Journal of Hazardous Materials, 20 (1988) 55–71
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

FIRE ENGULFMENT TESTS ON A 5 TONNE LPG TANK

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SUMMARY

Experiments have been conducted on the behaviour of a 5 tonne horizontal cylindrical LPG tank engulfed in kerosene pool fires. Five tests were carried out with commercial propane fill levels from 22% to 72%. Fire durations were up to thirty minutes. Extensive measurements were made of the fire characteristics, external and internal tank metal temperatures and the wall heat fluxes. Bulk and boundary layer fluid temperatures were measured at 26 points inside the tank, which together with internal pressure histories allowed characterisation of the internal fluid behaviour. Standard pressure relief valves were fitted and their operation monitored - they operated reliably and controlled the tank pressure throughout the fire tests. The results further extend and complement those on fire engulfed 0.25 and 1 tonne tanks. The complete set of results provides direct information on the behaviour of LPG tanks of different sizes and fill levels and a sound basis for the development and validation of predictive models.

INTRODUCTION

A sound knowledge of and the ability to predict the behaviour of pressurized LPG tanks engulfed by fire is necessary to assist the definition of design and operating procedures for LPG storage and transport.

We need to characterise the fire, the magnitude and distribution of the heat flux to the tank, heat transfer through the tank skin and to the contents, vaporization and pressure increase, pressure relief valve (PRV) operation, any increase in metal temperatures particularly in the vapour space, and the long term behaviour of the tank pressure during PRV operation. The latter two factors determine the ultimate integrity of the tank structure.

This paper reports experiments on a 5 tonne tank filled with LPG to various levels and engulfed in realistic kerosene pool fires. The vessel was extensively instrumented and the tests encompassed the initial fire build up and tank pressure rise, PRV operation and the behaviour of the tank and contents for fire durations of up to thirty minutes.

The experimental findings further extend and complement those on 0.25 and 1 tonne tanks (ref. 1-3). The complete set of results provides direct information on the behavior of LPG tanks of differents sizes and fill levels and a sound basis for the development and validation of predictive models. This paper deals with experimental findings, theoretical models based on these results are the subject of separate papers (ref. 4,5).

THE TEST FACILITY

The essential part of the facility was the 5 tonne test tank and its surrounding fire bund located on isolated moorland (Figures 1 and 2). A plan and elevation of the tank and bund are shown in Figure 3. The tank was built to BS 1500 and was originally used on a road tanker. The total internal volume was 10.25 m^3, other dimensions are given in Figure 3. One end of the tank had a manhole cover used for filling and venting. Internal instrument cables passed through fire protected side flanges.

Two standard external PRVs were set to open at 14.3 bar gauge. The valves discharged through a 100 mm diameter inverted 'Y' connector into a single 152 mm diameter 1.5 m long flare stack ending 2.3 m above the tank top.

The entire tank and sub-chassis assembly rested on four load cells to measure the mass of the contents and PRV discharge rates.

The fire bund was a refractory brick lined pit surrounded by a wall to minimise wind effects on the engulfing pool fire. The bund was flooded to a water depth of 0.6 m during tests - the kerosene floated on top.

The pool fire was ignited remotely. It was also put out by remote command using up to six foam extinguishers. The entire bund contents could also be drained into a remote catch pit within 5-10 minutes. As a further precaution against overheating the tank could be cooled with a water deluge.

Instrument and control links were led from the tank and bund through fire protected ducts to a control centre some 800 m away. A substantial reinforced stone building 250 m from the tank served as a forward control and observation point.

INSTRUMENTS

The fire - Calorimeters, immersed thermocouples and photography characterised the engulfing pool fire. Three water tube calorimeters surrounded the tank and measured local total fire heat fluxes. Their positions are indicated in Fig. 3. A measure of the effective flame temperatures was obstained from six 3mm diameter stainless steel sheathed mineral insulated type K thermocouples. Video, cine and time synchronized 35 mm still photography recorded the fire and PRV behaviour allowing measurement of fire dimensions and the extent of engulfment. The pool fire and any PRV flare are influenced by local wind conditions, these were therefore continuously monitored.

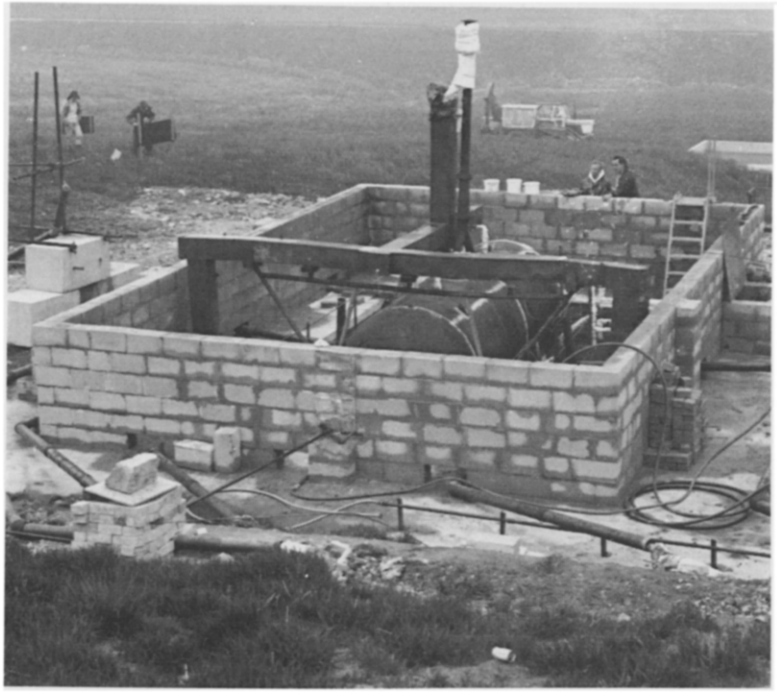

Figure 1: 5 tonne LPG tank and surrounding fire bund

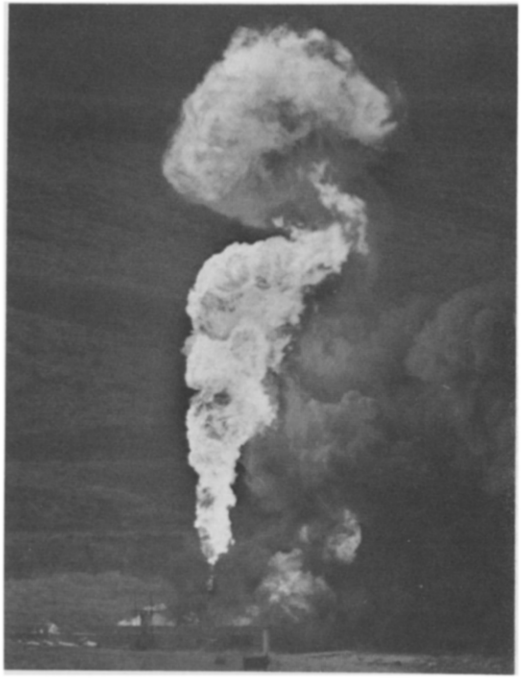

Figure 2: Bund fire and PRV flare at time of second PRV opening in 72% fill test

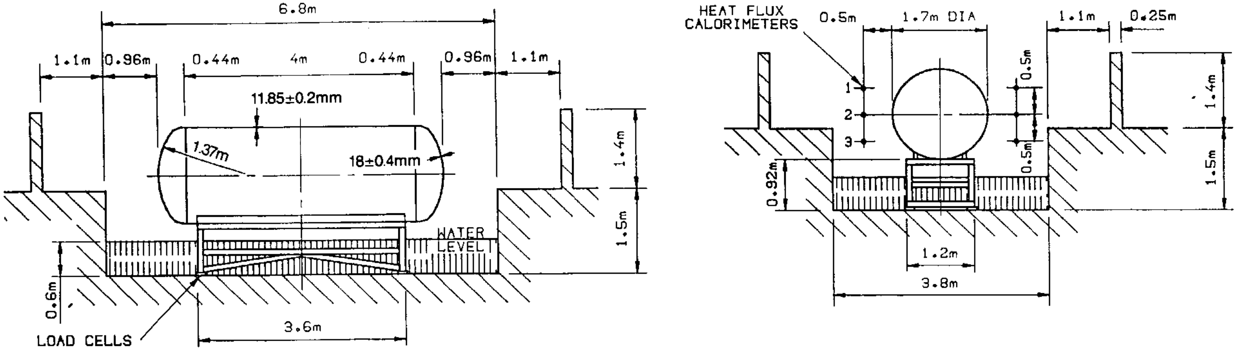

Figure 3: Tank and fire bund dimensions

The tank

(1) Temperatures - The tank had 55 3mm diameter stainless steel sheathed, type K thermocouples placed as shown in Figure 4.

External and internal metal skin temperatures were measured by 31 thermocouples. 16 were paired to allow calculation of heat fluxes through the walls. All were attached by welding a coupon to the tank surface to hold the thermocouple in place; air gaps and the surroundings were then weld filled and finally the whole area was ground away to a smooth contour. This fixing method avoided weakening the tank wall but gave temperatures accurate to better than ±5^{o}C at 400^{o}C and ±1.5^{o}C near ambient.

Bulk fluid temperatures were measured by 13 thermocouples on two vertical tank diameters (Figure 4, cross sections BB and DD). The number immersed in liquid depended on the fill level. Some individual thermocouples initially in the liquid phase became uncovered during a test as the contents were vented.

Boundary layer temperatures were monitored in 9 places. The stand-off distances were 1-15mm. These measurements allow us to investigate boundary layer behaviour and any transition between convective, nucleate or film boiling heat transfer.

(2) The tank pressure was measured at the top (vapour) and bottom (liquid) by transducers of accuracy ±0.1 bar.

(3) Tank contents - The liquid phase could be sampled for subsequent analysis. The entire tank and sub-chassis was supported on four load cells that measured the mass of contents and the mass loss by venting. The load cells also responded to the PRV exhaust thrust. The weighing system had an overall accuracy of ±10 kg in the 22% and 72% tests and ±20 kg in the others.

The pressure relief valves - Each valve had an effective area of 8.87 x $10^{-4}m^{2}$, derived by assuming choked flow in tests in which air flow rates through the PRV were measured. This measured area corresponded to a maximum discharge rate of LPG under tank conditions of some 3.5 kg/s.

The static and dynamic pressures of the venting fluid and its static temperature were measured at the flare stack exit.

DATA COLLECTION AND PROCESSING

Some 90 instrument readings were recorded at a rate of one complete scan of each sensor per second. Individual outputs were amplified as appropriate and digitised. Whilst the nominal accuracy of the A/D converter was 12 bits,

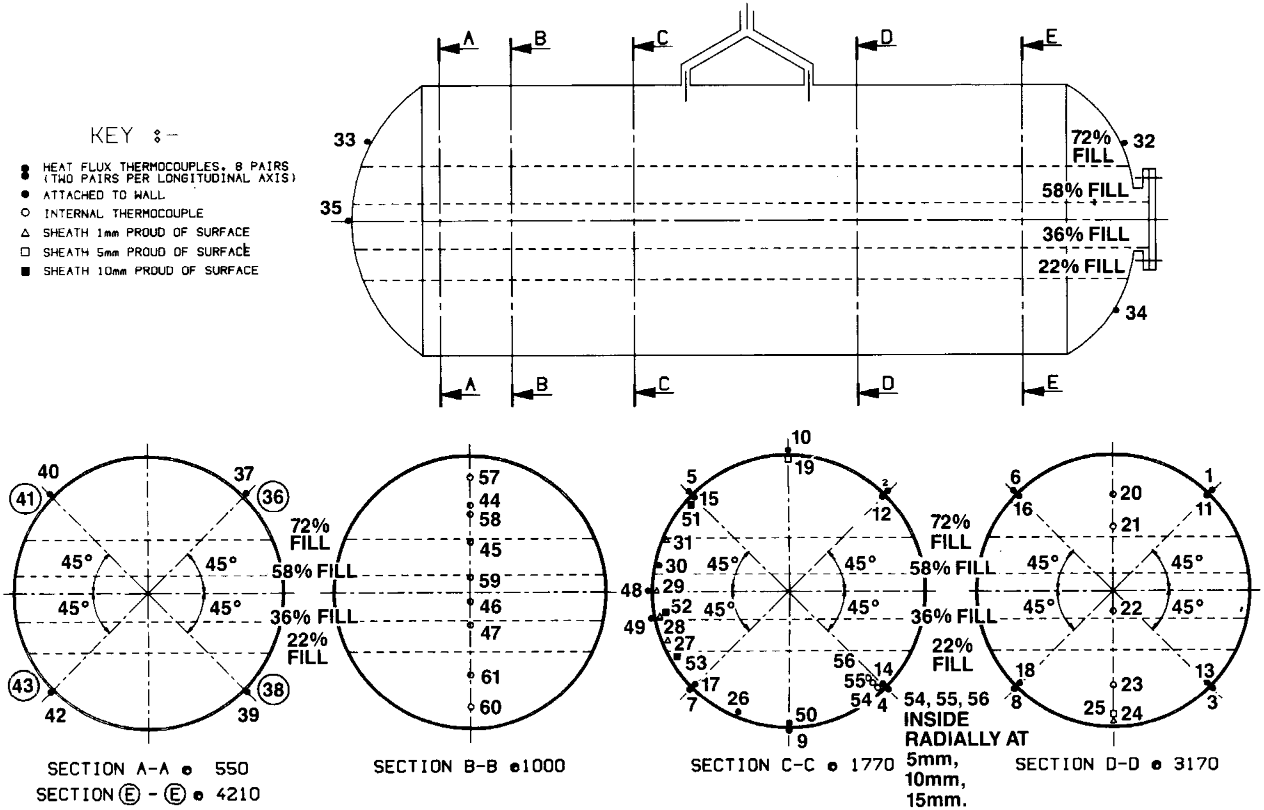

Figure 4: Thermocouple positions

this was actually degraded by system noise to ±0.2% FSD. The digital signals were sent serially to the control centre and received by a mini-computer.

The computer could store one hour of data and then do the conversion into engineering units. During a test up to six measurements could be graphically displayed in real time. These usually included the tank pressure and critical wall temperatures. The highest wall temperature reading at any instant was displayed digitally and the theoretical burst pressure of the tank calculated each second assuming that the whole of the tank skin was at the maximum temperature. Warning signals were given when the actual tank pressure reached 75% of this calculated burst pressure. After a test the results were stored on disc and could also be immediately recalled as graphic displays allowing a very rapid evaluation of the experiment.

TEST PROCEDURES

The same tank was used in all experiments. Before each test it had a metallurgical examination and a 19 bar hydraulic test. New PRVs were fitted except for the final 72% fill test which used valves that had previously been subjected to the previous 38% fill test fire. Once all internal sensors had been checked and calibrated the tank was sealed and leak tested at 10 bar. Rigorous safety procedures were enforced in subsequent operations. The tank was nitrogen purged and the six remotely operated bund fire extinguishers armed. The bund was then water filled and the tank filled with propane following standard filling procedures. During and after filling only limited access was permitted near to the tank. Kerosene was then put in the bund and the electrical ignitors installed. At this stage no one was allowed in the open within 600 m of the tank.

The fire was ignited remotely by a signal from the data collection computer. Critical measurements were displayed by the computer and the test area was scanned by TV cameras. The fires were allowed to burn until the burst calculations indicated the approach of a critical condition - this was usually when part of the wall had reached about 600°C. At this juncture the fire was extinguished and the bund contents dumped to the remote catch pit. The PRV usually continued to flare and recording of measurements was continued for an hour from the fire start. Once the tank skin temperature had fallen to less than 400°C the water deluge was turned on to assist cooling and extinguish any small fires remaining in the bund. The tank was then left until the following day when the remaining contents were safely vented and the tank nitrogen-purged again.

TEST RESULTS

Scope of test program and general results

The aim was to assess directly the thermal response of a 5 tonne LPG tank to total or near total engulfment in realistic kerosene pool fires. Five tests were done with initial propane fill levels ranging from 22% to 72% (the fill is defined as the percentage of the total tank volume occupied by liquid at 5°C). The test conditions and some of the features of fire and tank behaviour are summarised in Table 1. An essentially complete set of measurements was obtained for all tests except the 38% fill experiment - this was a demonstration test that suffered some data loss due to lightning and was terminated early.

Fire durations for the fully instrumented tests were 11.6 to 31 minutes. The durations are to some extent a measure of the time to which there may be some possibility of a loss of containment. In our tests this corresponded to peak metal temperatures of 570 to 660°C attained after the contents had been vented so that only some 450 to 840 kg of LPG remained.

In all tests wind speeds were low but the direction varied. In Table 1, the wind direction is given as the minimum angle between tank axis and wind direction. An angle between 0 and 45 indicates a wind direction predominantly along the tank axis (in either direction) while an angle between 45 and 90 indicates a cross wind.

While there were significant differences in wind conditions in the tests, the average fire heat fluxes were alike. Total fire engulfment was established in two to two and a half minutes. The similarity in fire flux to the tank between tests and hence the internal fluid evaporation rates is reflected in the times to the first opening of the PRV valve. These varied little, from 5.2 minutes in the 72% fill test to 6.9 minutes for the 36% fill. During the fires the standard PRVs contained the tank pressure to within a maximum value of 15 bar abs. The PRV opened and closed at least twice in all tests with the exception of the 38% fill. Sometimes the PRV opened and closed several times after the fire was extinguished.

Fire conditions

Fig. 2 shows the pool fire during the 72% fill test and the PRV flare shortly after ignition. The fire fluxes measured by the immersed calorimeter loops are shown for three of the tests in Fig. 5. The fire flux histories are remarkably similar with fluxes pealing at about 85 kW/m^2 in spite of the variability of the fires and wind conditions between tests. The fluxes for the 22% and 38% fill tests are the average for three calorimeters, those for the 72% are averages from two calorimeter loops. The measurements for

TABLE 1

Test conditions and general results

Fill level, (%)	22	36	38	58	72
Mass of fluid, (kg)	1170	1930	2000	3109	3860
Average fluid temperature at start, (°C)	5.7	1.5	6.0	3.8	6.4
Init. pressure, (bar a)	5.5	5.2	5.8	5.6	5.8
Wind direction relative to tank axis, (deg)	35	62	37	50	45
Average wind speed, (ms^{-1})	1.3	4.6	6.0	4.8	4.7
Fire duration, (s)	699	1260	568	1569	1863
Fire duration, (min)	11.6	21.0	9.5	26.1	31.0
Time to 1st PRV opening (s) (min)	373 6.2	415 6.9	376 6.3	401 6.7	312 5.2
Opening pressure, (bar a)	14.3	14.4	-	15.5	14.7
Max. pressure during discharge, (bar a)	13.6	13.2	-	15.0	14.7
Time valve open during fire, (s)	330	838	192	1169	1474
Total mass discharged during fire, (kg)	530	-	-	2276	3400
Max. skin temp., (°C)	635	657	529	610	572

smoothed using a ten second running average. The greatest flux was always to the uppermost calorimeter: in the 38% test the uppermost instrument indicated 90 kW/m^2 and the lowest 75 kW/m^2. Similar differences occurred in the other tests. The flux densities presented here are not corrected for the absorptivity of the calorimeter loop surfaces. If this is assumed to be 0.8 then the maximum average flux densities were 105 kW/m^2, fully consistent with other measurements.

The corresponding fire temperatures measured by the six thermocouples around the tank fluctuated considerably from 1050 to 600 K depending primarily on wind gusts. Wind effects inducing overall flame deflections were probably also responsible for the higher flame and wall temperatures measured on the downwind side of the tank.

Total engulfment was not maintained throughout the tests as occasionally parts of the tank surface were visible.

The fires were very smoky, indicating some possible lack of aeration at times. This is supported by the manner in which the PRV flare ignited in the 22% (low wind speed) test. Ignition of the vent jet was above the tip of the pool fire - the flame then burned back and stabilised close to the flare stack.

Internal pressure

Internal fluid pressures are shown in Fig. 6. The pressures increased relatively rapidly once the fires had become established. The PRV opening pressures were 14.3 to 15.5 bar absolute and the pressure was then controlled for the fire duration, generally reaching a secondary maximum and then declining.

Wall temperatures and heat fluxes

(1) Liquid wetted walls - The outer liquid wall temperatures ranged over 50 to 120°C in the 22% test, 70-140°C in the 58% and 60-130°C in the 72% fill test. There were lower temperatures of 45 to 80°C in the 36% test. For comparison, the saturated LPG liquid temperature under the tank pressure conditions was about 40°C. In individual tests there were temperature differences at any one time between different parts of the tank skin.

The inner liquid wall temperatures were typically 20°C lower than the corresponding external wall values and were less variable around the tank than the outer ones. These values are consistent with the expected inward heat flow from the fire, but also indicate that thermal conduction is significant along the tank skin as well as through it.

Apparent outward heat fluxes were seen for a small part of the 58% test

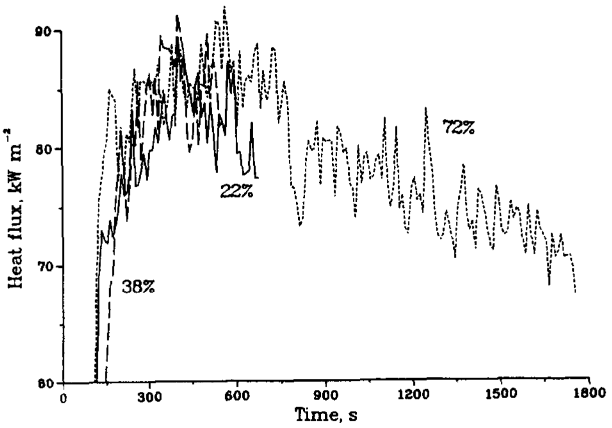

Figure 5: Calorimeter heat fluxes for three fill levels

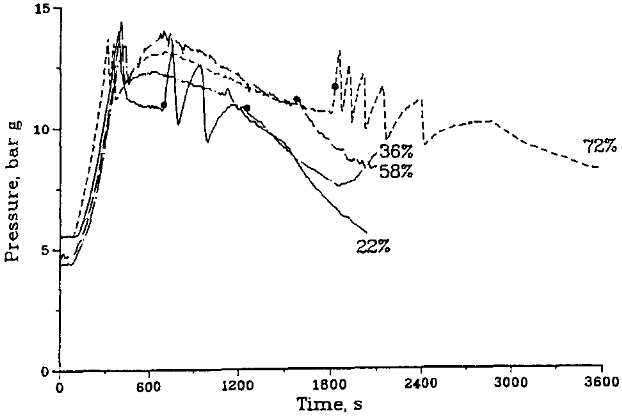

Figure 6: Tank pressure vs time for all tests (• indicates when the bund fire was extinguished)

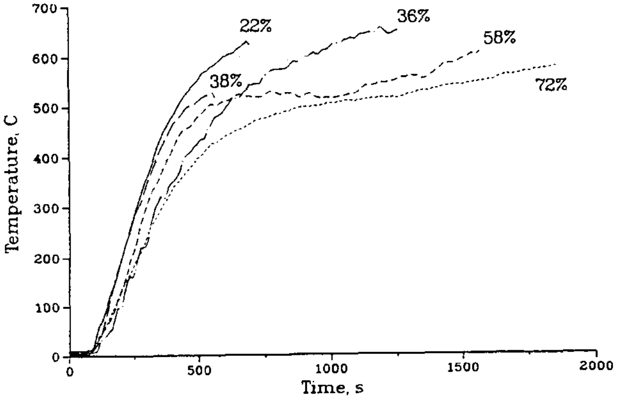

Figure 7: Peak wall temperatures for all tests

although the results need to be interpreted with care in the light of possible significant lateral heat conduction. Similar but less extreme behaviour also occurred in the 22% and 72% tests, where the apparent heat fluxes through the wall fell to low values but remained inwards. These apparent outward or abnormally low inward heat flows were at times when the temperatures within parts of the bulk liquid were apparently greater than that derived from saturated LPG vapour pressures. This phenomenon will be further discussed in a subsequent section on the liquid phase conditions.

(2) Dry walls - Peak dry wall temperatures for four tests are shown in Fig. 7 as a function of time from the fire ignition. All the vapour space wall temperatures behaved similarly, increasing rapidly once the fire had become established, but rising less rapidly once venting commenced.

In individual tests large temperature differences existed at any one time both across the tank and from end to end. For example, at the end of the 58% test the maximum skin temperature measured just before the fire was extinguished was 610°C (Table 1 and Fig. 7) whereas elsewhere the dry skin temperatures were as low as 440°C. These differences are ascribed to non-uniformities of the fire flux.

In general the temperatures across the dry walls fell 20 to 50°C corresponding to an inward flux. In the 22% test an apparent outward heat flow occurred for some of the time. This may have been due to a non-uniform fire including a temporary loss of total engulfment. Another possibility is lateral conduction along the tank skin of fire flux entering the skin above the liquid level with a component being conducted downwards through the metal into the liquid wetted region and a part conducted upwards to be re-radiated away.

Liquid conditions

In most tests there were spatial variations in the measured temperatures in what was nominally the liquid space. Variations may arise from a number of factors including the extent of liquid mixing and/or bulk circulation, boundary layers, the presence of hot vapour bubbles and the possibility of liquid slopping and splashing so that some thermocouples alternately see liquid and hot vapour.

The range of temperatures recorded is illustrated by the measurements made during the 72% fill test shown in Figs. 8a and 8b (bulk liquid) and Fig. 9 (close to wall). During PRV operation parts of the tank show little vertical temperature stratification and liquid thermocouples (45, 46 and 47 in Fig. 8) all read about 40°C before becoming uncovered. In contrast thermocouples

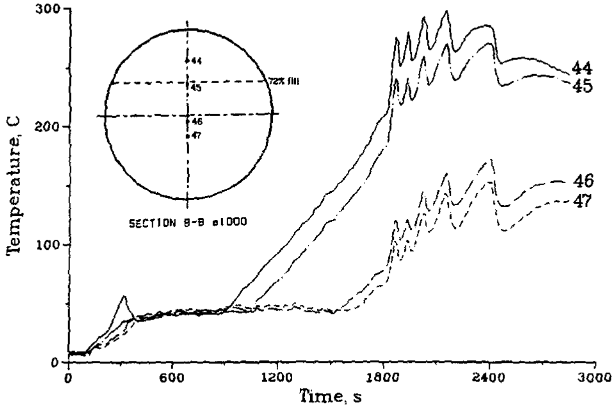

Figure 8(a): Liquid temperatures for 72% fill test

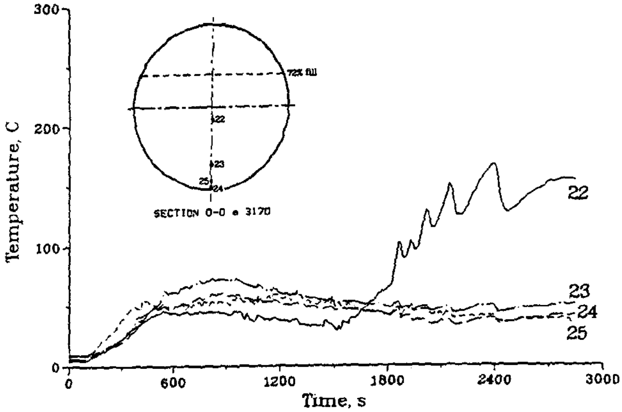

Figure 8(b): Liquid temperatures for 72% fill test at the other end of the tank are hotter than the saturated liquid temperature except for number 22 which is the closest to the nominal liquid surface. Anomalous behaviour was seen in other tests too. In the 22% fill test some thermocouples recorded saturated temperatures (60 and 61 in Fig. 10) but in other parts of the tank liquid zone temperatures were apparently up to 15°C higher. In the 58% fill test, temperatures in the liquid space increased to 70-120°C some time after PRV opening and then declined again. Furthermore the temperature peak occurred at different times at different positions along the tank. In the 36% fill test the bulk liquid was essentially isothermal at the saturation temperature and therefore likely to be well mixed. Only one liquid thermocouple close to the tank bottom showed any deviation.

It is difficult to ascribe the high temperatures to either superheated liquid or to a froth of liquid and vapour bubbles. Significant liquid superheat is very unlikely in commercial propane contained in a well used steel tank containing thermocouples and a supporting framework that would provide ample nucleation sites. Significant lack of thermodynamic equilibrium in a froth is also improbable.

We attribute the apparent superheating to alternate exposure of thermocouples to liquid close to its saturation temperature and then to superheated vapour. We then need an explanation for such behaviour. Work by ref. 6 on freon vapourisation in relatively small cylindrical vessels shows violent recirculation of the tank fluid after PRV opening. This is probably unlikely in our much larger tank. The maximum liquid evaporation rate for each test can be derived from the PRV vent rate and never exceeds 3.5 kg/s. The relatively small quantity of liquid that needs to be evaporated, and the small volume of vapour generated to maintain this discharge rate is typical of gentle nucleate boiling and not likely to induce any violent fluid circulation. Furthermore the abnormal temperatures are not directly related in time to PRV opening and in the temperature excursion in the 58% test was long after the PRV had opened. The phenomena requires further investigation with ideally direct observation of the tank contents and liquid zone density measurements. Fast response thermocouples would also be beneficial. At this stage we consider likely explanations are local slopping and violent interfacial motions induced by non-uniform heating and poor longitudinal mixing, or the existence of large superheated gas bubbles within the bulk liquid.

There is no evidence for a hot thick boundary layer in the liquid. The temperatures near to the tank sides (Fig. 9) are not significantly greater than those in the bulk liquid. Temperature measurements just above the initial liquid level (e.g. 44 in Fig. 8a) indicate some upwelling of liquid

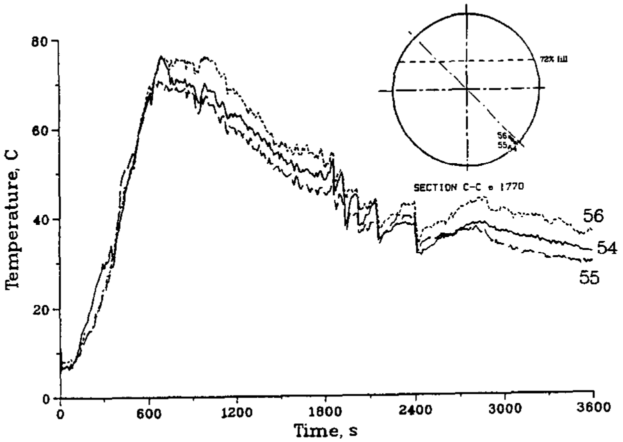

Figure 9: Boundary layer temperatures for 72% fill test

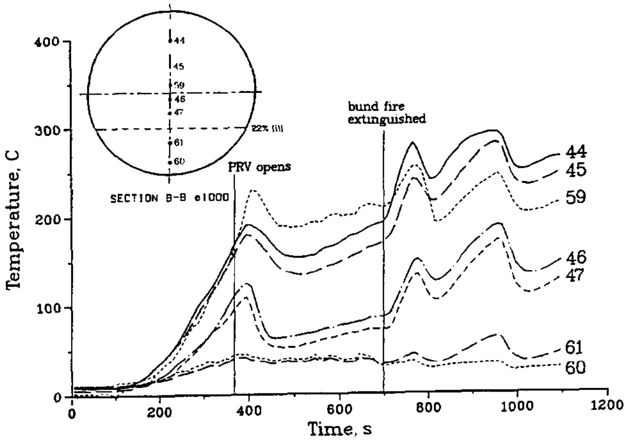

Figure 10: Fluid temperatures for 22% fill test

once the fire is established. This is to be expected since the liquid space will then contain rising vapour bubbles.

The vapour space

The vapour space temperatures increased rapidly as the fires became established. The vapour was superheated, receiving part of its heat from the hot dry walls. There was substantial vertical temperature stratification both before and during PRV operation - this is illustrated in Fig. 10 for the 22% fill test. The vapour temperatures fell on PRV opening but the stratification was maintained. This indicates poor vapour space mixing and the absence of any significant flashing or frothing of the whole tank on a 5 tonne scale. The temperatures shown in Figure 10 increased again after PRV opening, and indeed after the pool fire was put out. This was because the tank walls remained hot and continued to transmit heat to the vapour space.

PRV operation

The times to opening and closing of the PRV in each test are summarised in Table 1 and pressure histories are shown in Fig. 6.

The first PRV opening was always within 5% of the set pressure, but subsequent openings and closings were at progressively lower pressures. In all tests the PRVs controlled the tank pressures. Only one PRV operated except possibly for short intervals in the 58% and 72% fill tests. Figure 11 summarises the mass loss by venting in each test.

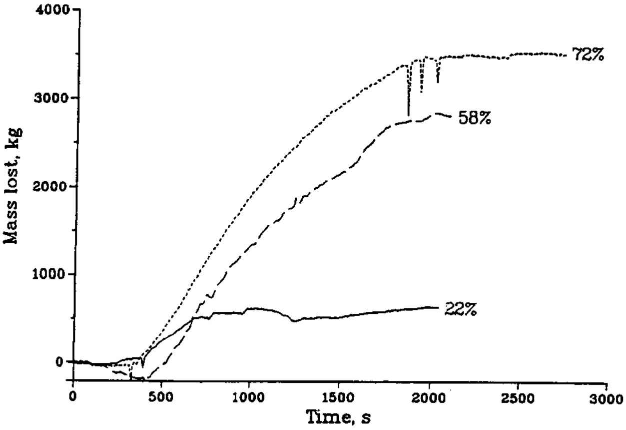

Figure 11: Mass loss for three tests

CONCLUSIONS

Experiments have been conducted on the behaviour of a 5 tonne LPG tank engulfed in kerosene pool fires. Tests were done with initial commercial propane fill levels of 22% to 72%.

The engulfing fires were fully established within three minutes of ignition with fluxes of 100 kW/m^2. The tank pressure increased steadily until the standard PRV opened 5 to 7 minutes after ignition. All the PRV releases ignited. The PRV limited the tank pressures to less than 15 bar absolute throughout the fire duration.

The fires were extinguished when calculations indicated that there was an approach to some possibility of a loss of containment. This corresponded to peak tank skin temperatures of 570 to 660^oC. The fire durations were 12 to 30 minutes increasing with increasing fill level.

Extensive measurements were obtained of fire heat fluxes, tank skin temperatures, through wall heat flow rates, fluid pressures and temperatures, and PRV operating characteristics.

The results extend and complement earlier ones on 0.25 and 1 tonne tanks. The complete set provides direct information on the response of LPG tanks of differing size and fill levels to fire engulfment and a sound basis for the development and validation of predictive models.

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