On the Transition From Non-BLEVE to BLEVE Failure for a 1.8 M^3 Propane Tank

A. M. Birk

J. D. J. VanderSteen

Department of Mechanical Engineering,
Queen's University,
Kingston, Ontario, Canada

A series of fire tests were conducted on nine, 1.8 m^3 (500 US gal) *ASME code propane pressure vessels to study the significance of pressure relief valve behavior on tank survivability to fire impingement. In these tests three tanks ruptured (i.e., finite failure) and six boiling liquid expanding vapor explosion (BLEVEd) (total loss of containment). The difference between the BLEVE and non-BLEVE failures was due to a difference in the fire conditions. It is believed that these tests show some insight into the BLEVE process. In all tests the fire consisted of an array of nominal* 590 kW (2 MBTU/h) *liquid propane burners. A pool fire was not used because of the uncontrolled nature of open pool fires. It was believed that very repeatable fire conditions could be achieved by using a series of burners. In the tests where the outcome was a non-BLEVE there were two burners mounted* 30 cm *above the tank on the tank vapor space. These burners were used to weaken the steel and to initiate a failure. To heat the liquid, there were between 4 and 12 burners applied below the liquid level. When one burner was added on the vapor space, all of the remaining tanks BLEVEd. This was true over a range of fill levels (at failure) of between 10% and 50% by volume. It is believed this added burner was just enough to weaken the tank so that any initial rupture would grow towards a total loss of containment and BLEVE. This paper presents the details of this test series and shows how severely heated length and liquid energy affected the outcome.*

[DOI: 10.1115/1.2349579]

Introduction

When a tank holding a pressure liquefied gas such as LPG or propane is heated by fire there is a chance that the tank will fail. If the failure results in a total loss of containment (full opening of cross section) then the outcome is a boiling liquid expanding vapor explosion (BLEVE). However, if the tank ruptures but the rupture does not grow to result in a total loss of containment then the outcome is a finite rupture with a transient jet release. The hazards from a finite rupture tend to be less than that from a BLEVE. The question then is, why do some tanks fail as a BLEVE and others as a finite rupture?

A series of fire tests were conducted on nine, 1.8 m^3 (500 US gal, $D=0.953$ m, $L=2.7$ m, wall thickness=7.1 mm) ASME code propane pressure vessels (commonly referred to as tanks in the propane industry) to study the significance of pressure relief valve (PRV) behavior on tank survivability to fire impingement. In these tests three tanks ruptured (i.e., finite failure) and six BLEVEd (total loss of containment). The difference between the BLEVE and non-BLEVE failures was due to differences in the fire condition. In all tests the fire consisted of an array of nominal 590 kW (2 MBTU/h) liquid propane burners. A pool fire was not used because of the uncontrolled nature of open pool fires. It was believed that very repeatable fire conditions could be achieved by using a series of burners. This was necessary to be able to isolate the effects under study.

In the tests where the outcome was a non-BLEVE there were two burners mounted 30 cm above the tank on the tank vapor space. These burners were used to weaken the steel and to initiate a failure. To heat the liquid, there were between 4 and 12 burners applied below the liquid level. When one burner was added on the vapor space all of the remaining tanks BLEVEd, regardless of the number of liquid space burners. It is believed this added burner was just enough to push the tank towards a BLEVE outcome. This conclusion was made because three of the six BLEVEs were of the two-step kind where the failure begins with an initial jet release.

BLEVE Versus Finite Rupture

Birk et al. [1] carried out a series of fire tests of 400 liter (100 US gal) automotive propane tanks and showed that a BLEVE will happen when the tank is severely weakened and when there is enough energy available in the tank contents to drive any initial failure to total loss of containment. Based on testing done with over forty 400 liter tanks, Birk et al. [1] were able to produce a BLEVE map for the tank tested and this map showed how the BLEVE outcome depended on both the tank strength and the contained energy. This BLEVE map is shown below in Fig. 1.

It should be pointed out that this map only applies to the tanks tested and the specific fire conditions used (i.e., severely heated length, etc.). As a result it is useful for explaining trends but it is not a practical plot to use for all tank scales and fire conditions.

For a BLEVE to happen the tank must first be weakened to the point where an initial pinhole rupture is formed. For the case of a fire heated tank this pinhole may form due to plastic thinning of the wall in the heated area or it may form at a flaw in the tank wall. For a BLEVE to take place this pinhole must grow to cause a total loss of containment (TLOC).

The pinhole normally grows in a direction perpendicular to the principal stress (in this case hoop stress). As this hole grows vapour is initially escaping from the tank and the pressure is dropping. If the tank is very weak due to heating over a large area then the crack may rapidly grow (>200 m/s) the full length of the tank to give a TLOC and BLEVE. In this case the failure is so rapid that the liquid may not have enough time to be involved with the process (i.e., liquid must change phase to vapor to do

---

Contributed by the Pressure Vessels and Piping Division of ASME for publication in the Journal of Pressure Vessel Technology. Manuscript received April 17, 2006; final manuscript received April 19, 2006. Review conducted by G. E. Otto Widera.

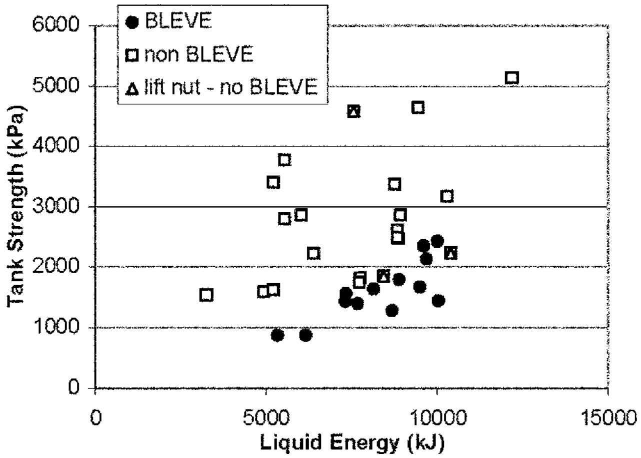

Fig. 1 Bleve map for 400 liter tank (see Ref. [1])

Fig. 2 1.9 M^3 tank with burners (2001 tests with three vapor space burners and ten liquid space burners)

work on the tank wall). In other words it was the vapor space energy that maintained the wall loading long enough to destroy the tank.

However, in other cases the crack may stop in stronger material or it may stop because of the decreased pressure in the tank. In this case the vapor space energy is spent without failing the vessel.

If the crack stops, this does not mean the event is over and a BLEVE is not possible. As the pressure is dropping in the tank the liquid is being sent into a state of superheat. If the pressure drop is very rapid (large hole and/or small vapor space) a significant amount of superheat may be established in the liquid before the bulk of the liquid responds by flashing. The flashing of the liquid and the resulting pressure transient may cause sufficient loading of the tank wall to restart the crack and cause the total loss of containment. It has been shown in many experiments that there can be a significant pressure recovery in a tank holding a pressure liquefied gas after initial depressurization by a rupture [1–3]. This process has been recorded in full-scale ASME code pressure vessels by Birk et al. [1,4].

Once a massive flash response is initiated the rapid phase change can send liquid droplets up to impact the top of the tank wall as recorded by Ogiso et al. [2]. Using water heated to up 155°C (i.e., well below the atmospheric superheat limit of water) Ogiso observed impact pressures of about 5–7 atm above the saturation pressure of the water. In the tests of Ogiso these impact pressures died away after a time of about 150 ms.

The flashing will cause liquid to be entrained into the vented stream and this two-phase material will reduce the vented material enthalpy flux to the point where the pressure begins to recover in the vapor space [5]. The increase in pressure from the pressure recovery adds to the wall loading and this may contribute to restarting the failure crack and sending the tank to TLOC and BLEVE. This type of BLEVE where the crack stops and is restarted is sometimes called a two-step BLEVE [6]. It is suggested that these kinds of two-step BLEVEs are in a transition region between a finite failure and a BLEVE.

If there is only local heating of the vapor space wall then the crack is likely to stop in stronger cool material. If the final rupture length is kept below some critical size then the pressure forces on the flaps produced by the failure opening are not sufficient to propagate the failure. However, if the hole size is larger then the critical size then the crack can sometimes be restarted and driven through cool strong wall material.

Present Tests

As noted earlier the tests described here involved nine tests of 1.8 m^3 ASME code propane tanks. In these tests three tanks ruptured with finite failure and six BLEVEs were observed. Of the six BLEVEs, three were of the two-step type when stopped and then was restarted by the pressure transient in the tank. It is believed that these tests are one example of a tank just at the transition between a BLEVE and a non-BLEVE failure.

The tests had the following main characteristics:

- all started 80% full with commercial propane at between 10 and 20°C;
- all tanks had a computer controlled pressure relief device set to open at 1.9 MPag with blowdown varied between 5% and 45%;
- all tests ending in BLEVEs had three vapor space burners and a 21 mm nozzle on the PRV;
- all non-BLEVE tests had two vapor space burners and a 24 mm nozzle on the PRV; and
- the number of liquid burners was varied between 4 and 12.

The tests were done to study the effect of PRV blowdown on the outcome of the fire test. It was concluded that larger blowdown delays failure and reduces hazards. This aspect of the test has been reported by Birk et al. [7].

Apparatus

The basic apparatus is shown in Figs. 2 and 3. The tank was mounted on support stands about 1 m above a concrete pad. The burners were mounted on steel frames. The mechanical pressure relief valve was removed from the tank and was replaced by a fast opening, full port ball valve and a converging nozzle. The opening of the simulated PRV was computer controlled. In all cases the PRV opened at 1.9 MPag (275 psig) and the blowdown (open pressure-close pressure)/(open pressure) was set to between 5% and 45%. The nozzle was either 24 or 21 mm in diameter.

The burners used for this test series were standard 590 kW liquid propane fueled utility torches. A feed pressure of 275 kPa (40 psig) was used for all tests and the torches were located 30 cm (12 in.) from the tank wall.

A total of 48 type K thermocouples (tcs) (3 mm, SS, sheathed) were located in the tank (16 at midplane center, seven each at midplane left and right, and nine each at front and backend). The tank was also equipped with two pressure transducers mounted on the tank bottom.

The tank wall in the vapor space was instrumented with four unsheathed thermocouples mounted in the wall at the tank top under the burners. Three of the tcs were located under the aim point of the burners and one was located between the aim point of

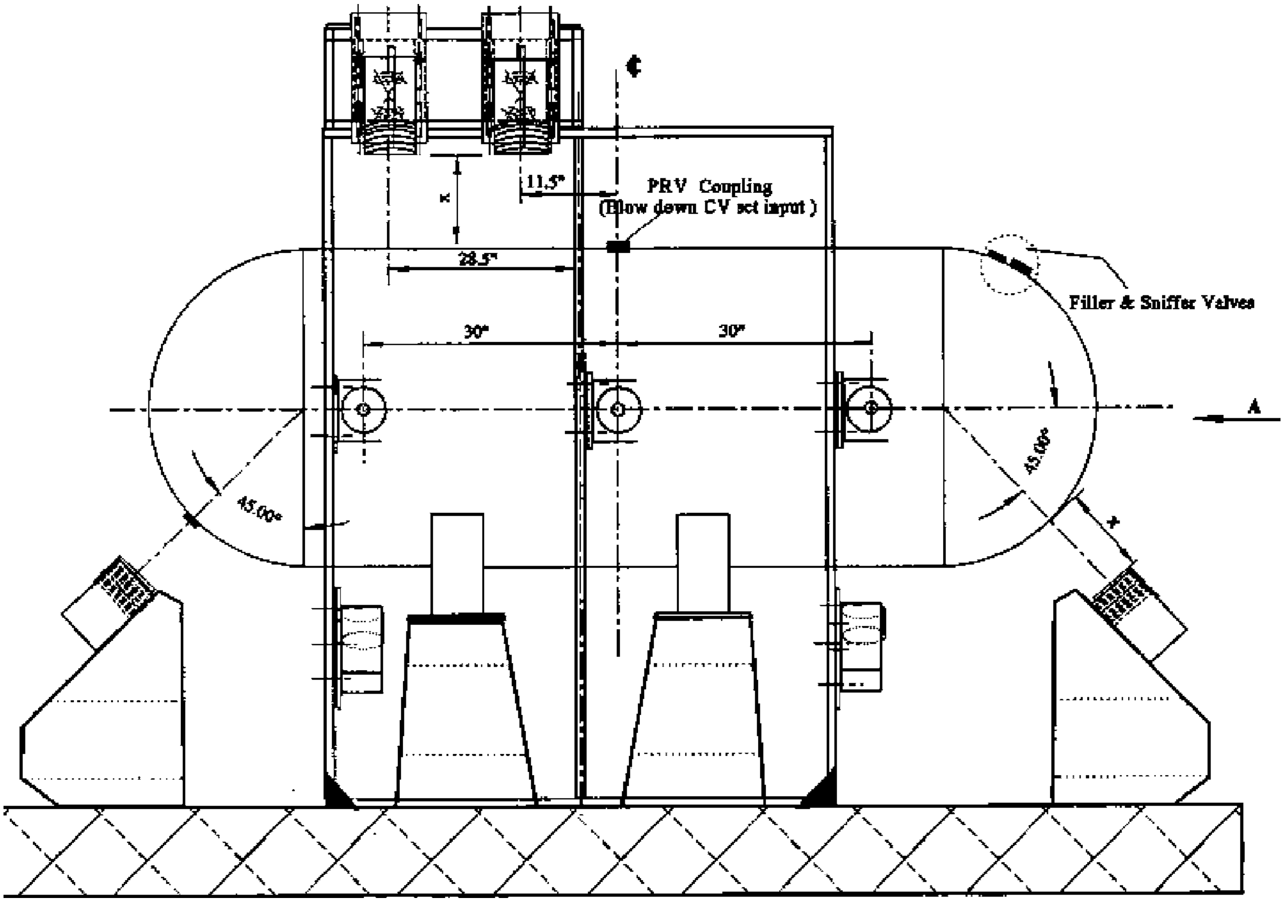

Fig. 3 Sketch of tank showing 2000 series test setup (two vapor space burners and 12 liquid space burners)

two of the burners. It should be noted that the tank ruptured in a line parallel and about 4 cm away from the wall thermocouples. The holes drilled for the thermocouples were never the starting point of the rupture.

The standard tank mounted PRV was removed and replaced with a computer controlled fast opening air driven ball valve with a machined smooth converging nozzle for mass flow measurement. This was done to have complete control over the PRV system behavior. The PRV system was attached to the top midpoint on the tank and a length of 5 cm pipe (approximately 10 m) directed the flow to the ball valve and flow nozzle apparatus. Pressure and temperature were measured just before the flow-metering nozzle.

Test Procedure

The basic test procedure was to purge and fill the tanks to 80% capacity with commercial propane and then ignite the burners. Two or three vapor space burners were used to weaken the tank to initiate failure. 4–12 burners were used on the liquid space to heat the liquid. Fewer burners on the liquid would result in reduced heat input to the liquid, a slower emptying of the vessel through the PRV, and a higher liquid fill at failure.

All data were recorded until either the tank failed or the tank vented empty through the PRV system. The main variables in the tests were blowdown and the number of vapor and liquid space burners. The PRV orifice size was a secondary variable since it only affected the PRV mass flow which affected the PRV cycling frequency, not the tank pressure limits.

Results

The following figures show some of the basic data obtained from the tank instruments. Full details of the tests and the results were published as a Transport Canada report in 2003 [4].

Figure 4 shows the measured pressure from tests 01-2 and 01-3.

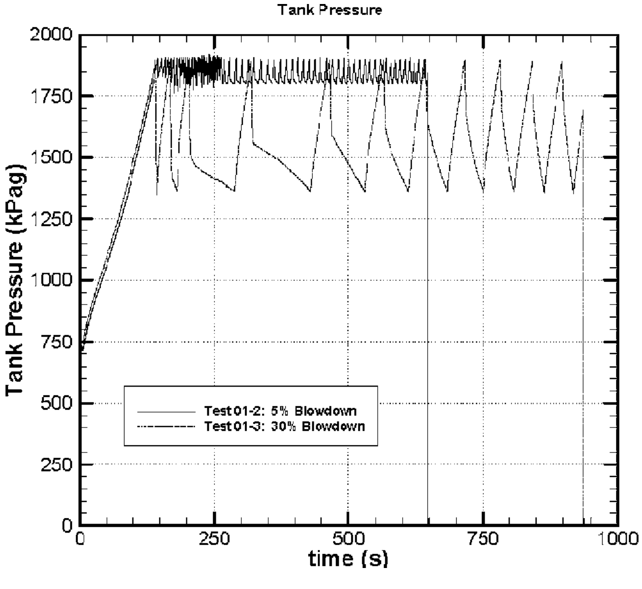

Fig. 4 Typical pressure versus time plots

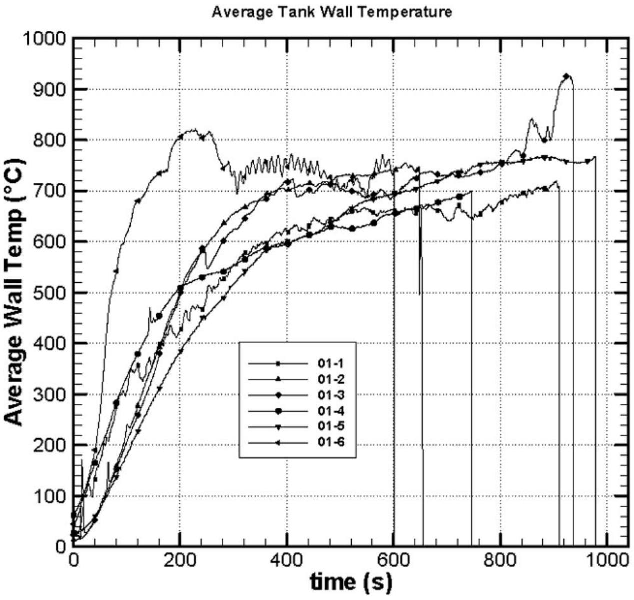

Fig. 5 Average of measured vapor space wall temperatures under burners

This plot shows the typical pressure response obtained using the computer controlled PRV. As can be seen with the small blowdown the valve cycles were high frequency due to the rapid drop in tank pressure when the PRV pops full open. With the larger blowdown the PRV cycles were much slower. As can be seen from the figure the large blowdown case resulted in a lower average pressure state for the tank and a much later failure time (failure indicated by sudden drop of pressure).

Figure 5 shows the average measured wall temperature from all the tests. As can be seen there are some differences in the wall temperatures. This is probably due to some wind effect, which would deflect the fire slightly, and this would move the peak wall temperature off the thermocouple location and thus reduce the indicated wall temperature. We believe the wall temperatures were actually quite similar from test to test.

It is possible to group tests of similar wall temperature. Tests 01-2 and 01-3 are very similar and tests 01-1, 01-4, and 01-5 are very similar. Test 01-6 is the only test that stands out and this was because of a change in fire condition (four burners on liquid space instead of ten and higher burner fuel pressure). For this reason test 01-6 should be considered to be a special case in this test program.

Figure 6 shows the average vapor temperatures for the small and large blowdown cases. As can be seen the large blowdown cases achieve higher vapor temperatures because of the longer periods with the PRV closed (i.e., reduced convection and purging of the vapor space). Figure 7 shows the average measured liquid temperatures, and as can be seen, the large blowdown cases result in lower liquid temperatures. This is because of the average lower pressure state in the large blowdown tanks. This is a very important benefit of large blowdown because it results in significantly reduced energy in the liquid and this can affect outcome (BLEVE or no BLEVE).

Test Summary

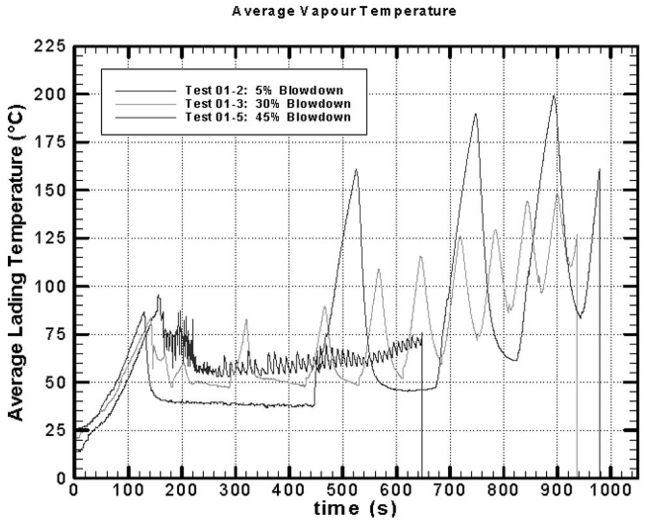

Fig. 6 Average vapor temperature for various blowdowns (2001 tests)

The outcome as noted earlier was that all the tanks exposed to two burners on the vapor space suffered a finite rupture with jet release and all the tanks with three vapor space burners suffered a total loss of containment and BLEVE. Table 1 gives a summary of all the tests. It should be noted that the steel (SA 455) for the cylinders of these tanks came from the same heat number. The ultimate tensile strength was measured to be 560 MPa. No impact tests were conducted on this steel.

Tank Failure

In all of the tests the tanks failed by plastic thinning under the vapor space burners. After a period of significant plastic deformation and thinning the wall failed in a ductile manner with the failure plane perpendicular to the wall surface. Based on high-speed video the failure starts as a small hole that grows along the tank axis. In the cases where the tanks suffered a total loss of containment and BLEVE the fracture changed to a shear failure with the failure surface being about 45 deg to the tank surface. This shear failure takes over after the crack leaves the severely heated (and thinned) region of the tank wall.

In all cases the severely heated region was at the tank top over a fraction of one end of the tank. This means that a local hot spot was created by the burners. The tanks did not fail when the nominal tank hoop stress exceeded the material ultimate strength in the heated zone. This is the usual failure assumption for long cylinders heated in fires (see, for example, Ref. [8]). In the present tests

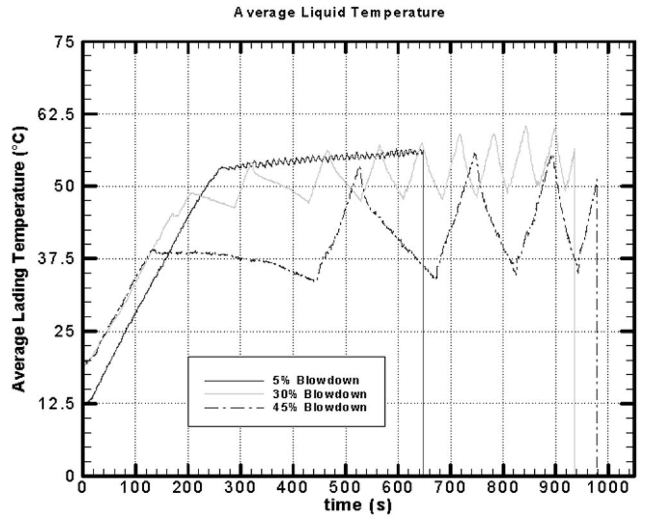

Fig. 7 Average liquid temperature for various blowdowns (2001 tests)

Table 1 Summary of test results

Test	Burners	Blowdown %	Outcome	Fail time (min)	Fill at failure (%)
00-1	2 on vapor 12 on liquid	20	69 cm rupture	13.0	14
00-2	2 on vapor 12 on liquid	5	22 cm rupture	13.5	20
00-3	2 on vapor 8 on liquid	20	53 cm rupture	17.2	17
01-1	3 on vapor 10 on liquid	30	BLEVE (1.2 s delay)	15.2	17
01-2	3 on vapor 10 on liquid	5	BLEVE (0.3 s delay)	10.8	35
01-3	3 on vapor 10 on liquid	30	BLEVE	15.6	13
01-4	3 on vapor 10 on liquid	5	BLEVE	12.4	21
01-5	3 on vapor 10 on liquid	45	BLEVE	16.3	12
01-6	3 on vapor 4 on liquid	5	BLEVE (1.6 s delay)	10.0	49

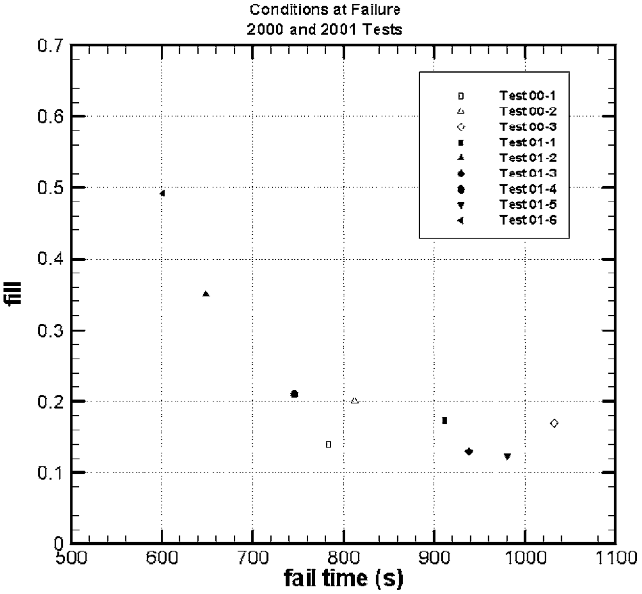

Fig. 8 Tank fill versus failure time

(i.e., local heating with heated length $L < D$) the failure was observed when the nominal hoop stress exceeded about 150% of material ultimate strength in the heated zone. This ultimate strength was estimated based on the minimum allowable ultimate strength for SA 455 (480 MPa at ambient temperature). Most of the tanks failed when the vapor space wall was around 720°C. At this temperature the SA 455 was estimated to have an ultimate strength of around 90 MPa. This was based on scaling high temperature properties of TC 128 steel [9]. Table 2 shows the predicted failure times based on hoop stress equals ultimate and hoop stress equals 150% ultimate versus the observed failure time. As can be seen the assumption that failure occurs when the hoop stress equals the ultimate strength was always conservative. If we used hoop stress=150% of ultimate for failure then the time estimate was better but not always conservative. It is very likely that this factor of 1.5 simply comes from uncertainties in the high temperature properties of the SA 455. It is also likely that the von Mises stress is a better indicator of failure in conditions of local heating. The local heating causes distortion in the stress field and as a result the nominal hoop stress may not be the true failure stress. The nominal von Mises stress in the cylinder is 0.87 of the hoop stress and we know that the actual ultimate strength of the tested material was about 16% higher than the minimum allowable for SA 455. These combine to explain most of the 1.5 factor.

In one test (01-6) the wall temperatures increased so rapidly that the failure was predicted much too early using either method. There is some question about the accuracy of the early wall temperature measurements in this test.

Table 2 Observed tank failure times versus predicted failure times based on stress and average wall strength in the heated zone

Test	Fail time (s)	If hoop = ultimate (s)	% error	If hoop = 150% ult (s)	% error
00-1	784	450	−43	900	+15
00-2	820	401	−51	800	−2
00-3	1032	795	−23	1150	+11
01-1	911	632	−31	1300	+42
01-2	648	298	−54	631	−3
01-3	938	376	−60	939	+0
01-4	746	581	−22	939	+26
01-5	980	636	−35	1100	+12
01-6	601	140	−77	189	−69

Upon initial rupture the crack grows at high speed (speed of elastic wave in the steel) at a rate of approximately 200 m/s. At this speed, the tank fully opens (crack length = 3D) in about 15 ms. However, in some cases the crack stops (as in 00-1, 00-2, and 00-3) as it enters stronger material. In some cases the crack stops and then is restarted by the pressure transient in the tank (i.e., two-step BLEVE in 01-1, 01-2, 01-6). In these two-step BLEVEs the effective average crack speed was of the order of 2 m/s.

Fill Level

The fill is important for several reasons. A large fill means the vapour space is small and this results in a more rapid pressure drop upon initial failure. A very rapid pressure drop will send the liquid into superheat and this will result in a powerful boiling response.

Ogiso et al. [2] showed that the impact pressure caused by liquid hitting the upper surface of the tank during the pressure transient is a function of the liquid temperature, the liquid mass, the distance from the liquid surface to the impact surface and the rate of initial depressurization.

Figure 8 shows the estimated fill of the vessels at time of failure. As can be seen all but two of the tests ended with the tanks less than 20% full of liquid. BLEVEs were observed over fill ranges from just over 10% to just less than 50% by volume. The non-BLEVE cases ranged between 15% and 20% fill. It is unfortunate that there is no high fill data point for the tests with two vapor space burners. It is possible that the added liquid energy at high fills may have caused a BLEVE in a two-burner case. This will be investigated in future testing.

The fill at failure is a function of the heating of the vessel and the time of failure. Less heating of the liquid results in a higher fill when the vessel fails.

Liquid Temperature

Figure 9 shows the tank pressure P versus liquid average temperature T for all the tests. The atmospheric superheat limit temperature T_{sl} for propane is 53°C and some publications [10] still suggest that this is a critical temperature for a BLEVE to take place. If propane is suddenly depressurized at this temperature it

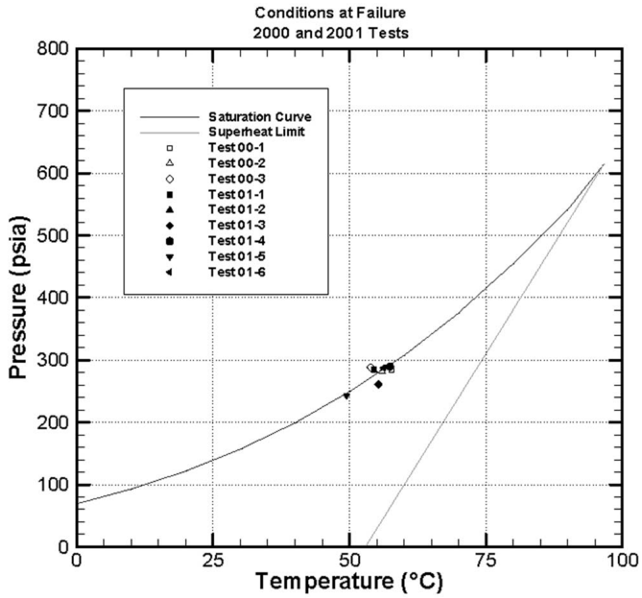

Fig. 9 Tank pressure versus liquid temperature at failure

can theoretically (see Ref. [11]) be taken all the way down to atmospheric pressure before the superheat limit is achieved. At this point homogeneous nucleation takes place and a significant fraction of the liquid changes phase in a very short period of time and this would give the most powerful phase change explosion. As can be seen from the figure, all of the tests were conducted with the liquid temperature very near to the T_{sl}, but not all failures resulted in a BLEVE.

In practice it appears the tank never depressurizes all the way down to atmospheric during the initial pressure drop and the theoretical limit of superheat is not achieved. Boiling is initiated at the liquid-wall boundary and at impurities suspended in the propane long before the superheat limit is achieved (see, for example, Ref. [3]). As a result the phase change process takes place over a much longer time and the resulting process does not usually produce a shock.

Energy

Figure 10 shows the energy stored in the vessel at the time of failure. The energy shown here is the isentropic expansion energy that is available to do work during the depressurization. As expected, the lower fill tanks have less energy.

In the present tests the tank energy fill did not appear to be the determining factor. It was the extent of the weakening of the tank that determined whether the tank would BLEVE or not. In this case three burners would BLEVE the tank and two burners would not. As noted earlier, it is unfortunate that we do not have a higher energy data point for the two burner tests. A higher energy level may have resulted in a BLEVE for the shorter heated length. This will be discussed further later when all the data is compared.

Wall Temperature

In these tests the tank strength was dictated by the wall temperature in the severely heated area of the vapor space. Figure 11 shows the range of wall temperatures at failure observed from the tests. As can be seen, the wall temperatures for the two burner tests were very similar but the tests with the three burners had a larger range. It is not clear why this happened; it may have been due to wind effects, and liquid heating and swelling effects. In any case, the data does show that it is not the wall temperature alone that determines if a tank will BLEVE or not. BLEVEs took place with wall temperatures lower than in the non-BLEVE cases.

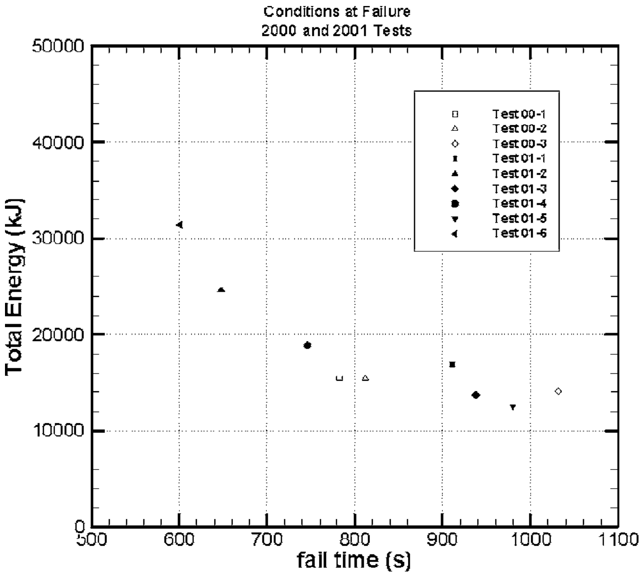

Fig. 10 Tank lading energy versus failure time

Critical Heated Length

In the present tests part of the vapor space wall was severely heated by burners and the remaining vapor space wall was not heated significantly. This produced a very defined weakened area under the burners that will experience plastic thinning while the cool material around it will experience virtually no deformation.

For the case of a small, weakened area one would expect the surrounding strong material to hold the pressure without deformation and this would tend to reduce the stress in the heated zone as it deforms. This would suggest slower deformation and a later failure time for the smaller heated zone. This was in fact observed—for comparable tests with 5% blowdown the failure time was 13.5 min for the two burner tests and 11.6 min for the three burner tests. However, even with reduced stress the severely heated zone sees large plastic deformations.

When the tank wall fails due to plastic thinning, the crack usually grows rapidly through the weak material but it may not grow

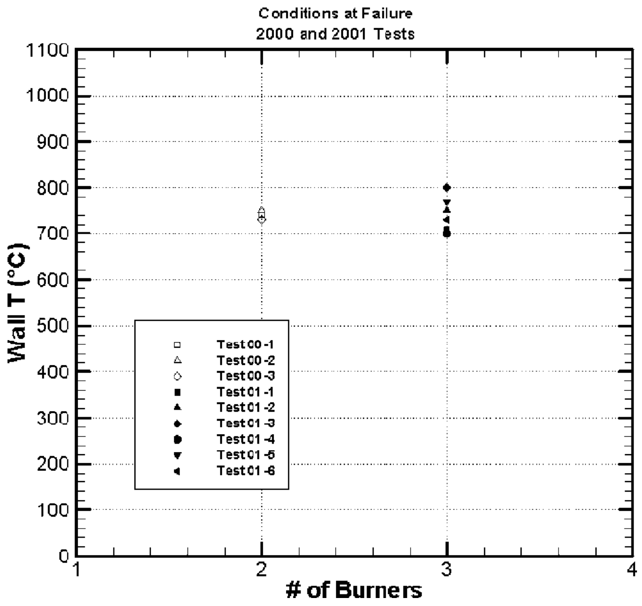

Fig. 11 Average wall temperature versus number of vapor space burners

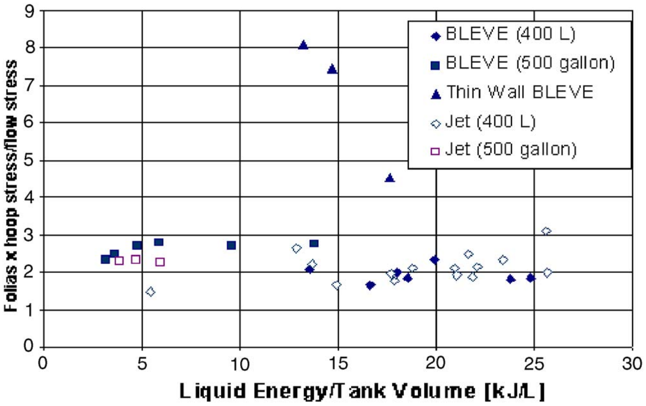

Fig. 12 Folias crack tip stress ratio versus liquid energy at failure (data from tests of 500 gal tank and 100 gal tank (see Ref. [1])

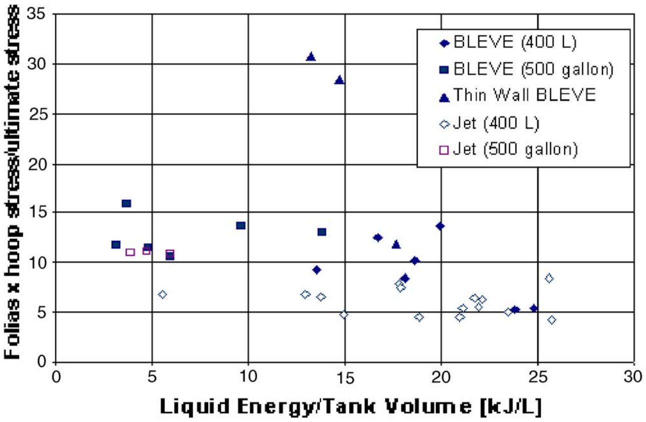

Fig. 13 Temperature modified folias crack tip stress ratio versus liquid energy at failure (data from tests of 500 gal tank and 100 gal tank (see. Ref. [1])

through the strong surrounding cool material, unless the pressure transient in the tank is sufficient to keep the crack growing. For the crack to grow the crack tip stress must be above some critical value.

Baum and Butterfield [12] studied the depressurization of ambient temperature, gas pressurized pipe with machined axial flaws of various lengths. They found that upon rupture, the crack would continue past the ends of the machined flaws to open the full length of the pipe when $m\sigma_h/\sigma_f > 3$ where

m = $(1+1.05L^2/(4Rw))^{1/2}$;
= Folias bulge parameter;
R = pipe radius;
w = wall thickness;
L = defect length;
σ_h = hoop stress, remote from defect$=PR/w$;
σ_f = flow stress = $(\sigma_{\text{ult}}+\sigma_{\text{yld}})/2$; and
P = internal gage pressure.

The stress at the crack tip is $m\sigma_h$ and therefore the above relation suggests the crack tip stress must be three times the flow stress for the crack to propagate into strong material and result in full opening of the pipe. The above equations suggest a critical length of about 102 cm (approximately 1.07 D) for the current test series (i.e., tanks had $D=0.953$ m, and wall thickness of 7.4 mm, with flow stress of 380 MPa).

In the present tests the defect length correlates to the severely heated length under the vapor space burners. For the six tests that resulted in BLEVEs the three vapor space burners were located with the burner front 30 cm from the tank surface and the burners were on 30 cm centers. This provided a severely heated length of approximately 90–100 cm. The closer burner spacing also would give a more uniform heating over the heated length. This heated length of say 95 cm is about 5% smaller than the critical length calculated above.

For the three tests that ended in finite ruptures the two burners were located with the burner front 30 cm from the tank surface and the burners were on 43.2 cm centers. This provided a severely heated length of approximately 75–85 cm. This length of say 80 cm is about 20% less than the critical crack length calculated earlier.

Recall that the tests of Baum and Butterfield [12] were for gas-pressurized pipe and in our test cases the tanks were pressurized with vapor and saturated liquid. This means the pressure forces caused by the flashing liquid will maintain the crack tip stress for a longer period of time after initial failure than would the case of gas only. It is reasonable to assume that the critical value of the crack tip stress would be affected by the presence of the flashing liquid. It is expected that full opening of the pipe or vessel with a flashing liquid will take place at a lower value of the crack tip stress. It is also expected that the critical crack tip stress will be reduced as the liquid energy is increased. Also, with the severe heating it is expected that the stress riser due to bulging will be changed.

Figure 12 shows the crack tip stress ratio $m\sigma_h/\sigma_f$ versus the liquid isentropic expansion energy per unit volume of tank at the time of failure. In this case the flow stress is for ambient temperature material. The plot includes data from the BLEVE tests of Birk et al. [1]. In all cases the Folias bulge parameter m has been calculated using the severely heated length in the tests. We see from this plot that there is no clear dividing line between BLEVE and non-BLEVE. We see that for our tests the critical crack tip stress is $1.5 < m\sigma_h/\sigma_f < 3$.

In an attempt to separate out the BLEVEs from the non-BLEVEs the flow stress was replaced by the estimated material ultimate strength (based on the average wall temperature) in the severely heated zone. This figure is plotted in Fig. 13.

As can be seen this plot does appear to separate out the BLEVEs from the non-BLEVEs. We also see a general trend towards lower critical crack tip stress at higher liquid energies. This is a much more practical plot than the BLEVE map shown earlier. From this new plot we have a better method of predicting a BLEVE if we know the tank conditions (i.e., fill, average liquid temperature, severely heated length, average wall temperature in heated length, ultimate strength in heated length, pressure at failure, etc.).

However, there are too few data points to have high confidence in this plot so great care should be taken if it is used for predictive purposes. One important point is that this plot suggests that if a 500 gal tank had been tested with two vapor space burners and it had failed with higher liquid energy it would probably BLEVE.

Liquid Impact Pressures Versus Heated Length

The critical crack length may also be related to possible impact pressures generated during the depressurization. Ogiso et al. [2] carried out a series of tests with hot water to study the pressure transient during sudden depressurizations. He did the tests with horizontal cylinders and with vertical lengths of pipe. He suggested that if the breach area was greater than 6% of the liquid surface area then there would be a strong pressure response with liquid impact pressures on the tank upper surfaces.

In the present tests we saw failures with no BLEVEs with openings that were in the order of 0.1 m^2 with liquid surface areas around 2 m^2 (i.e., breach area = 5% of liquid surface area). In other words, the BLEVE outcomes observed in the present tests involved hole sizes that were in the range >5% of the liquid surface area and therefore liquid impact pressures may have had some role to play in the total opening of the vessels in this test program. Unfortunately no instruments were included to measure liquid impacts and therefore this cannot be argued any further.

Conclusions

The following conclusions have been made based on the outcomes of these tests:

- The time to initial failure depends on the fire condition and on the design of the tank and pressure relief system. It has been shown that a large blowdown PRV will result in delaying a failure due to the reduced average stress state in the tank.
- If a rupture takes place in a vessel holding a liquid at or near its atmospheric superheat limit, it will not always produce a BLEVE outcome. For a BLEVE to take place the vessel must open completely and this will only happen if the tank has been weakened sufficiently to initiate a rupture, and if the pressure transient during failure is sufficient to drive the failure crack to fully open the vessel.
- It appears that if the length of the severely heated (weakened) part of the vapor space exceeds some critical value, then a BLEVE outcome is likely over a range of fill conditions (10–50% in the present tests). This critical length was around one diameter for the present tests. However, if the heated zone is smaller than this critical value (in our tests the smaller heated zone was 0.8 D) a BLEVE will not happen for lower liquid fill levels. It is possible that higher fill levels with higher liquid energy may cause a BLEVE failure even with small heated zones.
- The critical heated length agrees with the critical defect length reported by Baum and Butterfield [12] for gas-pressurized pipe to open completely after initial failure.
- It was possible to produce a plot based on a modified folias parameter that divided BLEVE from non-BLEVE outcomes. If this plot proves to be correct then it can be used to predict a BLEVE outcome if the properties of the heated zone and the liquid energy conditions are known.

The above conclusions apply to the tanks and methods used in this test series. Caution should be taken when using the information given here.

Acknowledgment

This work was funded by the Transportation Dangerous Goods Directorate of Transport Canada and by a NSERC operating grant.

References

[1] Birk, A. M., Cunningham, M. H., Ostic, P., and Hiscoke, B., 1997, “Fire Tests of Propane Tanks to Study BLEVEs and Other Thermal Ruptures: Detailed Analysis of Medium Scale Test Results,” TP 12498E, Transport Canada.

[2] Ogiso, C., Takagi, N., and Kitagawa, T., 1972, “On the Mechanism of Vapor Explosion, Loss Prevention and Safety Symposium,” PACHEC, Japan, Session 9, pp. 233–240.

[3] Barbone, R., Frost, D. L., Makis, A., and Nerenberg, J., 1994, “Explosive Boiling of a Depressurized Volatile Liquid,” *Proceedings of IUTAM Symposium on Waves in Liquid/Gas and Liquid Vapour Two-Phase Systems*, Kyoto, Japan.

[4] Birk, A. M., VanderSteen, J. D. J., Davison, C., Cunningham, M. H., and Mirzazadeh, I., 2003, “PRV Field Trials—The Effects of Fire Conditions and PRV Blowdown on Propane Tank Survivability in a Fire,” TP 14045E, Transport Canada.

[5] Venart, J. E. S., 2000, “Boiling Liquid Expanding Vapor Explosion: Possible Failure Mechanisms and Their Consequences,” Institute of Chemical Engineers Symposium Series, Hazards XV: The Process, its Safety and the Environment.

[6] Birk, A. M., and Cunningham, M. H., 1994, “A Medium Scale Experimental Study of the Boiling Liquid Expanding Vapour Explosion,” TP 11995E, Transport Canada.

[7] Birk, A. M., Cunningham, M. H., VanderSteen, J. D. J., Davison, C., and Mirzazadeh, I., 2002, “Fire Tests to Study the Effect of Pressure Relief Valve Behaviour on the Survivability of Propane Tanks in Fires,” 36th Loss Prevention Symposium, American Institute of Chemical Engineers, New York.

[8] Birk, A. M., 1983, “Development and Validation of a Mathematical Model of a Rail Tank-Car Engulfed in Fire,” Department of Mechanical Engineering, Queen’s University, Kingston, Ontario, Canada.

[9] Townsend, W., Anderson, C. E., Zook, J., Cowgill, G., 1974, “Comparison of Thermally Coated and Uninsulated Rail Tank-Cars Filled With LPG Subjected to a Fire Environment,” FRA-OR&D 75-32, U.S. DOT Report.

[10] 1994, *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires and BLEVEs*, AIChE Centre for Chemical Process Safety, New York.

[11] Reid, R. C., 1979, “Possible Mechanism for Pressurized Liquid Tank Explosions or BLEVEs,” Science **203**, pp. 1263–1265.

[12] Baum, M. R., and Butterfield, J. M., 1979, “Studies of the Depressurization of Gas Pressurized Pipes During Rupture,” J. Mech. Eng. Sci., **21**(4), pp. 253–261.