blast data from BLEVEs tends to be from small-scale vessels. A recent test in Germany has provided one data point for a full scale European rail tank car BLEVE (Balke, Heller, Konersmann, & Ludwig, 1999).

The following are some examples of blast data from BLEVE tests.

4.1. *BLEVE blast from 400 L ASME code propane tanks*

During the summers of 1992–1994 a series of fire tests were conducted using 400 L, ASME code, automotive propane fuel tanks. Table 1 summarizes the dimensions of these tanks.

The tanks were exposed to various fire conditions which involved a combination of pool fire and/or liquid propane torches (Birk et al., 1997). The propane torches were applied to the top of the tank to heat the vapour space wall. The liquid pool fires were primarily used to heat the liquid contents of the tanks.

The tanks and surroundings were instrumented to measure the following:

(i) Internal pressure
(ii) High speed internal transient pressure (during failure)
(iii) Propane temperature distribution in liquid and vapour regions

Table 1
Summary of tank design features

Dimension	2150 kPa g MAWP ASME code	Thin wall non-ASME code
Capacity (L)	403	403
Length (m)	1.52	1.52
Diameter (m)	0.61	0.61
Wall thickness (mm)	6.35	3.0
Head thickness (mm)	6.35	6.35

MAWP—maximum allowable working pressure.

Table 2
Summary of tank and lading property data from 400 L tank tests

Test	Failure pressure (kPa)	Average liquid temperature (°C)	Liquid mass (kg)	Wall thickness (mm)	Outcome BLEVE type
93–4	1500	46	139.0	6.35	
93–8	2446	66	106.6	6.35	
93–9	2122	22	162.5	3.0	
93–11	2680	73	80.2	6.35	
93–12	2108	58	109.6	6.35	2 step
93–13	2170	57	83.6	6.35	
93–14	2377	25	167.5	3.0	
93–15	1494	43	139.0	3.0	
94–5	2090	58	145.5	6.35	
94–12	2270	55	159.1	6.35	

Table 3
Summary of 2000 L propane tank fire tests

Test	Fail press. (kPa g)	Fail liquid temp (°C)	Fail vapour temp (°C)	Fill
01–1	1863	54	127	0.17
01–2	1846	55	68	0.35
01–3	1699	55	116	0.13
01–4	1894	57	101	0.21
01–5	1573	49	145	0.12
02–1	1803	57	61	0.51
02–2	1563	47	52	0.52
02–3	1813	52	79	0.53
02–4	1858	54	57	0.61

(iv) Tank external wall temperatures
(v) Tank and propane mass
(vi) Regular and high-speed video
(vii) Field blast overpressure
(viii) Remote thermal radiation

These various measurements were used to characterize the condition of the tank at the time of failure. For more detail of the testing methods and the results obtained the reader is directed to Birk et al. (1997).

In the present experiments blast gages were located at both 10 and 20 m from the tank sides and ends. This arrangement of gages was selected to show the directional nature of the blast as well as how the blast overpressure decayed with distance.

Tables 2 and 3 shows a summary of the tank and lading condition for the tests that ended with BLEVEs. Both single-step and two-step BLEVEs were observed. The temperatures shown in the table are average liquid temperatures and may not be the saturation temperature corresponding to the measured tank pressure at the time of failure. The average temperature may be lower than the saturation temperature because of liquid temperature stratification (see Birk & Cunningham, 1996).

Fig. 9 shows the measured blast overpressure (first peak) for the 400 L tank tests vs. the liquid isentropic expansion energy. The key feature to note here is that the measured blast overpressure is decreasing as the liquid energy increases. This suggests the liquid was not the source of the blast wave.

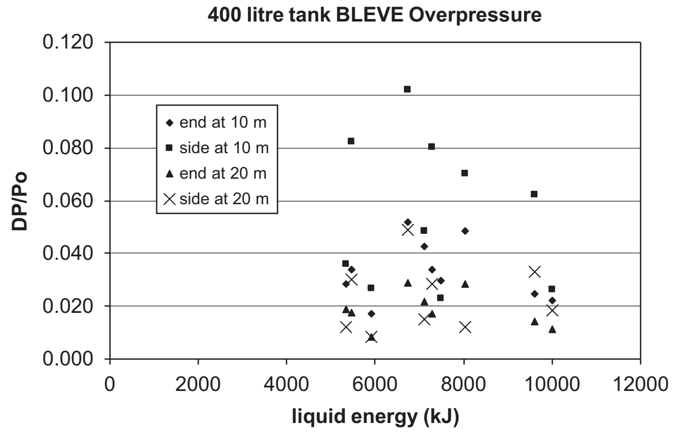

Fig. 9. Measured blast overpressure vs. liquid isentropic expansion energy (overpressure based on first peak).

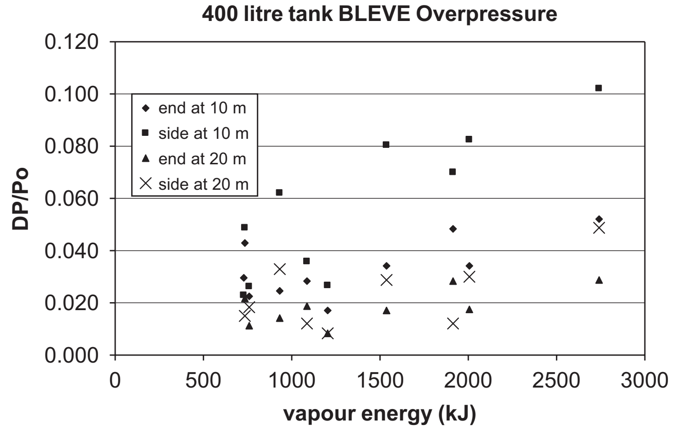

Fig. 10. Measured blast overpressure vs. vapour isentropic expansion energy (overpressure based on first peak).

Fig. 10 presents the same overpressure data but now it is plotted with the vapour isentropic expansion energy. The vapour energy was based on the vapour saturation properties at the measured tank pressure at failure. In this case the measured blast appears to increase linearly with the vapour energy. It should also be noted that this data includes propane at and above the atmospheric superheat limit temperature Tsl.

It should be noted that the pressures measured at the tank sides were at times two times as large as that measured at the tank ends. This is consistent with information in the literature.

Fig. 11 shows all the blast data from the 400 L tests as a plot of measured overpressure vs. scaled distance Rbar. In this case the scaled distance has been determined from the vapour isentropic expansion energy at the time of tank failure. A factor of two was applied to the energy but no factor has been applied here for ground and tank shape effects. The plot also shows the overpressure decay curve for a propane BLEVE starting at 2 MPa tank pressure. As can be seen this decay curve predicted the upper limit of the overpressures very well.

4.2. *Blast from 2000 L tank tests*

Over the summers of 2000, 2001 and 2003, 2004 our research team conducted 19 fire tests of 2000 L ASME code propane tanks. Of these tests we observed ten BLEVEs. One example (test 04–01, Birk, Poirier, Davison, & Wakelam, 2005) resulted in a very powerful BLEVE with a sharp high frequency explosion sound heard at 370 m from the tank side. The blast from this BLEVE broke some of the windows on the exposed side of an office trailer located 170 m from the tank. This blast also deformed the side walls and roof of the main instrument trailer that was located behind a concrete blast wall 35 m from the tank. From Kinney and Graham (1985) we can estimate the overpressure at the 170 m building to be

10–15 mbar	Windows broken
35–75 mbar	Windows shattered, minor damage to some buildings

Based on our observation of the damage we would estimate the overpressure to be of the order of 10–15 mbar at 170 m.

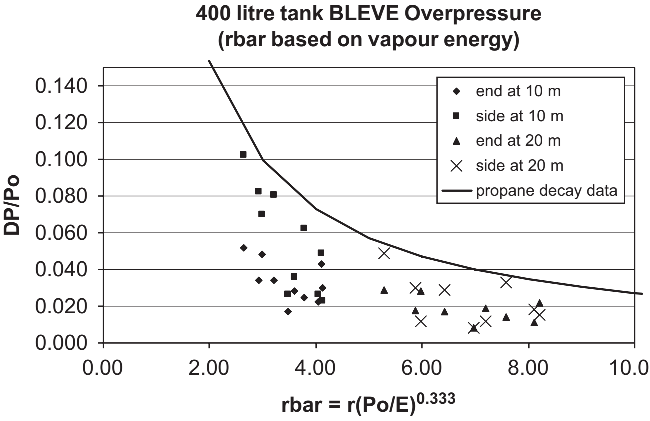

Fig. 11. Measured blast overpressures from BLEVEs of 400 L ASME code propane tanks (overpressure based on first peak).

The tank was estimated to be 65% full of propane at an average liquid temperature of 60 °C. At 170 m, the target is well into the far field and the TNT equivalent method can be used. Based on isentropic expansion energy the following is predicted for this case.

(i) Liquid expansion energy = 38 MJ
(ii) Vapour expansion energy = 4.4 MJ
(iii) TNT for liquid = 16.2 kg
(iv) TNT for vapour = 1.9 kg
(v) At 170 m scaled Rbar = 23.6 m for liquid energy
(vi) At 170 m scaled Rbar = 48.4 m for vapour energy
(vii) Overpressure from liquid energy at 170 m = 19.3 mbar
(viii) Overpressure from vapour energy at 170 m = 9.4 mbar

First it should be noted that this is a far-field problem (Rbar> >2). Note that the liquid has 8.6 times the energy of the vapour and yet at the target the overpressure from the liquid is only double that of the vapour. Clearly for far-field analysis, the effect of distance quickly dissipates the shock overpressure. This calculation assumed 100% of the isentropic expansion energy goes into the blast. A factor of 2 was applied to the energy to account for the ground effect and 1.1 and 1.4 for ground reflection and the tank shape effect.

As can be seen from the above both the liquid energy and the vapour energy are sufficient to explain the broken windows. The vapour energy alone appears to give the most appropriate overpressure estimate considering the limited damage observed. Both estimates are useful here for the far field. Which one should we use for the near field? The data about to be shown suggests the liquid energy approach will grossly overestimate the near-field overpressures.

The following table summarizes the BLEVE outcomes of other 2000 L tank tests conducted in 2001 and 2002.

Figs. 12 and 13 show the measured blast overpressures for all the 2000 L tank tests vs. the scaled distance for both cases were we have used the vapour energy and the liquid energy. The data was taken at 10–40 m from the tank side and ends. The figures also show the propane decay curves. As in the 400 L test results we have applied a factor of two here to account for the half space but no factors have been applied for the ground and tank shape effects.

In Fig. 12 we see the upper limit of the observed overpressures is well predicted using the vapour energy alone. The highest observed pressures were from two-step type BLEVEs. In the most powerful two-step BLEVE observed the some of the actual overpressures exceed the propane decay curve by up to 28%. This is probably a directional effect. Recall that we have not applied any factors to account for ground reflection and tank shape. If we had applied the shape factor of 1.4 this would have more that compensated for this discrepancy.

From Fig. 13 we see that the liquid energy approach always overpredicts the observed overpressures. If we

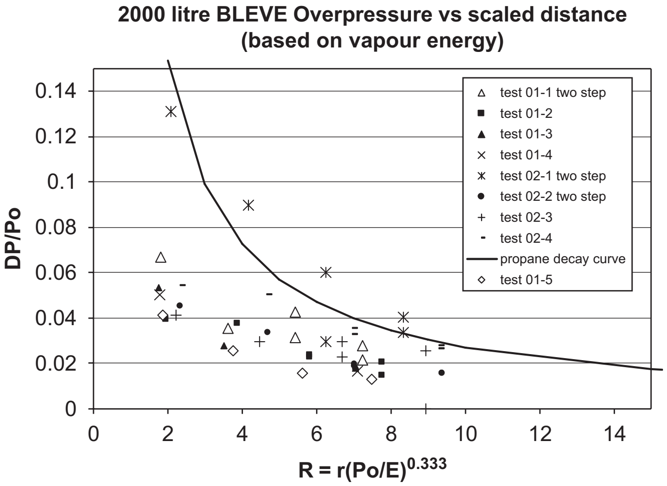

Fig. 12. Measured overpressures vs. scaled distance (based on vapour energy) from BLEVEs of 2000 L propane tanks at 10 to 40 m from the tank side and end (data from Birk et al., 2003). (Overpressure based on first peak.)

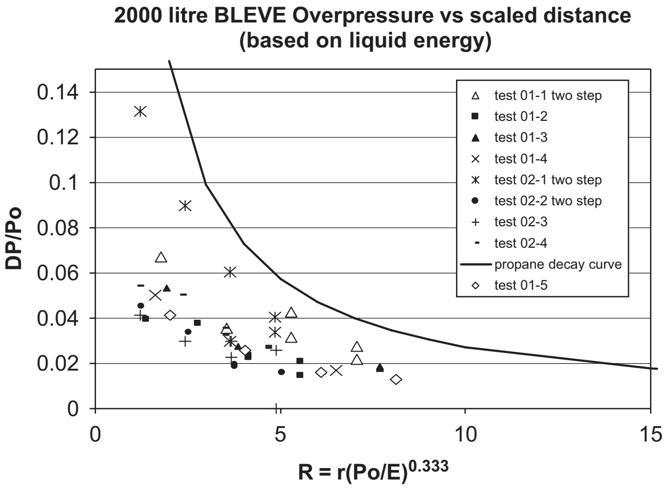

Fig. 13. Measured overpressures vs. scaled distance (based on liquid energy) from BLEVEs of 2000 L propane tanks at 10 to 40 m from the tank side and end (data from Birk et al., 2003). (Overpressure based on first peak.)

apply any factors for tank shape and ground reflection the overprediction is even worse.

4.3. BAM data

This data came from a full scale fire test of a rail tank car by BAM in Germany (Balke et al., 1999).

The basic data for this test is as follows:

Tank volume = 45.36 m^3
Initial liquid fill = 22% by volume
Initial lading temperature = 15 °C (assumed)
Failure pressure = 25 bar
Liquid temperature at failure = 69 °C

From this data we can calculate the isentropic expansion energy in the tank at the time of failure:

Vapour mass = 2318 kg
Liquid mass = 3308 kg
Tank volume fill = 0.18

Vapour isentropic expansion energy = 314 MJ
Liquid isentropic expansion energy = 262 MJ

Equivalent TNT for vapour = 134 kg
Equivalent TNT for liquid = 112 kg

Table 4 gives a summary of the blast overpressures observed in the BAM full scale test. The estimated blast effects are summarized in Table 5.

We did not apply a ground reflection or tank shape factor here. In all cases Rbar is much larger than two and therefore we are in the far field and the TNT method should give reasonable results.

As can be seen from the tables both the vapour and liquid energies explain the pressures observed. Both methods overpredict the measured first shock overpressure. In this case both methods give a similar answer because of the low fill level of the tank (i.e., the vapour and liquid energies are almost the same).

The blast wave forms shown in Balke et al. (1999) show a typical double shock waveform from a bursting gas filled vessel. This suggests the energy from the vapour caused the measured shocks. Therefore we can conclude that in this large scale event the blast was due to the vapour space. However, we should note that the low liquid fill level would tend to suppress the liquid contribution to this event because the liquid would experience a rather slow pressure drop during rupture.

5. Discussion

The results from the various scales considered suggest that it is the vapour energy that is the source for the shock wave from BLEVEs. This shock produces the explosion noise and causes the near and far field shock damage. Usually, the damage caused by the shock from a BLEVE is small compared to the damage potential of fireballs, projectiles and close in dynamic pressure loading from the flash vapourization.

The flashing liquid does produce high velocities and dynamic pressure loading of objects near the tank with associated drag forces on local objects, but this is only in a region very close to the tank (within say 10 m for our 2000 L tank, and say 40 m for a 120,000 L rail tank car). The size of this cloud can be estimated from the liquid energy and the work done to push the atmosphere out of the way. If the BLEVE were to take place in a confined

Table 4
Shock overpressure (peak to valley) data from van den Berg et al. (2006)

	Overpressure at 100 m	Overpressure at 150 m	Overpressure at 200 m	
First shock peak to trough (kPa)	4.4	3.3	2.8	
First shock peak (kPa)	2.5	1.4	1.2	
Time for shock to traverse 50 m		0.15 s	0.15 s	Approximate shock speed 333 m/s (i.e., sonic-weak shock)

Table 5
Calculated blast properties (100% of energy into blast, half-space effect = 2, tank shape effect = 1.0, ground reflection 1.0)

	Overpressure at 100 m	Overpressure at 150 m	Overpressure at 200 m
Vapour energy (kPa)	4.5	2.9	2.2
Rbar vapour	5.5	8.2	10.9
Liquid energy (kPa)	4.2	2.8	2.0
Rbar liquid	5.8	8.7	11.6

space such as tunnel this flashing liquid effect would be much more powerful and damaging.

Energy from the vapour is available to do work on the surroundings immediately after tank rupture, whereas the energy from the liquid is not. The liquid must flash to vapour before it can do expansion work on the atmosphere. This phase change process is believed to be too slow to produce a shock wave AIChE Centre for Chemical Process Safety (1994), Baker et al. (1983). If the tank opens fast enough the vapour space can produce a shock wave that will travel out at supersonic speed for a large distance. This is what produces far field shock damage. The overpressure results from the testing of 400 and 2000 L propane tanks support this conclusion. The results showed that increasing shock overpressure correlated with increasing vapour space energy while shock overpressure was observed to decrease in many cases with increasing liquid energy. When it came to predicting shock overpressures the method using the liquid energy was generally overconservative. This was true even when the liquids were at or above the atmospheric superheat temperature.

The data shown suggest that the liquid phase change for the BLEVE tests considered did not produce shocks. They did produce powerful high velocity two phase flows during the flashing phase. This produced close in dynamic pressure loading of nearby objects.

The question still remains—can the liquid flashing be explosive at even larger scales? The data from the single full scale tank car test from BAM Balke et al. (1999) also suggests the blast is due to the vapour energy and not the liquid. However, these conclusions remain with some uncertainty due to the low fill level of the BAM test tank.

The foregoing is not suggesting that the liquid energy and its rapid phase change are not a destructive process. Birk et al. (1997) have shown that liquid energy is an important factor for the tank destruction in some BLEVEs. The liquid energy can drive tub rocket projectile events. The liquid energy does do damage close by the tank. However, it is believed the far field shock damage is due to the vapour space energy.

The blast due to combustion of the cloud is another subject and is beyond the scope of the present work.

6. Conclusions

This analysis has shown that recent data from BLEVE experiments supports conclusions from others that the liquid energy has very little impact on the shock overpressure from a BLEVE event. The scale range considered here covers 0.4 to 45 m^3 and applies for liquid temperatures below, at and above the atmospheric superheat limit temperature Tsl. It is suggested that the process of rapid liquid flashing after tank failure is too slow to produce a shock wave. The shock observed in practice from BLEVEs is driven by the vapour energy. The results also show very strong directional effects for failures of cylindrical tanks located near the ground. This is consistent with the current literature.

The flashing liquid energy results in a powerful two-phase flashing cloud close in to the tank. This expanding cloud produces significant dynamic pressure loading of nearby objects and can propel tank parts over large distances. However, it is believed the liquid flashing process is too slow to produce a shock wave that can travel into the far field.

It is till possible that at larger scales the liquid flashing process can produce a shock. However, the data presented here suggest the shock is produced by the vapour energy alone.

It is recommended that analysts predicting BLEVE shock overpressures should calculate it from the vapour and liquid energies separately and combined. To be conservative the analyst may want to use the higher of the calculations. However, they can probably count on the far field shock damage being closer to that calculated from the vapour energy alone. For accident reconstruction, the far field overpressure damage will probably correlate best to the vapour energy.

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