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Liquid temperature stratification and its effect on BLEVEs and their hazards

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Abstract

Recent fire tests involving over forty, 400 l automotive fuel tanks filled with commercial propane have shown that the likelihood of a BLEVE and the severity of its hazards are significantly affected by the detailed thermodynamic condition of the lading at the time of failure.

When the liquid in a tank is heated by fire impingement on the tank external shell, the liquid near the heated wall will tend to rise because of buoyancy effects. This leads to the development of temperature stratification where the liquid near the top of the tank will be at a higher temperature than liquid lower down. The pressure in the tank is dictated by the warmest liquid. This means that when the liquid is stratified the pressure in the tank is higher than the pressure one would calculate from the average liquid temperature. If the tank fails at the pressure relief valve (PRV) set pressure the resulting release will be less powerful if the liquid is stratified.

When the PRV is activated on a tank it usually vents vapour to the surroundings. This vapor flow results in boiling action in the liquid and this boiling causes heat transfer and mixing and these cause destratification of the liquid. The time for destratification increases with the scale of the system. Eventually, the PRV may eliminate the stratification and the liquid will consist of a near isothermal liquid mass. If the tank fails when it is full of liquid, and the liquid is uniformly at the saturation temperature for the PRV set pressure, then the resulting BLEVE and hazards will be maximized for the given tank.

Based on recent fire test data, this paper discusses how temperature stratification and destratification is affected by the fire type and the PRV action. The paper also discusses how this temperature stratification effects the likelihood of a BLEVE, and the severity of the associated hazards including fireball heat flux, blast overpressure and projectiles.

Keywords: BLEVE; Liquid temperature stratification; Pressure relief valve; Blast; Projectiles; Fireball

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1. Introduction

When a tank carrying a pressure liquefied gas (PLG) is exposed to external fire impingement there is a chance that the tank will fail. If the failure mode is catastrophic then this will lead to a boiling liquid expanding vapour explosion (BLEVE). The immediate hazards from a BLEVE are blast and projectiles. If the material is flammable then fire and explosion effects are a hazard. If the commodity is toxic then exposure is a hazard.

Fire-induced BLEVEs follow a common scenario. A tank partially filled with a PLG is exposed to fire impingement above the liquid level. This fire exposure leads to high wall temperatures and material weakening. The internal pressure leads to creep and thinning in the hot wall areas and this may eventually lead to formation of a tear or fissure in the tank wall. If the tear propagates the entire length of the tank then a BLEVE takes place. If the fissure stops short then a transient jet release takes place.

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, for example) the bulk of the liquid is sent into a state of superheat. If the degree of superheat is large it causes violent flashing of the liquid which can be explosive. Generally speaking, a large degree of superheat requires a very rapid pressure drop. Reid [1] suggested that for a BLEVE to take place, the sudden pressure drop must take the liquid to the superheat limit spinodal so that homogeneous nucleation takes place in the bulk liquid. Later reseachers such as McDevit et al. [2] showed that BLEVEs could take place without reaching the superheat limit. However, it is generally accepted that the BLEVE will be most powerful if the atmospheric superheat limit is reached.

Birk and Cunningham [3] 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. For tanks severely weakened by fire a BLEVE can take place with the propane at ambient temperature. In these cases the vapour space energy is sufficient to drive the tank to catastrophic failure. However, as the tank strength increases, the liquid energy plays a more important role in the tank failure. 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.

The data from these tests of 400 l tanks have been analysed in further detail and the results show that the detailed thermodynamic state of the liquid plays an important role in the tank failure process and the resulting hazards. Specifically, this paper shows how liquid temperature stratification affects the likelihood of a BLEVE, and the severity of the associated blast, projectile and fireball hazards. This is of practical interest because it has been shown by Birk and Cunningham [3] that the chance of a BLEVE can be reduced by lowering the liquid temperature, and for a tank without thermal insulation or water spray protection systems, this can only be done by either reducing the PRV set pressure or by maintaining liquid temperature stratification. Reductions in PRV set pressures have practical limits since low PRV set pressures would result in unwanted releases. However, there are not such limitations on liquid temperature stratification.

2. Liquid temperature stratification

When a tank is heated in a fire the liquid is not usually heated uniformly. In all of the fire tests conducted on LPG tanks (see, for example, [4–6], etc.) the liquid temperature varied significantly from the bottom of the tank (where liquid is cooler) to the top (where liquid is warmer). This temperature stratification effect has also been extensively investigated by Venart et al. [7] in a laboratory setting. Liquid temperature stratification prior to PRV action has also been studied numerically by Hadjisophocleous et al. [8].

Fig. 1 shows how the liquid temperature varies from the bottom to the top of a tank exposed to an engulfing fire. The figure also shows the saturation temperature based on the measured tank pressure. As can be seen from the figure it is the warmest liquid in the tank that drives the tank pressure.

The temperature stratification is due to the fact that when the liquid near the wall is heated it tends to become less dense than the surrounding liquid and it rises to the top. This stratified temperature distribution will remain until other processes dissipate the temperature gradients (such as bulk mixing, phase change or heat conduction).

Liquid stratification is affected by

(1) liquid thermal and transport properties,

(2) liquid vertical dimension and geometry of container,

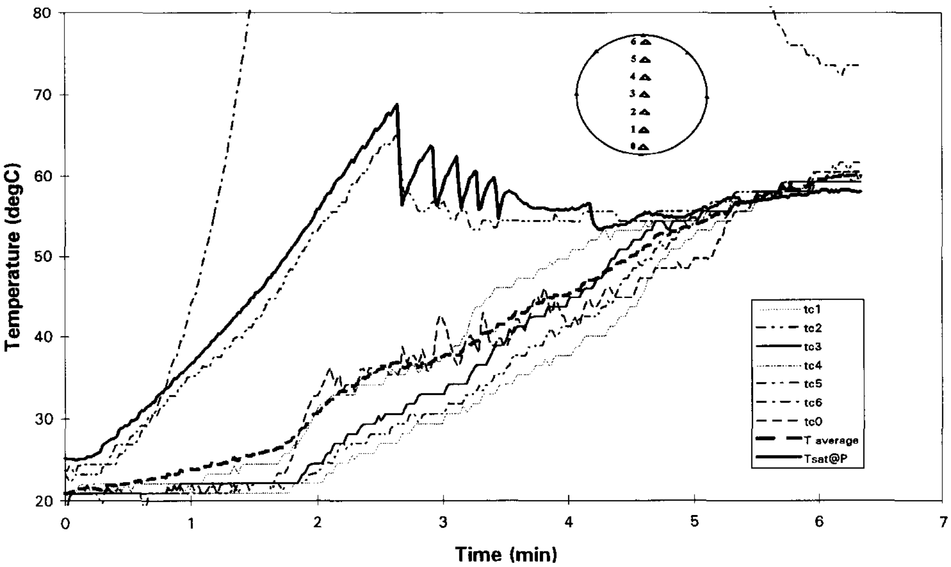

Fig. 1. Lading temperature versus time (for 400 l ASME propane tank, 80% full, test 93-12, torch from above, pool fire from below, Data from Birk and Cunningham [6].

(3) distribution and rate of heat addition (engulfing, partial engulfing, torch, etc.),
(4) PRV operation (cycling vs. continuous flow).

Up until recently, there has only been limited data available on liquid temperature stratification in tanks exposed to fire impingement. To our knowledge, no fire test results have been published that investigate how liquid temperature stratification effects BLEVEs. This paper presents new data on how temperature stratification plays an important role in a fire-induced BLEVE.

3. Fire tests

A series of over 40 fire tests were conducted involving 400 l automotive fuel tanks. In these tests tanks were exposed to torch and pool fires to study the mode and severity of thermal failures. The tanks were instrumented to measure:
(1) wall temperatures
(2) liquid and vapour temperature distributions
(3) tank and lading mass
(4) tank pressure
(5) tank transient pressure during failure
(6) field blast overpressure
(7) remote thermal radiation
(8) video and still images from various angles.

Further details on instrument type and placement can be found in Ref. [6].

In each test the tanks were exposed to torch fires applied to the tank top to weaken the tank to initiate a thermal rupture. The torches were capable of heating the tank wall above the vapour space to 700 °C or more in approximately 4 min.

The tanks were suspended over pool fires fueled by JP4. The pool fires were used to heat the liquid in the tanks at different rates. The pool fire severity was controlled by on–off control of a fuel pump that delivered fuel to the fire pan.

A typical test would involve a tank filled to 80% capacity with propane at 25 °C. The torch fires would be started and would burn for some time and then the pool fire would be started. The wall heated by the torches would experience rapid temperature increase and weakening. The pool fire would be moderated so that the liquid temperature would reach the desired state when the tank was expected to rupture (tank failure times varied from 3 to 8 min typically). The maximum liquid temperature was limited by the PRV set pressure. The average liquid temperature at failure was significantly affected by the liquid temperature stratification.

The test fluid was propane and the PRV set pressures were around 2.1 MPa and therefore liquid properties were similar for all tests. In these tests all tanks had the same diameter (0.61 m) and the initial fill levels were all the same at 80%, and therefore the initial vertical dimensions and tank geometry were similar for all the tests.

3.1. Fire test results

The liquid temperature stratification and destratification was found to be a function of the fire conditions and the PRV action. PRV action proved to be highly unpredictable in the present tests since commercial valves were used. In some cases the PRVs cycled and in others the PRVs remained partially open.

Figs. 2–4 show how the degree of liquid stratification varied for some typical tests. The graphs show the degree of liquid temperature stratification as a pressure ratio β defined as

$$\beta = \frac{P}{P_{\mathrm{sat}}},$$

where P is the actual measured tank pressure and P_{sat} the saturation pressure based on the mass average liquid temperature.

With this way of showing stratification, the ratio β is greater than 1 when the liquid is stratified and $\beta = 1$ when the liquid is at saturation conditions. The maximum possible β can be calculated from

$$\beta_{\mathrm{max}} = \frac{P_{\mathrm{prv}}}{P_0},$$

where P_{prv} is the pressure relief valve set pressure and P_0 the initial tank pressure.

This maximum β would be achieved if a very thin boundary layer were heated to the saturation temperature for the PRV set pressure and the remainder of the liquid was still at the initial temperature. In the present tests the PRV set pressures were typically 2.1–2.5 MPa and the intial pressures were approximately 1.0 MPa, thus giving a β_{max} of between 2.1 and 2.5.

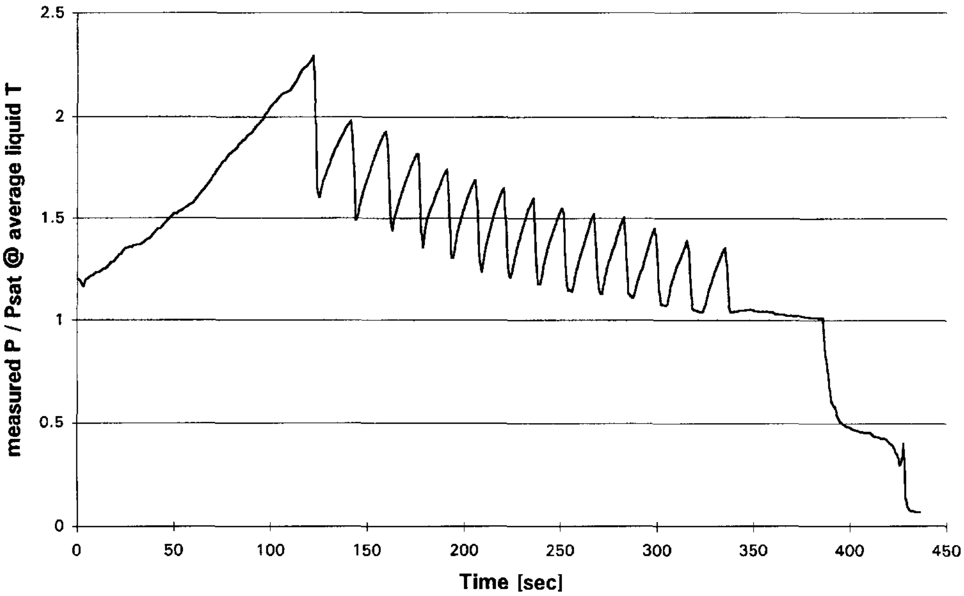

Fig. 2. Ratio of measured pressure to saturation pressure based on average measured liquid temperature (400 l propane tank, 80% full, 2% fire engulfment (torch from above – minimal pool fire from below), test 93-4).

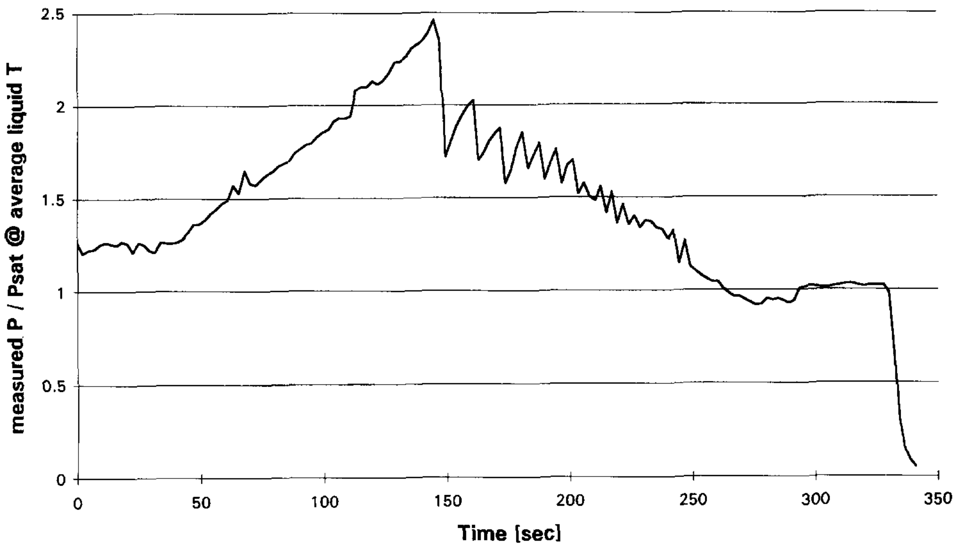

Fig. 3. Ratio of measured pressure to saturation pressure based on average measured liquid temperature (400 l propane tank, 80% full, 23% fire engulfment (torch from above – pool fire from below), test 92-10).

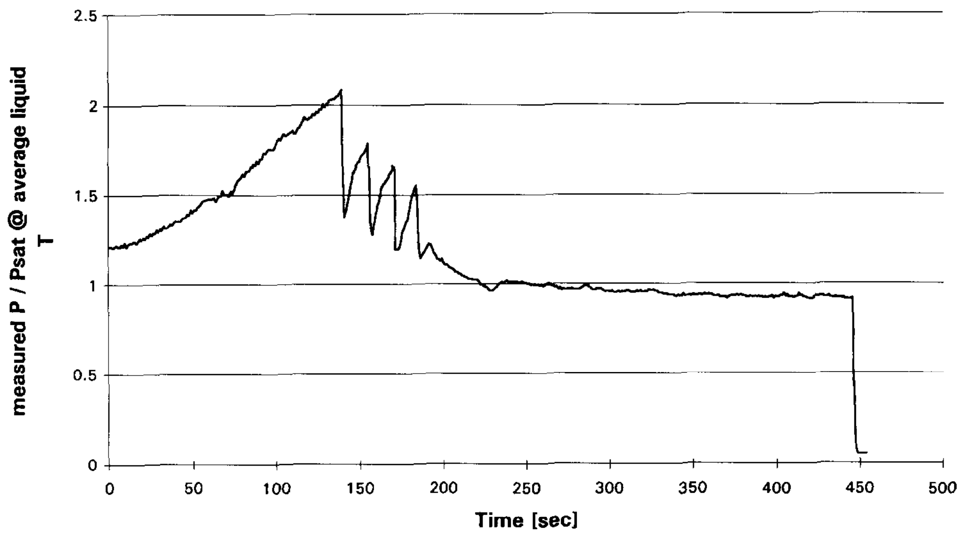

Fig. 4. Ratio of measured pressure to saturation pressure based on average measured liquid temperature (400 l propane tank, 80% full, 46% fire engulfment (torch from above – pool fire from below), test 93-6).

The plots shown are for three different fire cases. Fig. 2 shows a tank exposed to a torch fire from above. Figs. 3 and 4 involve torch fires from above and partial engulfing fires from below. The approximate percent engulfment for Figs. 2, 3 and 4 are 2%, 23% and 46%, respectively. In these tests the percent engulfment was determined by reviewing video footage of the tests. Video frames were reviewed to see how much of the total tank area was coverd by the pool fire. This fraction was then averaged over several frames during the fire test. It should be noted that the fires varied considerably due to on–off control of the fire fuel and the effects of wind and therefore the fraction of engulfment quoted is approximate.

As can be seen from the figures, as the tank is exposed to fire the liquid stratification builds. This is indicated by the β pressure ratio growing from a starting value near 1.0 to a value very near the expected β_{max}. When the PRV opens the resulting boiling causes mixing and phase change in the liquid and this reduces the stratification and hense β begins to drop. If the PRV flow is large enough and of long enough duration the stratification will dissipate and β will drop back down to a value of unity. If the PRV closes, the stratification will once again begin to build. If the PRV is too small, or if the PRV cycles then the stratification may not dissipate at all until the tank fill level drops significantly. The action of the PRV depends on the heat input and the PRV design.

It should be noted that the mode of PRV action (i.e. cycling vs. continuous flow) is dictated partly by the fire conditions and partly by the design of a particular PRV. The PRV flow is not just a function of the PRV size and pressure setting. If a PRV is sized for full fire engulfment of a tank then the PRV will either cycle or stay partially open under partial engulfment conditions.

It appears from these plots that destratification is strongly affected by the heat input. The larger the heat input, the larger the PRV flow rate and the faster the liquid destratifies. The mode of PRV action (cycling vs. continuous flow) may also play a role in the destratification time. Fig. 5 shows the approximate time for destratification for the tank as a function of fire engulfment fraction. These results are based on the tests by Birk and Cunningham [6] and Appleyard [5]. In both cases these tanks had diameters of 0.61 m. As can be seen, the time for destratification increases as the degree of engulfment decreases. The scatter in the data is most likely due to variation in PRV action and fire variability. The time for destratification is important because it is also an indication of the time to reach peak liquid energy and this affects the likelihood of a BLEVE.

3.2. *BLEVE mechanisms and liquid stratification*

In a previous paper on the subject, Birk and Cunningham [3] showed that BLEVEs can follow different paths. If a tank is severely weakened, then any fissure that forms in the wall propagates rapidly along the tank and this leads to a very rapid total loss of containment and BLEVE. In this case the crack may propagate at 150–200 m/s along the tank length. With this very rapid destruction of the tank it is unlikely that the liquid (i.e. liquid flashing) played a role in the destruction of the tank.

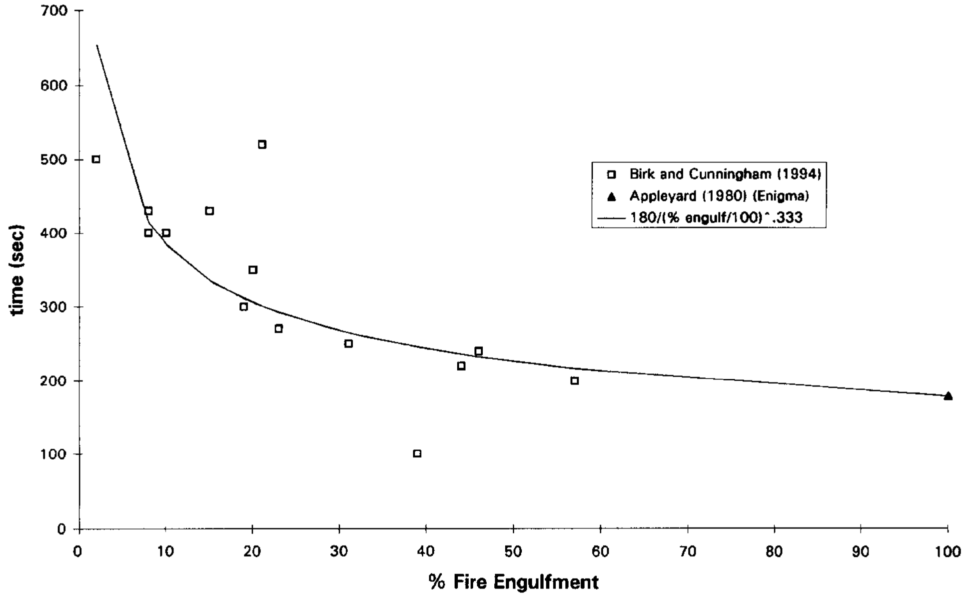

Fig. 5. Time to destratify liquid temperature vs. % fire engulfment (data from Birk and Cunningham [6] and Appleyard [5]).

However, in some cases where the tank was not weakened so severely, the initial fissure arrested in stronger wall material. This finite fissure resulted in a sudden depressurization and a strong flashing/boiling response by the liquid. With this flashing, tank pressure recovery took place, and in some cases this pressure recovery was enough to restart the crack and send the tank into catastrophic failure and BLEVE. In this case the liquid energy played a very important role in the tank failure process.

In other cases where the fissure arrested a transient jet release was observed. These jet releases varied widely depending on the size of the fissure and the liquid energy in the tank. In those cases where the fissure was large (i.e. length of fissure similar to tank diameter) the resulting release and fireball was virtually identical to a BLEVE.

Fig. 6 shows a BLEVE map from Birk and Cunningham [3] where the tank strength is plotted on the vertical scale and the product of liquid mass fill and average liquid temperature (i.e. proportional to liquid energy) is plotted on the horizontal scale. As can be seen from the plot the BLEVE and non-BLEVE cases are separated by a straight or upward curving line. This shows that higher liquid energies (i.e. high liquid temperatures and fill levels) mean that BLEVEs can take place with stronger tanks. It should be noted that the range of liquid energies shown on the map is due to variations in liquid fill at failure, liquid temperature stratification and changes in PRV set pressures.

Temperature stratification plays an important role in the average liquid temperature. For a given tank pressure the average liquid temperature decreases as the

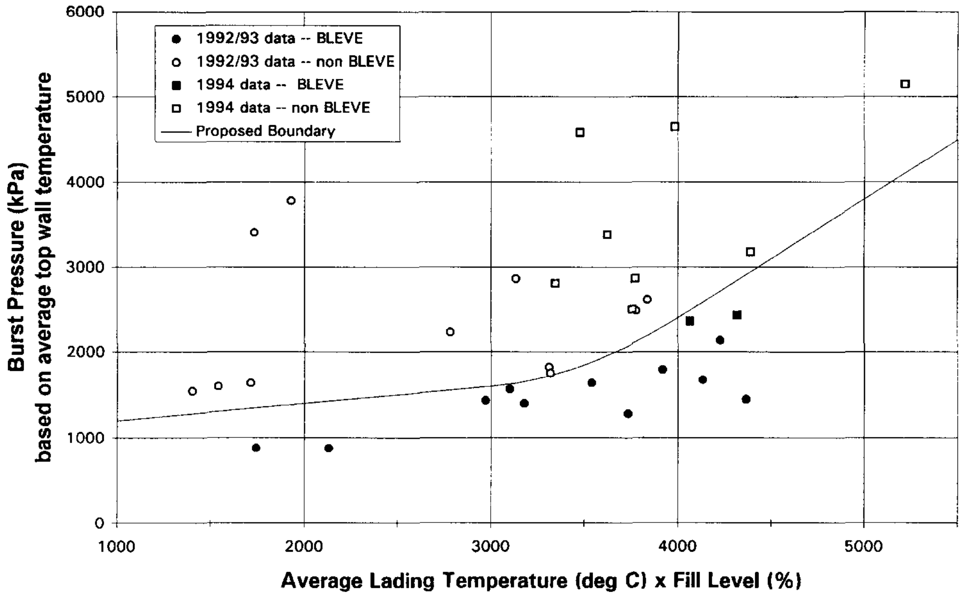

Fig. 6. BLEVE map for 400 l ASME propane tank (from Birk and Cunningham [6]).

liquid becomes more stratified. This is because the tank pressure is dictated by the warmest liquid layer in the tank and not the average temperature. This then means that for a given relief valve set pressure there will be less liquid energy if the liquid is stratified.

The boiling response upon sudden depressurization should be affected by more than just the average liquid temperature. If the liquid is stratified and it is then suddenly depressurized the warmer upper layers of the liquid will be sent further into superheat than the lower cooler layers. This means boiling will start earlier in the warmer liquid and if this boiling results in pressure recovery in the tank, it may suppress the boiling of the lower cooler liquid. It should be noted that the boiling is already suppressed slightly at the bottom of the tank due to the higher hydrostatic pressure. If the liquid were at a uniform temperature then this boiling suppression would not take place to the same degree, and the resulting pressure recovery would be stronger and therefore more likely to fail the container. This aspect of temperature stratification requires further study.

Fig. 7 shows the results from a series of fire tests leading to tank failures as reported by Birk and Cunningham [6]. The plot shows temperature stratification at the time of failure vs. the time at failure. These tanks all failed at pressures between 2 and 2.4 MPa and therefore the average liquid temperature increases as the temperature stratification decreases. Tanks that suffered a BLEVE are indicated. In most cases the BLEVEs occurred with low temperature stratification (i.e. higher average liquid temperature). The four BLEVEs with large stratification involved thin wall or mechanically weakened tanks. In other words, for a given PRV set pressure, a

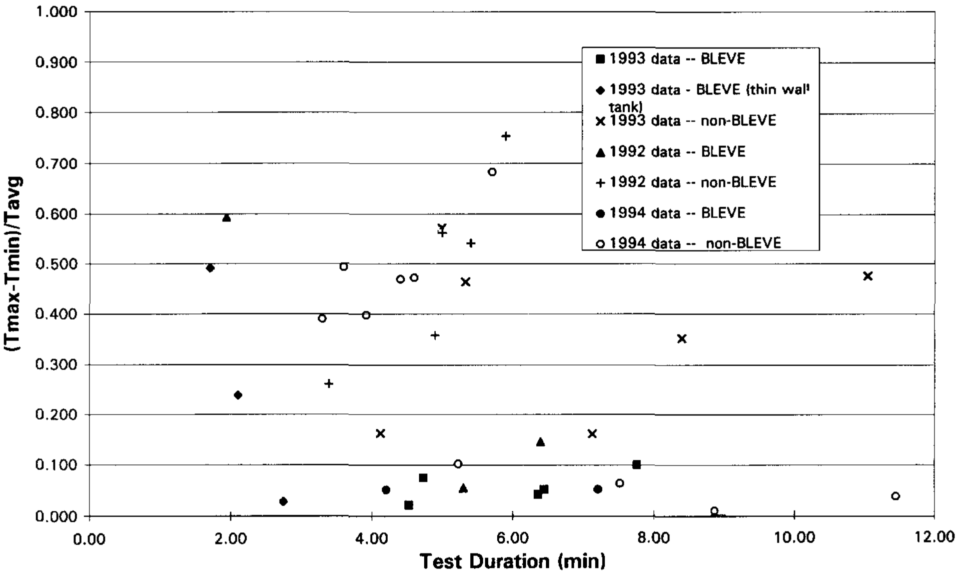

Fig. 7. Lading temperature stratification at failure (400 l ASME propane tanks, data from Birk and Cunningham [3]).

thermally stratified liquid is less likely to suffer a BLEVE because it is less able to drive a partially failed container to catastrophic failure.

4. Destratification and liquid energy

When the PRV opens the liquid begins to destratify due to boiling action. The time to destratify depends on the tank scale and the PRV action which itself is controlled by the degree of fire exposure. If a tank is engulfed in fire the resulting large PRV flow will tend to destratify the liquid quickly, whereas if the tank is exposed to a small fire, or torch fire from above the liquid may not destratify at all.

The time to destratify is an important time scale because of how it affects liquid energy. The severity of a tank failure is directly related to the liquid energy. This was shown in the BLEVE map of Fig. 6. It will be shown later how liquid energy affects blast, projectiles and fire ball hazards.

The liquid energy is related to the liquid temperature and the mass of liquid in the tank. When a tank is impinged by fire the liquid temperature rises until the PRV first opens. When the PRV is open the liquid begins to destratify and this means the liquid average temperature continues to rise until it is uniformly heated to the saturation temperature for the tank PRV set pressure. While the PRV is open liquid is being lost to vapourization and venting. However, experiments show that while the liquid is destratifying, the average mass flow

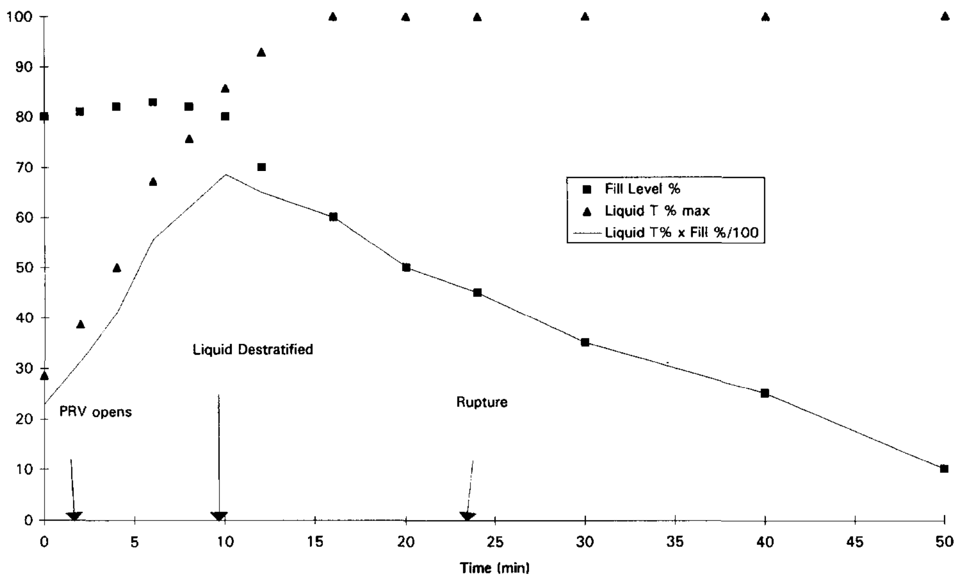

Fig. 8. Variation of liquid fill, temperature and energy vs. time for tank engulfed in fire (data from Townsend et al. [4], RAX 201).

through the PRV is less than when the liquid is isothermal. This is because of subcooled boiling that is taking place where some of the vapour bubbles generated at the wall collapse into the liquid core (i.e. part of fire heat goes into heating liquid core the remainder goes into vapour generation for venting). This bubble collapse is one mode of heat transfer in the destratification process. Once the liquid reaches saturation conditions, the PRV flow is related to the total heat input (i.e. all the heat goes into vapour generation for venting). This means that the time to reach the peak liquid energy is closely tied to the time for destratification of the liquid.

Figs. 8 and 9 show how the liquid temperature, liquid level and the product of the two (i.e. proportional to liquid energy) varied in two fire tests of propane tanks. In one case the tank is a 130 000 l tank-car [4] and in the other the tank is a 800 l propane tank (i.e. 1/5th scale rail tank car [5]. As can be seen from the plots the peak liquid energy occurs around the time the liquid is isothermal. Also note that in these two cases the tanks failed some time after the peak liquid energy was achieved.

Fig. 5 showed how the time to destratify is affected by the fire engulfment fraction. From this we conclude that as the fraction of fire engulfment decreases, the time to peak energy increases. From Figs. 8 and 9 we see that fully engulfed tanks tend to fail some time after the peak liquid energy has been achieved. If partial engulfment delays the time to peak energy then it is possible that partial engulfment could synchronize liquid peak energy with time to failure thus giving an even more powerful BLEVE.

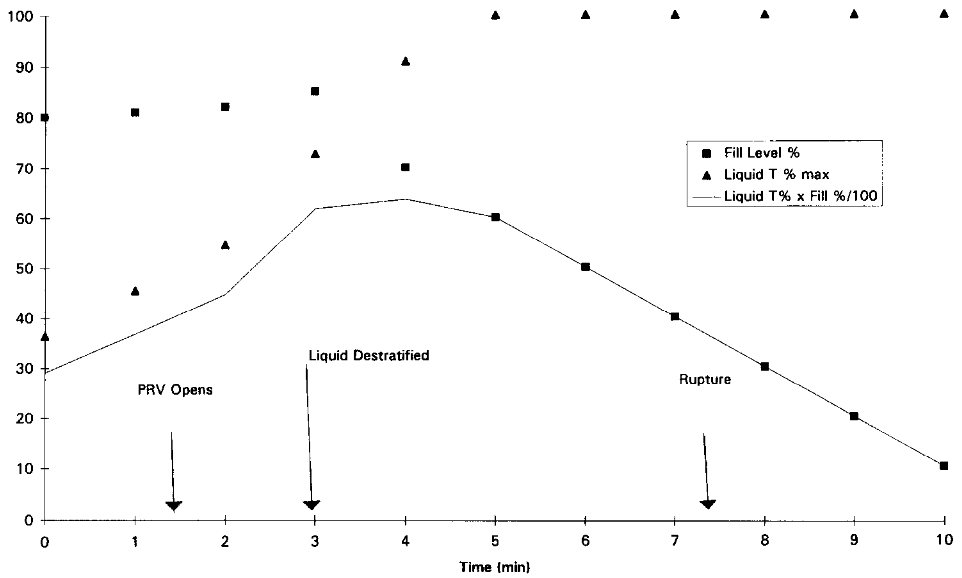

Fig. 9. Variation of liquid fill, temperature and energy vs. time for tank engulfed in fire (data from Appleyard [5], Enigma).

5. Liquid stratification and pressure relief

Pressure relief valves are critical safety devices that are installed on PLG tanks. These devices are intended to maintain the tank internal pressure below some set pressure. They are designed to open and relieve pressure in the event that the internal pressure rises due to effects such as solar heating or minor fire exposure. These devices alone are not able to protect a tank from severe fire exposure because they are not capable of stopping the tank from losing strength due to severe temperature increases.

Based on the experiments and on simple thermodynamic considerations, it is clear that higher PRV set pressures increase the chance of a BLEVE because high settings result in increased liquid and vapour energies. Therefore, PRV set pressures should be set as low as practical for the application.

There are also sound theoretical arguments and experimental evidence (see, for example, [1–9]) that show that PRV set pressures should not be near the atmospheric superheat limit as this maximizes the strength of the liquid boiling response upon sudden depressurization. For propane the atmospheric superheat limit temperature (52 °C) should be considered the upper limit for setting PRV pressures since it is a real indication of the severity of the liquid boiling response upon sudden depressurization. For propane then, the upper limit on set pressures should be around 1.7 MPag (245 psig). If this setting is exceeded for practical reasons then the tank strength should be increased to reduce the chance of thermal failure.

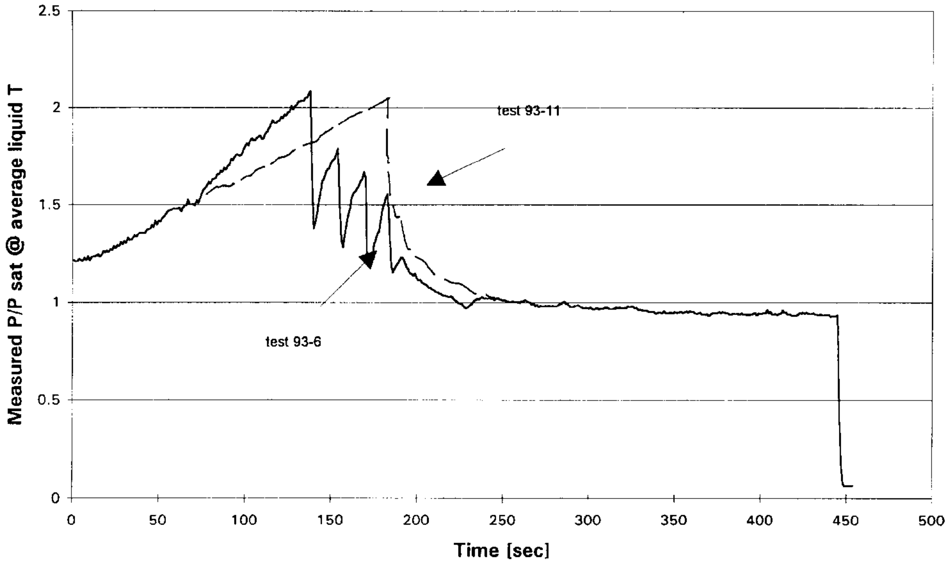

Fig. 10. Comparison of destratification for different PRV behavior – test 93-6 PRV cycles 4 times before remaining open, test 93-11, PRV opens and remains open (400 l propane tank, torch from above and pool fire from below, approx. 45% engulfment).

PRV operating mode (i.e. cycling vs. continuous flow) may also affect liquid energy by affecting temperature stratification. As discussed earlier in this paper, liquid stratification is reduced or eliminated with prolonged PRV action. This is because when the PRV opens and vents vapour, boiling in the liquid consumes energy in the warmest liquid layers and the resulting bubble rise causes mixing and these effects combine to reduce the stratification.

Fig. 10 shows two tests (400 l propane tanks, 80% full) with similar fire engulfment (about 45% engulfment) but different PRV action. In test 93-6 the PRV cycles four times before remaining open, while in test 93-11 the PRV opened and stayed open. In both cases when the PRVs remained open they may have been only partially open (this is a subject of ongoing research).

In test 93-6 (cycling PRV) the pressure ratio dropped from 2.1 to 1.1 in approximately 85 s, while in test 93-11 the pressure ratio dropped from 2.1 to 1.1 in approximately 60 s. This difference appears to be due to the regeneration of stratification during cycles when the PRV is closed. This suggests that cycling PRVs slow the destratification process. Further study is needed here with more controlled heat input conditions.

6. Liquid stratification and fireballs

Fireball geometries vary widely from test to test. However, the literature does identify some reasons for the variability (see, for example, Ref. [10]). For example,

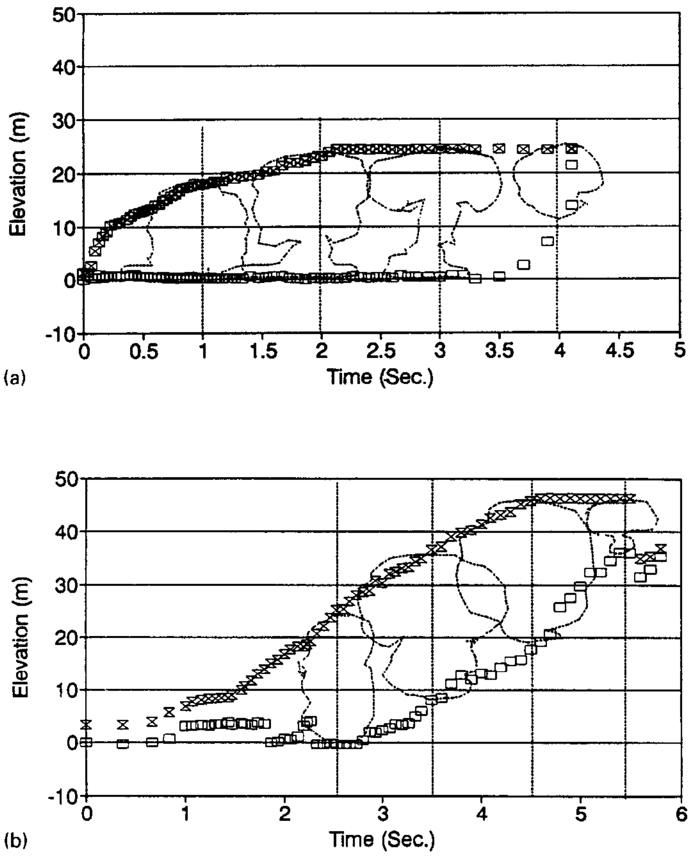

Fig. 11. Fireball shapes for cases with and without liquid temperature stratification (data from Birk and Cunningham [6]): (a) 400 l tank, failure pressure 2.6 MPa, 3 mm wall thickness, 80% full, T liquid = 37 °C, (b) 400 l tank, failure pressure 2.2 MPa, 6 mm wall thickness, 76% full, T liquid = 56 °C.

it has been recognized that tank pressure at failure affects the upward and outward momentum of a release of flammable material and this affects the upward rise of a fireball, and how efficiently it burns. However, the results of our tests suggest that pressure alone is not enough to explain the differences in the shape, size and duration of fireballs. For the same tank rupture pressure, the liquid average temperature can vary significantly due to thermal stratification.

For any given tank pressure, liquid stratification will affect the way the liquid flashes and expands. If the degree of stratification is severe then a smaller fraction of the contents will flash to vapour upon tank failure thus resulting in a different fireball. Observations from the tests of 400 l propane tanks suggest that BLEVEs where the liquid is significantly stratified give large ground fires and delayed or no fireball liftoff.

Fig. 11 shows two different fireballs from BLEVEs of 400 l tanks. Both tanks failed at approximately 2.2–2.6 MPa pressure with the tanks near 75% full. Both tanks failed due to similar torch exposure at the tank top. In Fig. 11(a) the tank had a 3 mm wall thickness so that it would BLEVE more easily. In this case the BLEVE took place with the liquid highly stratified with an average temperature of around 37 °C. For Fig. 11(b) the tank had a wall thickness of 6 mm and the tank BLEVEd with the liquid uniformly at 56 °C. The fireballs are very different. With the stratified liquid there is more of a ground fire and the fireball centre height never exceeded 20 m. With the non-stratified liquid the fireball is high in the air with burnout at 40 m elevation.

Part of the difference in these fireballs is in the way the tanks failed. In Fig. 11(a) the thinner tank opened up very quickly (10 ms). However, in the case of Fig. 11(b) the thicker tank failure started with a jet release and then this was followed by a catastrophic failure. The initial jet release contributed to the rapid rise of the fireball. It should be noted that the stratified liquid case (Fig. 11(a)) would not have BLEVEd if the tank wall thickness had been 6 mm as in Fig. 11(b).

Fig. 12 shows thermal radiation dose to near targets (at 20, 30 and 40 m from tank) vs. liquid temperature from the failure and BLEVE of 400 l propane tanks. The thermal dose has been normalized to the release mass by dividing it by the cube root of the mass. The failure pressure for these tanks were all between 2.0 and 2.4 MPag and therefore the difference in the average liquid temperature is due mostly to thermal stratification at failure. As can be seen from the plot the dose to near targets varies widely. However, there appears to be a trend towards

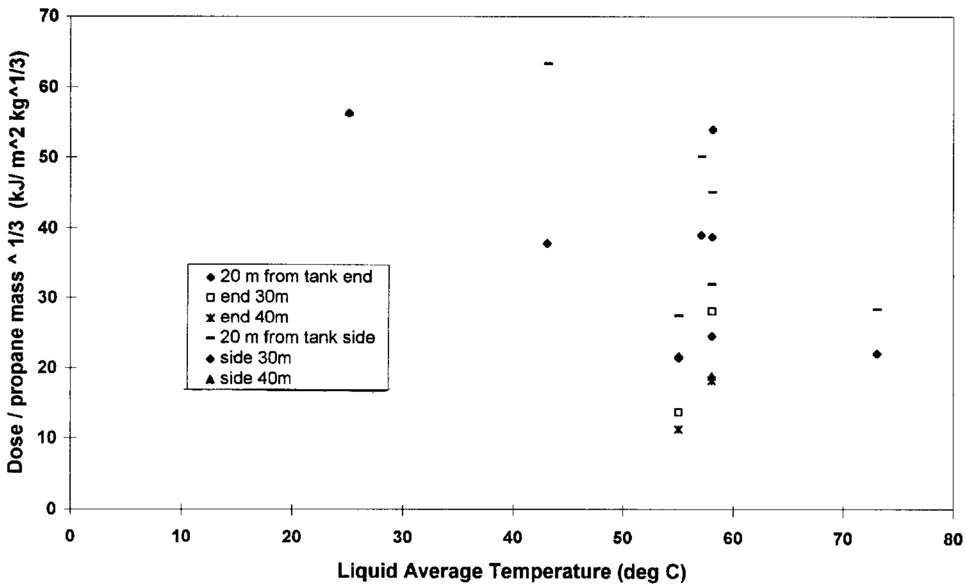

Fig. 12. Measured thermal radiation dose vs. average liquid temperature (BLEVEs of 400 l propane tanks, data from Birk and Cunningham [6]).

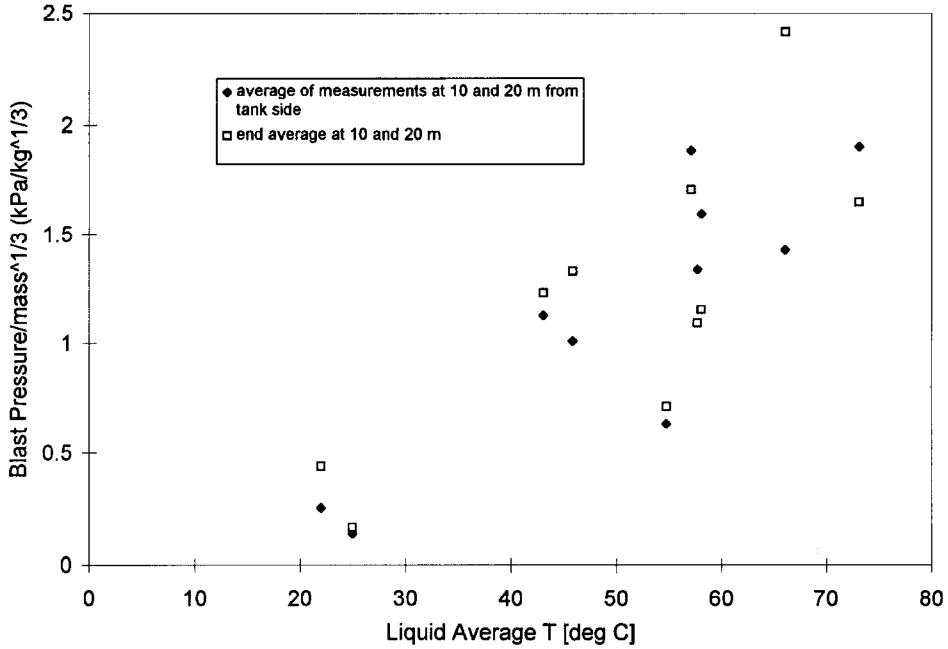

Fig. 13. Blast overpressure from liquid expansion vs. liquid average temperature (BLEVEs of 400 l ASME propane tanks, corrected for propane mass).

lower dose at higher liquid temperatures. This is probably due to the fact that higher liquid temperatures result is faster rising fireballs and this would reduce the heat flux to close in ground level targets. This then suggests that liquid stratification may increase the fire hazard to close targets because of reduced liftoff and larger ground fire.

7. Liquid stratification and blast

The blast from a BLEVE has several pressure spikes – one for the expanding vapour space, one for the flashing liquid and in some cases a third for the combustion wave. The vapour space energy depends on the tank pressure at failure and will not be affected by liquid stratification. However, for the same tank pressure at failure the blast peak from the liquid will decrease as liquid temperature stratification increases.

Fig. 13 shows some typical blast wave data presented as a function of liquid average temperature. As can be seen there is a clear correlation with liquid temperature. This again would suggest that since liquid stratification reduces the average liquid temperature then the blast strength is also reduced by liquid stratification.

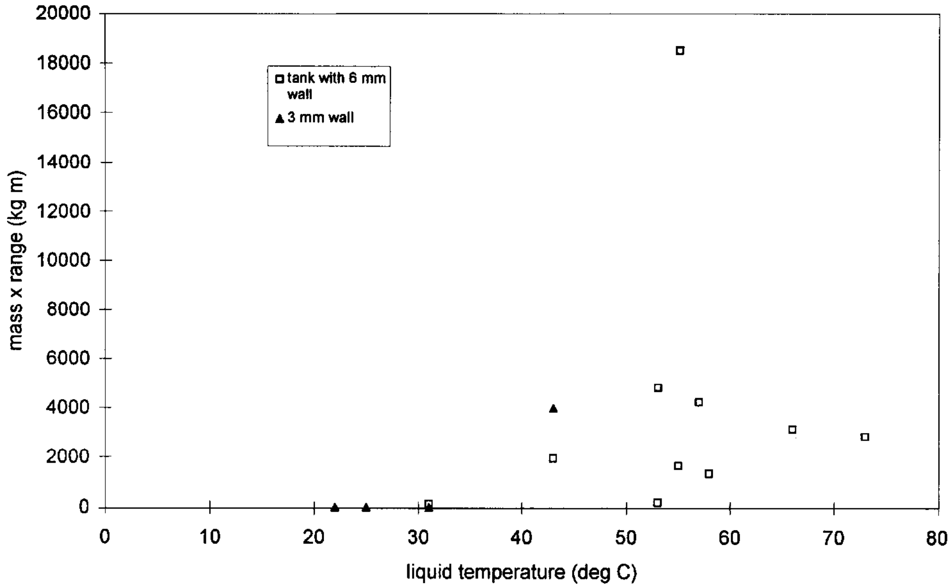

Fig. 14. Primary projectile mass×Range vs. average liquid temperature (for non-tub-rocket BLEVE of 400 l propane tanks, data from Birk and Cunningham [6]).

8. Liquid stratification and projectiles

Projectiles are also affected by the liquid temperature stratification. The warmer the liquid, the higher the isentropic expansion energy and the further the projectiles can be sent. This then suggests that if a stratified liquid has less energy then it will produce less projectile hazard.

The longest reaching projectiles are usually tub rockets where a major portion of the tank is propelled by the thrust of the flashing liquid. If the tank does not rocket, tank ends can be thrown large distances as the tank is opened and flattened on the ground.

Fig. 14 shows the product of projectile range and mass vs. liquid average temperature at the time of failure. It should be noted that no tub rockets occurred in these tests. Recall that in all cases the tanks failed with internal pressures between 2 and 2.4 MPa and the difference in liquid temperature is due mostly to thermal stratification. From the figure we see that projectile hazard increases with the average liquid temperature. With severe thermal stratification (i.e. liquid temperatures from 20 to 35 °C) there were no primary projectiles observed. When the liquid was destratified (liquid temperatures above 40 °C) projectile hazards increased significantly.

9. Mitigation

Based on the above arguements it seems reasonable to conclude that BLEVE hazards can be reduced by reducing liquid energy. This could be done by decreasing

PRV set pressures. However, this is not a practical solution in many cases. PRV set pressures must be selected so that PRVs are not being opened regularly due to variations is solar loading, or ambient temperature.

Another way to limit liquid energy is to take advantage of liquid temperature stratification. If a way can be found to maintain liquid temperature stratification, then the average liquid energy could be reduced without changing PRV settings. Practical ways to do this include careful PRV selection and design, thermal barriers, and internal partitions (see Ref. [11, 1]). This clearly is an area requiring more work.

10. Conclusions

Liquid temperature stratification has the following effects:

(i) for the same tank pressure, the total liquid energy is less when the liquid is stratified,

(ii) upon sudden depressurization, less liquid superheat is achieved with a stratified liquid and this effects the boiling response and pressure recovery,

(iii) reduced liquid energy reduces momentum of release which affects size and liftoff of fireball,

(iv) less energy in liquid reduces blast, projectiles,

(v) less liquid energy may increase ground fire hazard,

(vi) less liquid energy reduces chance of BLEVE.

The liquid temperature stratification is affected by scale, the fire exposure type, and the PRV action. It takes longer for large scale tanks to destratify. It takes longer for tanks partially engulfed by fire to destratify due to the reduced PRV flow. Cycling PRVs appear to slow the rate of destratification.

If it is accepted that a stratified liquid is better than a uniform temperature liquid then it becomes desirable to design thermal protection systems to support temperature stratification. For example, tank internal partitions can isolate the core of the liquid from the heated boundary, thereby keeping the liquid core cooler than the boundary. Such a partition was suggested by Birk [11]. These partitions can be designed to reduce bulk mixing of the liquid and at the same time can be used to help keep vapour space wall regions cooler.

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