THE FIRE ENGULFMENT OF LPG STORAGE TANKS

K Moodie*, K Billinge* and D P Cutler*

A series of fire engulfment trials have been carried out on uninsulated $^1/_4$ tonne and 1 tonne LPG tanks. The tanks, having various fill levels, were engulfed by kerosene pool fires. They were instrumented with thermocouples both internally and externally, pressure transducers and in some instances were supported on load cells.

Data was obtained on heat transfer rates to the total system and tank contents, the boiling regime, average wall temperatures, PRV discharge rates and tank failures. The thermal responses of the tanks were found to be similar to other data reported in the literature, and well predicted by a simple computerised model which is described elsewhere.

1 INTRODUCTION

Whenever highly flammable fluids such as LPG are either stored or transported in bulk there is the risk that any leak, may, if ignited, result in the storage vessel becoming engulfed by fire. This, in the case of LPG, may have particularly serious consequences because it is often stored as a pressurised liquid at ambient temperature. Thus if the vessel is heated externally, causing a rise in internal pressure and a loss in the mechanical strength of its walls due to the elevated temperatures, it may fail catastrophically and suddenly release its contents. Such a release may propel fragments of the vessel over considerable distances. In addition, significant amounts of fluid may flash to vapour, which if ignited can lead to fire ball behaviour with associated releases of thermal energy.

Pressure relief valves (PRVs) are therefore fitted to tanks to vent their contents at a pressure above the maximum working pressure, and at a rate that will prevent further pressure build up leading to loss of integrity. The valves are sized, according to most codes of practice, on the assumption of a uniform heat flux from the engulfing fire of about 100 kW/m^2 (no account being taken of non-uniform heating effects, nor of the maximum wall temperatures likely to be attained).

In order to make realistic assessments of the potential hazards it is necessary to know the thermal response of storage vessels in a fire engulfment. This is currently being investigated at the Explosion and Flame Laboratory of the Health and Safety Executive. Firstly, the development of theoretical models is being funded which will predict vessel behaviour for a range of fire engulfment scenarios, as described in (1). Secondly, an

*Health and Safety Executive, Explosion & Flame Laboratory, Harpur Hill, Buxton, Derbyshire

experimental programme of validation is being carried out in which a range of tanks of different sizes and different fill levels are being engulfed by kerosene pool fires. This paper is concerned with the latter aspect, particularly the results from tests on 1/4 and 1 tonne uninsulated tanks.

There appears to be only a limited amount of similar data currently available in the literature. The largest fire engulfment test previously undertaken appears to be that described by Anderson et al (2), in which a 64 tonne railcar was fire engulfed. Vessel wall temperatures for both inner and outer surfaces were recorded, together with the bulk liquid and vapour temperatures, the average heat flux from both the fire and the PRV flare. Measurements were also made of the liquid level in the tank and the thermal radiation from the PRV flare. The vessel failed catastrophically some 24.5 minutes into the test with an estimated 40% of the LPG still remaining in the tank. Fragments from the vessel were reported at considerable distances from the test site. The maximum wall temperature near the point where the vessel started to fail was of the order of 650°C and the internal pressure was 24.1 bar at failure. Similar tests on smaller capacity vessels (2½ tonnes) have been reported by the Federal Institute for Material testing, Berlin (3). Three fire tests were undertaken for LPG stored in accordance with the appropriate DIN standard, and again vessel skin temperature variations with time were recorded. In all these tests tank failures occurred within 7 to 12 minutes from the beginning of the fires, depending upon the initial temperature of the LPG.

Extensive laboratory simulations and theoretical predictions have been undertaken by Venart et al (4, 5 and 6). An electrically heated 40 l capacity cylindrical pressure vessel was used, that was fitted with observation windows at both ends and contained Freon 11 or Freon 12 to simulate the LPG loading. It was instrumented so that various aspects of the thermal response could be studied and compared with theoretical predictions. Nyland (7) has made extensive theoretical and experimental studies of the behaviour of pressurised gas process vessels subject to both total and partial fire engulfment. His predictions of vessel failures within a relatively short time after the beginning of the fire were confirmed experimentally.

2 EXPERIMENTAL FACILITIES

The fire engulfment trials were carried out by supporting the tanks over a bund and exposing them to pool fires of kerosene contained within the bund. Five tests in total were undertaken, two with a 1/4 tonne tank and three with a 1 tonne tank. The tanks were re-used after each test, but only after carefully checking that they had not been weakened excessively in the previous fire. In the second 1/4 tonne test the tank failed catastrophically as a result of a PRV malfunction.

3 THE TEST FIRE AND BUND DESIGN

The bund, which was used for all of the tests, consisted of a firebrick enclosure some 4m long by 2.4m wide by 0.6m deep. A 1m high windbreak wall surrounded the bund at a distance of 1m from it. The windbreak ensured that flame of at least 1 m thickness engulfed the tank under normal wind conditions. The test tanks were supported on firebrick piers so that the bottom of a tank was flush with the top of the pool walls. When testing the 1 tonne tanks four load cells were also fitted so that the weight of the vessel and its contents could be recorded continuously throughout a trial.

The burning rate of kerosene in the bund was approximately 0.64 l/s. Hence for these tests, having an intended duration of 30 minutes, a kerosene pool 120mm deep was necessary. The fuel was ignited electrically, having first of all being made more sensitive to ignition by the addition of 10 litres of petrol over its surface. A fluorocarbon foam fire extinguishing system was provided, which could be operated remotely and which would extinguish a fire within 45 seconds.

4 TANK INSTRUMENTATION

Tank wall temperatures were measured by eight stainless steel chromel-alumel thermocouples welded to the outer surface of a tank and positioned at two vertical planes equi-distant from the tank ends, as shown in Fig 1a. The bulk temperatures of the liquid propane and the vapour were measured by three thermocouples mounted vertically inside the tank, as shown in Fig 1b. PRV's were fitted to the tops of the tanks; their sizes were those recommended by the LPGITA code of practice (8). Short (1m) flare pipes were fitted to the PRV outlets. The relief valve assemblies were protected from the fire by an insulating blanket. Internal pressures were measured by a pressure transducer connected to a pressure tapping from the bottom of a tank.

The mass of the 1-tonne tank and its contents was measured using a four-point load cell weighing system with preamplifier and temperature compensation system enclosed in a waterproof container. The load cells and preamplifier were positioned on the floor of the bund and were submerged in 300mm of water. All transducer signals were carried out of the fire zone by means of mineral insulated multicore cables. The pressure transducers, thermocouples and weighing system were connected to chart recorders and an automatic data logger situated within a control room some 120 metres from the bund. The data logger sampled each transducer every 10 seconds. All of the fire tests were videotaped and still photographed. The test parameters and test conditions are summarised in Table 1.

5 TEST PROCEDURE

The test procedure was to connect up the instrumentation and data logging system, fit the PRV, fill the tank to the required level, fill the bund with kerosene, start the data recording system then ignite the fire. Typically, a fire took up to $1^1/2$-2 minutes to become fully established, after which the vessel contents would begin to heat up. The PRV's then opened within the following 2-5 minutes, depending on vessel size, fill level and initial temperature. In most tests successive PRV venting then occurred until the tanks were emptied of LPG and the vapour pressure fell below the relief pressure.

6 RESULTS AND DISCUSSION

All four successful tests followed a similar pattern of behaviour. Once a fire was established the tank wall temperatures began to rise. Those thermocouples attached to tank walls adjacent to the vapour space rose at a much quicker and approximately linear rate compared with those attached to walls adjacent to the liquid space. The latter rose to a plateau level before rising further. This behaviour is consistent with the results reported in (2) and reflects the fact that the convective heat transfer coefficient from the tank wall to the liquid is much higher than that to the LPG vapour. Once the PRV began to discharge fluid at a nearly constant internal pressure, the liquid outer wall temperature remained just above the corresponding boiling point, until sufficient liquid had boiled off to expose the thermocouples. The duration of the 'plateau' therefore varies with fill level and discharge rate. In the four successful tests this lasted between 1-14 minutes, after which all wall temperatures rose steadily to reach peak values similar to those of the vapour walls before the tests were terminated.

The maximum wall temperatures recorded by individual thermocouples were in the region of 600-800°C. These were considered to be consistent with the assumed flame emissivity of 0.56, the wall F factor, and the recorded average flame temperatures of a typical kerosene pool fire, as discussed by Roberts et al (9) for earlier engulfment tests. Typical flame temperature measurements, are shown in Fig 2, and illustrate that an average flame temperature of 900-950°C is typical for these tests, peaking at values of 1000°C. As these temperatures were well below the adiabatic flame temperature they indicate that the kerosene fires were deficient in oxygen, which was also suggested by the very yellow flames and copious smoke being produced.

The internal pressures in all cases rose to the relief valve set pressures within 3-5 minutes from the commencement of the fire. After cycling at least twice the PRV's remained open in four of the five tests until the internal pressure was eventually down to atmospheric or thereabouts. This fail safe behaviour was, upon subsequent examination of the valves, attributed to fire damage to the valve seats and to a weakening of the valve springs. It was also observed that at no time did the internal pressure remain at a level likely to cause tank rupture consistent with a reduction in tensile properties of the vessel wall due to the elevated temperatures. Thus failures of the type predicted in (7) were not to be expected at all during the latter stages of the fire engulfment.

6.1 1/4 TONNE TANK

Two tests were undertaken with this size of tank, both 40% full of propane (200 l), but only one test was completed without damaging the tank. A representative outer wall temperature for the vapour space and also one for the liquid space outer wall are shown in Fig 3. The bulk internal temperatures recorded by the three internal thermocouples T,M and B are shown in Fig 4. The internal pressure is shown in Fig 5.

These results show that the average upper wall temperature rose almost linearly, starting after 90 s from ignition, to reach a value of around 700°C at 8 minutes. The lower wall temperature, after a similar delay, rose in 180 s to a plateau value of 90°C, and remained so for a further 120 s, before rising linearly to 500°C after 8 minutes. The bulk temperature of the liquid propane as recorded by thermocouples M & B reached 47°C after 180 s, and remained more or less constant for a further 120 s, before rising at an increasing rate to reach 450°C after 8 minutes. The bulk vapour thermocouple reached 100°C in 180 s and thereafter rose to reach 150°C after 300 s, and 520°C after 8 minutes.

This sequence of variations is similar to those obtained for larger vessels as reported in (2) and (3) and tend to confirm the proposition that the majority of the heat is transferred to the liquid propane by nucleate boiling, both before and after the PRV has opened. Thus from Figs 3 and 4 the estimated inner temperature wall, allowing for the wall temperature gradient, can be seen to be always higher than the bulk saturated liquid temperature (the latter following closely the saturation curve for liquid propane). Thus at the moment venting begins T_W-T_{sat} has a value of some 20°C.

This is a higher value than the corresponding one used by Ramskill and Hunt (1) to model the nucleate boiling phase of heat transfer for the same heat flux, based upon the Rohsenow pool boiling correlation. One explanation for the difference may be the development of a two-phase boundary layer due to both the rapid increase in the number of nucleation sites and the vessel wall curvature. Such phenomena are reported to exist in (5) and may indicate the need for different correlation coefficients, but which also do not effect unduly the time response predictions for the PRV opening.

The bulk vapour and liquid temperatures show that some thermal stratification can exist within the vessel's contents. Thus at the moment venting begins the vapour is superheated by as much as 50°K, as shown in Fig 4. This superheat falls immediately after PRV opening to approach saturation as liquid is boiled off. Similar effects were also reported in (2).

The internal pressure curve, Fig 5, shows that the PRV first opened 180 s after ignition, which agrees well with the predicted time (1). Successive openings of the PRV occurred at reduced pressures until the valve failed open after 6 minutes. The total time that the valve was open during this 3-5 minute period was 88 seconds, during which approximately 46 kg of propane were discharged, at an average flow rate of 0.52 kg/s. This is a slightly lower rate than the choked vapour flow rate of the PRV fitted (0.70 kg/s), which when considered in the light of the 1 tonne results discussed later, suggests initially at any rate, that there may have been some liquid carry over into the vent system. This would imply that a considerable amount of two-phase swelling occurs when the PRV opens. If so then it does not appear to allow the liquid wall temperature to rise and initiate film boiling, as no appreciable liquid wall temperature increases were apparent until the liquid level had fallen below the thermocouples. This PRV/liquid interaction has been suggested as a mechanism for obtaining film boiling (6), but these results suggest either that a larger vent area/liquid surface area ratio is necessary before it will happen in this case, or scaling effects are becoming significant.

The average rates of heat transfer into the propane and tank wetted wall up to the onset of venting (constant mass) were calculated from the bulk temperature and pressure data. Changes in specific heat, thermal expansion etc were taken into account. It will be observed that the average rate of heat input into the propane was 123 kW before venting. This corresponds to a heat flux of 73 kW/m^2 assuming all of the heat to be transferred to the liquid propane via the wetted surface. The heat flux into the tank wall for the corresponding period was 24 kW/m^2. Thus giving a total heat flux of 97 kW/m^2 to compare with the value (100 kW/m^2) recommended for valve sizing.

The average heat flux into the system during boil-off was calculated from the mass discharge rates to be 80 kW/m^2.

These calculations show that the critical heat flux, Butterworth (10) necessary to take the boiling mode into film boiling is not reached, and provide a further indication that nucleate boiling predominates.

6.2 1/4 TONNE VESSEL RUPTURE

One test with a 40% fill provided the opportunity to study the consequences of a catastrophic failure, because the PRV, after first opening correctly, failed to do so subsequently. Consequently both the internal pressure and the vapour space wall temperature rose uncontrollably. The fire extinguishing system was not used and the vessel ruptured when the internal pressure reached 35 bar and the maximum wall temperature was 600°C. The resultant blast scattered fragments of the pressure relief system up to 170 m, but the bulk of the vessel remained within 20 m of the test site. The fireball was estimated to have had a maximum diameter of 21 m and to have lasted for 1-2 seconds. The PRV was examined after the test but the reasons for the failure to operate correctly have not been established.

A subsequent metallurgical examination of the vessel remains showed that there had not been any incipient cracks of significance and that the membrane wall had deformed and ruptured along the top of the vessel, (presumably where the wall temperature was at its highest value). This was consistent with an excessive hoop stress in the vessel wall rather than stresses from potential stress raisers such as a pipe fittings or access holes. The position of the initial failure would also seem to rule out the possibility of stresses from the thermal gradient in the wall at the liquid vapour interface being a significant cause of failure. Hence it is suggested that the burst pressure may be calculated from thick walled cylinder theory (11) to give:

$$P_b = \frac{2}{\sqrt{3}} \sigma_y A \ln K \qquad (1)$$

and $A = (2 - \sigma_u/\sigma_y)$ for $0 < T < 700^{\circ}C$, or $A = 1$ for $T > 700^{\circ}C$

where P_b is the burst pressure, K the outside diameter/inside diameter ratio of the cylinder and σ_y, σ_u are respectively the yield strength and ultimate tensile strength of the vessel material at the elevated temperature T. Thus taking the maximum wall temperature as the recorded value of 600°C and substituting the appropriate strength properties, the calculated burst pressure is 38 bar. This is within 8% of that observed. Furthermore if this formulae is taken as a criteria for vessel failure then it can be shown that all the other tests either depressurised safely or were stopped before reaching unsafe temperatures. Application of equation (1) to the data of (2) and (3) will predict all of the burst pressures with less than a 18% error. The greater inaccuracy is probably due either to doubt about the appropriate strength properties or in some cases the point where rupture began.

6.3 1-TONNE TANK

Three trials were undertaken using fill ratios of 40%, 80% and 20% respectively. The same type of data was recorded as in the previous tests but in addition the tank was weighed continuously. The vapour and liquid wall temperatures are shown in Figs 6 and 7 respectively for all three fills. The bulk liquid and vapour temperatures are shown in Fig 8, the internal pressures in Fig 9, and the weight losses in Fig 10.

The results from all three tests showed the same trends as the previous $1/4$ tonne test. The fires again took $1\text{-}1^1/2$ minutes to establish themselves, after which both vapour and liquid wall temperatures rose as previously but at slower rates. The upper surface temperatures rose at more or less the same rates in the 40% and 20% fill tests to reach 600-700°C in 12-15 minutes from ignition. In the case of the 80% fill the rate of rise was slower and about the same as that of the liquid space wall temperature. This was because the thermocouples were close to the liquid level until after the PRV had vented some of the contents. The lower surface temperatures, after a 60-90 s delay, rose to their plateau temperatures after 1(20%), 11(40%), and 18(80%) minutes, before rising to peak at values in excess of 500°C at which time the tests were terminated. Although the plateau temperatures followed the expected pattern, (apart from the 20% fill test, for which the thermocouples were barely below the liquid level when the test began), the values of $T_W - T_{sat}$ for the two other tests were higher than previously, but were nevertheless more typical of nucleate than film boiling.

The bulk liquid and vapour temperatures shown in Fig 8 were as expected. The liquid region thermocouple followed approximately the saturation curve during venting until it was uncovered, whilst the vapour spaces became superheated within relatively short times. The 20% fill showed the maximum superheat of 150°C, just prior to venting. The superheats again fell towards saturation as the PRV's opened and liquid boil off began.

The internal pressures, Fig 9, showed that the 80% fill vented first after 226 s when the pressure was 15.2 bar. There then followed a rapid sequence of three further valve operations before a final opening after 264 s. Thereafter it just coped with the flow of heat into the tank, the pressure slowly rising to a peak of 15.5 bar after 10 minutes, then slowly decaying until all of the propane had vented after 24 minutes. The 40% fill began venting after 262 s at a pressure of 13.8 bar. The valve remained open for the next 6 minutes, with the propane burning in a 8-10 m long flare. After 616 s the valve closed at 11.1 bar pressure. The valve reopened 12 s later at 12.6 bar pressure and remained so until all the propane had been ejected after 19 minutes. The 20% fill began venting after 297 s at a pressure of 17.1 bar. There then followed a sequence of nine opening and closing operations until after 6 mins 28 secs it remained open. All of the propane was exhausted after 13 minutes.

Heat flux calculations were carried out, as described previously, and the results are summarised in Table 2. The average heat fluxes into the propane were similar to that obtained for the 1/4 tonne test, apart from the low value of 33 kW/m^2 for the 20% fill. Although the total average heat fluxes both before and after venting are very similar. The lower heat fluxes in the case of the 20% fill may have been due to the tank being only partially engulfed, as the wind speed was exceptionally high during this test. These values again illustrate the fact that the critical heat flux for film boiling is not reached.

6.4 PRV DISCHARGE RATES

The tank weighed 0.99 tonnes and contained initially 870 , 420 and 160 kgs of propane to correspond with the three fill levels of 80, 40 and 20% respectively. The load cell output, Fig 10, confirmed that the times for the PRV's to first open were as obtained from the internal pressures. They also showed the initial thrust of the jet flare which was different in all three cases and possibly indicative of the different degrees of valve opening that may occur with nominally similar valves. The slopes of the curves represent the mass flow rates during discharge and show that in all cases the maximum discharge rate occurs during the first opening of the valves. Maximum (initial) and average valves for the three tests are also given in Table 2. These confirm the suggestion of two phase discharge discussed previously in connection with the 1/4 tonne results.

The actual PRV fitted to the tank had a flow rate of 1.16 kg/s measured with air at 15°C and 16.6 bar pressure. Thus the effective critical valve area, A_E, as determined from the choked mass flow equation for compressible flows is given by:-

$$A_E = \frac{m\sqrt{ZRT_o}}{P_o\sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}} \qquad (2)$$

where m is the mass flow rate, R the gas constant, T_O the initial temperature, Z the compressibility factor, P_O the initial pressure, and γ the specific heat ratio.

This gives a value for A_E of 2.76×10^{-4} m^2 for this particular valve. Assuming that propane is vented at a similar pressure through the same effective area, then from the bulk vapour temperatures immediately prior to venting, the maximum propane vapour flow rates, (using a compressibility factor of .75 as given by Sallet (10)) are for descending fill levels, 1.04, 0.88 and 0.97 kg/s. These may be compared with the maximum and average values shown in Table 2. It will be observed that in all three tests there appears to be some high quality two-phase flow or droplet carry over during the first discharge of the PRV. This is not unexpected with the 80% fill, as the vessel is almost liquid locked just prior to venting and the PRV is only just able to cope with the boil off rate as the pressure trace shows. It is perhaps surprising in the 20% fill case, especially as the valve throat area to liquid surface area is relatively small. One possible explanation may be that in this case the valve lifts further initially giving a larger effective throat area.

The average mass flow rates are slightly less than the choked flow values, and this is probably due to the increasing vapour temperature not accounted for in these comparisons. The results do however illustrate that the performance of an actual valve can be predicted reasonably well from the standard compressible flow equations, as used in reference (1).

7 CONCLUSIONS

1 The test data obtained from fire engulfment tests on two sizes of tanks compared favourably with other fire engulfment data reported in the literature and was shown (1) to agree with theoretical predictions.

2 The burst pressure of a 1/4 tonne tank was reasonably well predicted from its material strength properties at elevated temperatures.

3 The two tank sizes and different initial fill levels all responded to the fire engulfment in a similar manner, differing only in their time scales.

4 The maximum wall temperatures occurred in the vapour space walls and were of the order of 600-800°C when the tests were stopped.

5 Usually the PRV's operated satisfactorily and prevented excessive pressures from building up. However the fact that they remained open towards the end of a test may have been instrumental in preventing vessel failure.

6 Further information is required to help understand the boiling behaviour of the liquid, to identify the appropriate heat transfer correlations, and to help assess the quality and mass flow rates of propane discharging through PRV's A more comprehensive series of tests on a 5 tonne tank are therefore to be undertaken shortly in order to provide additional data.

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	1 Tonne Tank			1/4 Tonne
Percentage Fill	80%	40%	20%	40%
Tank Total Surface area (m^2)	10.4	10.4	10.4	3.8
Wetted Surface area (m^2)	6.28	4.32	3.02	1.68
Initial Volume of Propane (l)	1635	789	308	185
Initial Depth of liquid (m)	0.68	0.35	0.18	0.22
Ambient Temperature (°)	14.0	-3	-3	5
Tank Pressure (bar)	6.1	4.1	4.1	5.5
Initial Propane Mass (kg)	870	420	160	100

TABLE I:- Initial conditions, both tank sizes

	1 Tonne Tank			1/4 Tonne
Percentage Fill	*80%*	*40%*	*20%*	*40%*
Av. heat flux into propane before PRV opens (kW/m^2)	84	59	33	73
Av. heat flux into tank walls before venting kW/m^2	34	16	28	24
Av. heat flux into propane during early stages of PRV venting (kW/m^2)	50	54	76	85
Initial mass flow rates (kg/s)	2.1	1.35	1.54	-
Average mass flow rates (kg/s)	1.01	.74	.79	.52
Choked mass flow rate (kg/s)	*1.04*	*.88*	*.97*	*.70*

TABLE 2:- Heat Fluxes and discharge rates

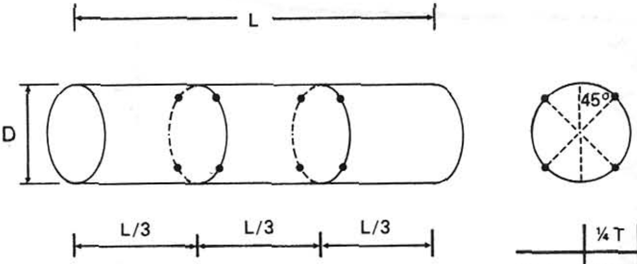

Fig 1a Positions of wall thermocouples

	¼ T	1T
L(m)	2.26	2.9
D(m)	0.51	1.0
A(mm)	25	50
C(mm)	219	324
E(mm)	250	385

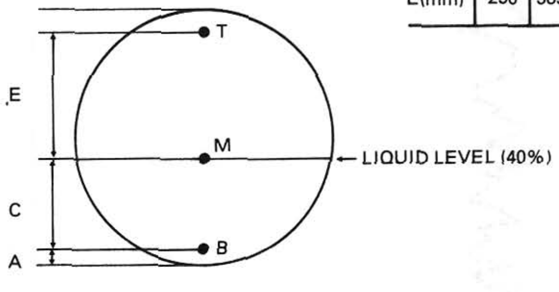

Fig 1b Positions of internal thermocouples

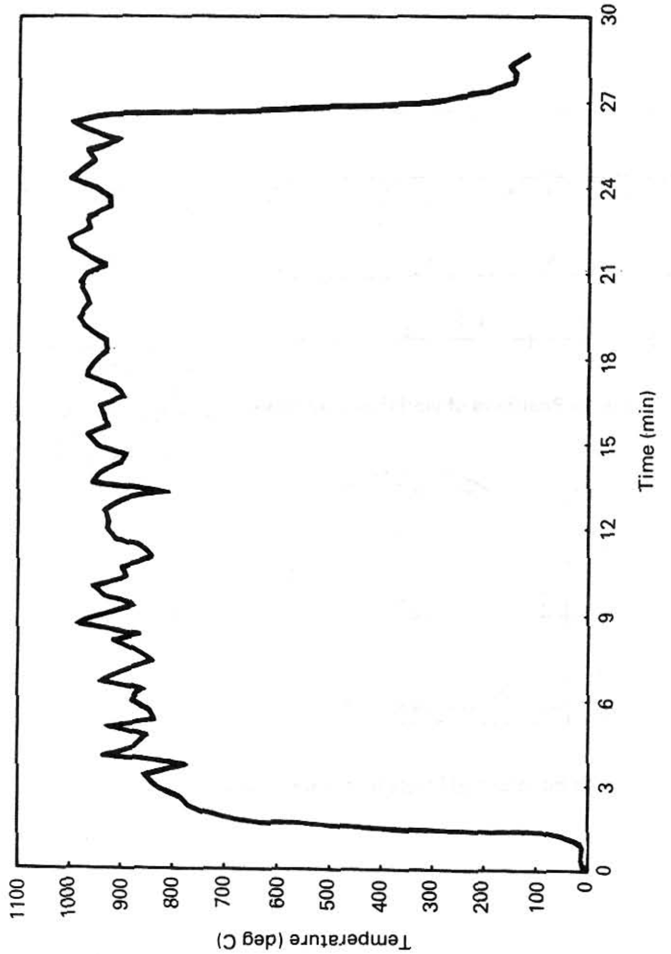

Fig 2 Flame temperature during the 1 tonne 80% fill trial measured near the middle of the tank side

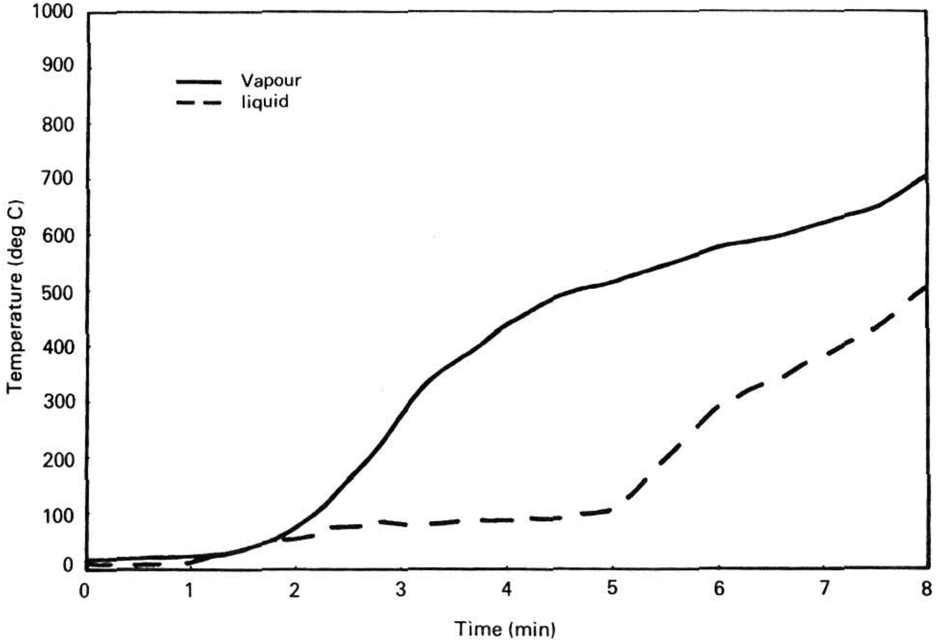

Fig 3 ¼ tonne trial : liquid and vapour space outer wall temperatures

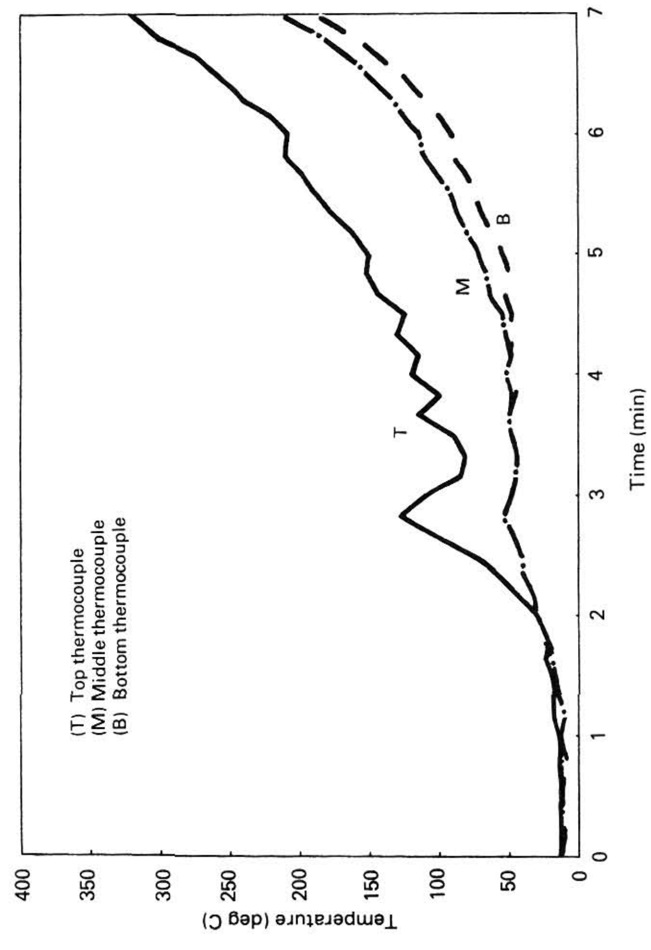

Fig 4 ¼ tonne trial : internal bulk liquid and vapour space temperatures

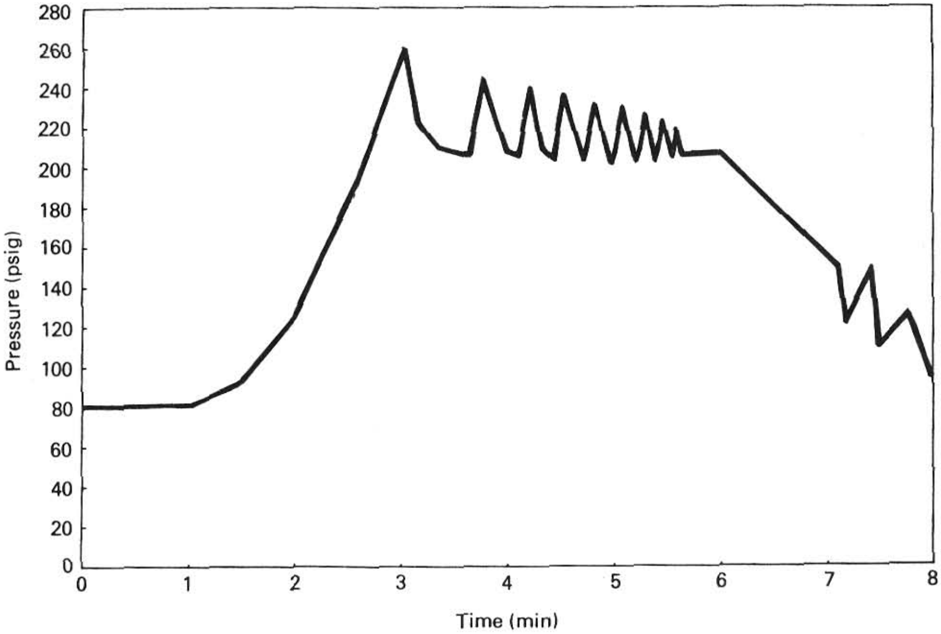

Fig 5 ¼ tonne trial : internal pressure

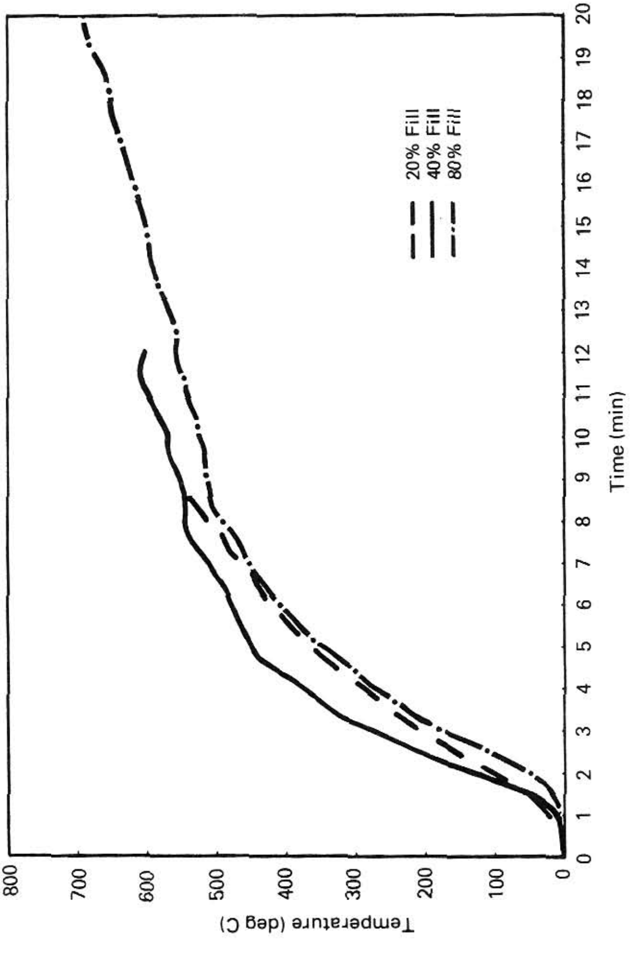

Fig 6 1 tonne trials : vapour space outer wall temperature

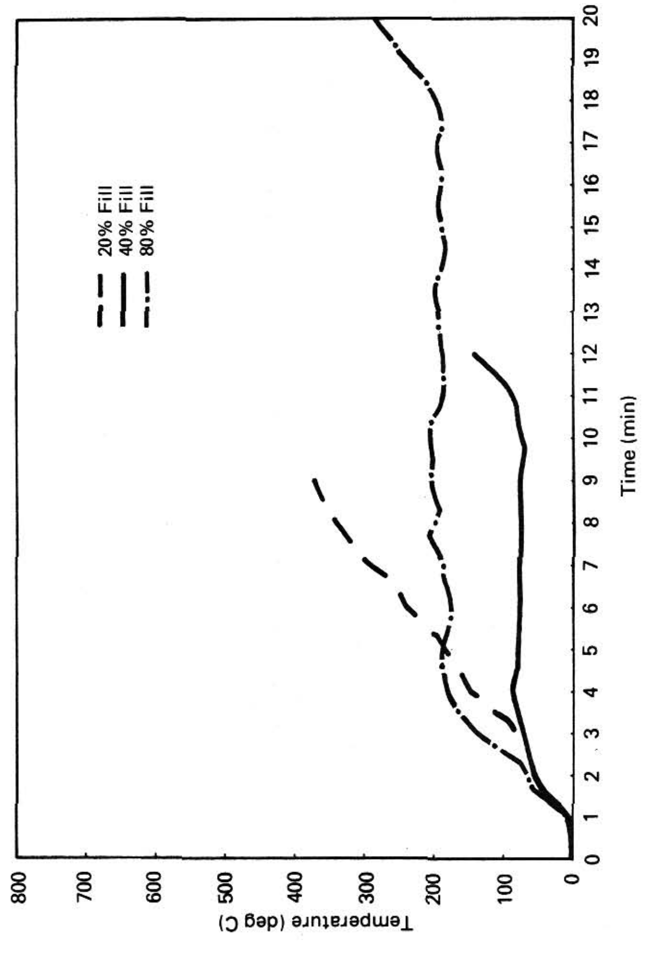

Fig 7 1 tonne trials : liquid space outer wall temperature

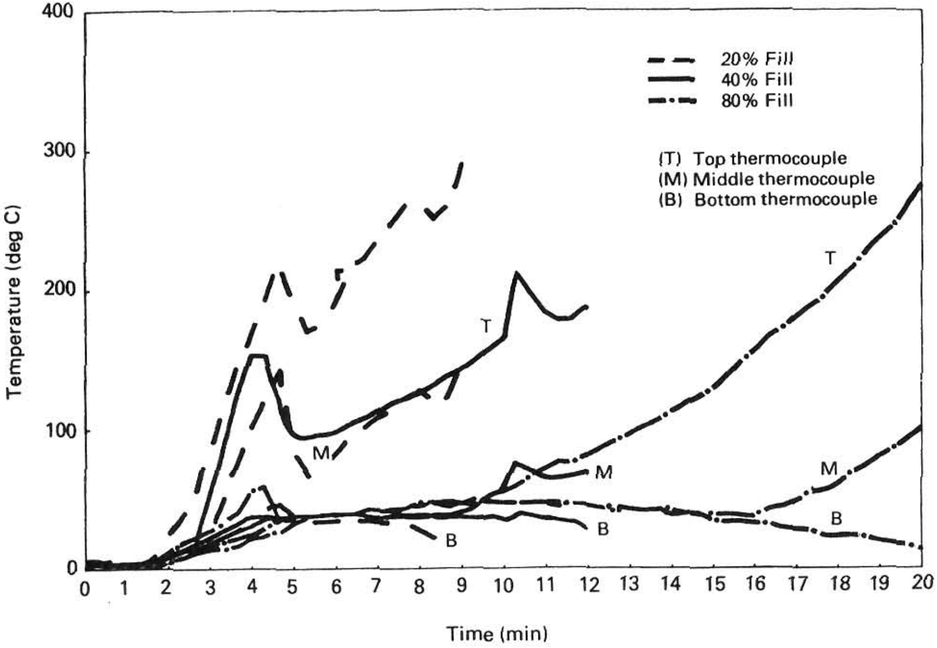

Fig 8. 1 tonne trials : *internal bulk liquid and vapour space temperatures*

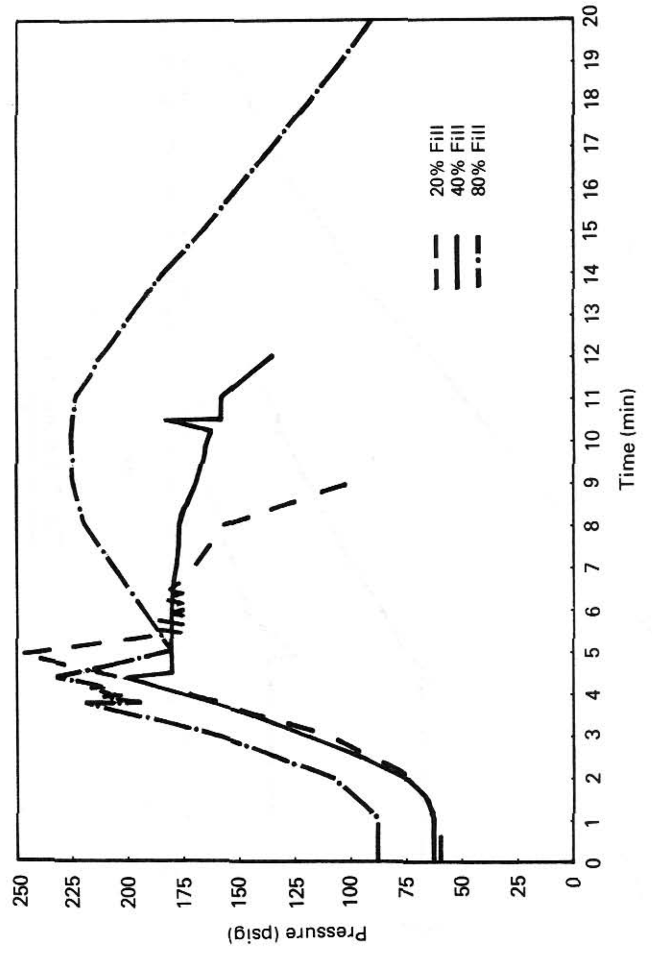

Fig.9 1 tonne trial internal pressure

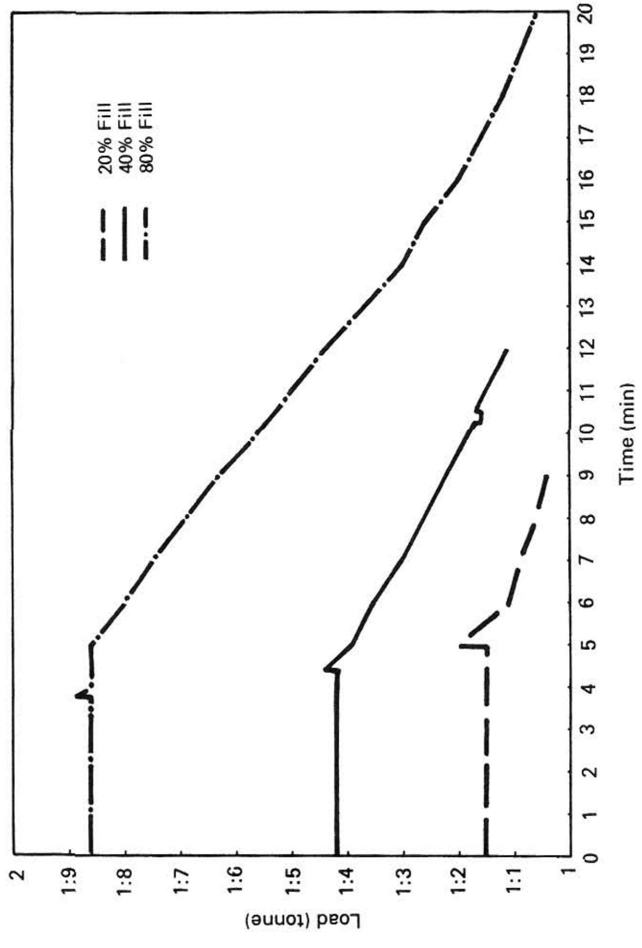

Fig.10 1 tonne trial: mass discharge rates