DIRECTED WATER DELUGE PROTECTION OF LIQUEFIED PETROLEUM GAS VESSELS

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The adequate fire protection of Liquefied Petroleum Gas (LPG) storage vessels to guard against their catastrophic failure and possibly Boiling Liquid, Expanding Vapour Explosion (BLEVE) is recognised to be of key importance. One means of achieving this is by directed water deluge that, for LPG vessels of 50 tonnes or larger, should be a fixed system on the vessel. The deluge rate currently recommended for such systems is designed to provide adequate protection against hydrocarbon pool fires. However, it is now recognised that the incident scenario most likely to threaten the integrity of such vessels is impingement by a hydrocarbon fuel jet fire. HSE therefore decided to sponsor studies of the effectiveness of directed water systems in protecting against jet fires.

This paper describes the work carried out by the Health and Safety Laboratory (HSL) in which a nominal 2 kg s^{-1} flashing liquid propane jet fire was impinged upon two tonne propane vessels protected by a range of water deluge systems. The results from the work show that a directed water deluge system designed to provide protection against a pool fire (using the minimum recommended rate of 9.8 dm^3 m^{-2} min^{-1}) provides inadequate protection against jet-fires. However, improved designs of water deluge systems proved more successful.

A number of aspects concerning the design of directed water deluge systems were studied, including: type of nozzle and their arrangement, water flow rate and pressure, effect of blocked nozzles and delayed deluge initiation. Critical design parameters are proposed for directed water deluge systems.

Keywords: directed water deluge, propane, LPG, fire protection, jet fires.

INTRODUCTION

An external fire can pose a significant threat to the integrity of a plant containing pressurised flammable materials. The particular purpose of providing fire protection to such vessels is to limit the heat transfer from the heat source to the pressure vessel. This delays the rise in temperature to critical levels, reduces the risk of escalation and gives additional time for emergency actions to be implemented. In respect of one of the means of providing fire protection of LPG storage vessels, namely directed water deluge, the deluge rate recommended[1] is that determined to provide protection against a hydrocarbon pool fire.

The particular water deluge rate recommended of 9.8 dm^3 m^{-2} min^{-1} over the whole of the exposed vessel surface derives from work by Bray[2] and Billinge[3] *et al.* as adequate for the protection of vessels containing pressure liquefied gases against hydrocarbon pool fires. It is not perhaps surprising that others have proposed comparable application rates with a view to providing similar levels of protection. For example, the National Fire Protection Association[4] in the USA, recommends 10.2 dm^3 m^{-2} min^{-1} as the minimum deluge rate. Whilst the American Petroleum Institute[5] specify a lower minimum requirement of 4.1 dm^3 m^{-2} min^{-1}, in taking account factors such as high-intensity flame impingement, water losses due to wind and partial clogging of water delivery nozzles, the same deluge rate as the NFPA is recommended. The Institute of Petroleum[6], in their model code of safe practice for bulk pressure storage of LPG, recommends that water deluge systems should be designed to permit application of at least 7 $dm^3\ m^{-2}\ min^{-1}$.

However, it is now recognised that the incident scenario that is potentially most likely to threaten the integrity of such vessels is jet-fire impingement. Jet fires are typically more severe than pool fires because of their high heat fluxes (up to 350 $kW\ m^{-2}$) and high mechanical erosive effects. Jet fires have higher velocities and can result in higher rates and higher amounts of heat transfer to a vessel than for a pool fire. HSE's Technology Division therefore sponsored a project to study the critical elements of deluge system design for protection against jet fires.

The experimental programme comprised several phases. The first phase was to determine the effectiveness of water deluge systems designed according to current practice; one designed to deliver the minimum recommended rate of 9.8 $dm^3\ m^{-2}\ min^{-1}$ and one designed to a tentative fire protection industry standard[7] that is used in the UK. The second phase was to investigate whether a directed water deluge system could be made effective against a jet fire. In phase 3 the sensitivity of the system to blocked nozzles and delayed water deluge initiation was investigated. The final phase was to confirm the effectiveness of the system in protecting a vessel containing various degrees of fill of LPG.

DESIGN OF DIRECTED WATER DELUGE SYSTEMS

The design codes currently used in the UK allow a significant degree of flexibility in the specification of directed water deluge systems. The most detailed code, BS 5306 Part 2[8], unfortunately does not explicitly cover water deluge protection of vessels containing pressurised flammable materials, such as LPG. The two other design codes in use are, the Fire Offices' Committee (FOC)[7] *Tentative rules for medium and high velocity water spray systems* (hereafter referred to as the Tentative Rules), and NFPA 15[4] *Water spray fixed systems for fire protection*. Whilst issued as an interim measure in 1979, the Tentative Rules provide the greater detailed guidance on the design of systems for the protection of "storage vessels containing inflammable gases, and liquids at atmospheric and higher pressures" i.e. including LPG vessels. The experimental work has therefore been carried out with regard to the FOC Tentative Rules and NFPA 15 designs are considered in relation to these.

TENTATIVE RULE DESIGN REQUIREMENTS

Different types of spray nozzles may be used in water deluge. Low velocity (LV) nozzles produce a fog-type spray with a fine drop size and a high capacity for heat absorption. High velocity (HV) nozzles produce a spray with a much coarser drop size, with good capabilities for penetrating through turbulent fire gases and convection currents. Medium velocity (MV) nozzles are general purpose, providing a mixture of the properties of low and high velocity sprays, with the result that they can be used in all categories of protection. According to the Tentative Rules, for liquids with flash points less than 66 ^{o}C and combustible gases, medium velocity sprays need to be installed with a view to bringing a fire under control and to provide cooling. For horizontal, cylindrical storage vessels, it is specified that protection should be by means of open medium velocity spray nozzles, not less than 6 mm bore, operating at pressures between 1.4 bar and 3.5 bar and should have cone angles between 60^{o} and 125^{o}. The recommendations for the spacing and operation of sprinkler nozzles are based upon "*an application rate of 10 mm min^{-1} over the vessel surface to limit the heat input to the vessel to 19.0 kJ min^{-1} per square metre of vessel surface.* [This may be an error – Bray's work[2] suggests that 19 $kW\ m^{-2}$ is the appropriate value] *It is assumed that the design of the vessel* *vents will be capable of maintaining the internal pressure within design limits for this heat input*."

Spray nozzles should be installed in accordance with relevant spray nozzle application charts. There are three different charts corresponding to spray nozzle stand-off distances of 0.45 m, 0.55 m and 0.65 m from the vessel surface. Each chart gives the K-factor for the nozzles for the allowed number of spray rows and spray angle for a given vessel diameter. The K-factor is calculated from:

$$K = \text{Flow rate } (dm^3\ min^{-1}) / \text{Pressure}^{0.5}\ (barg) \quad (1)$$

and relates the flow rate to the water pressure. The rules specify that, if a spray nozzle with an orifice corresponding to the K-factor value determined from the graph is not commercially available, the next larger orifice should be used. The longitudinal spacing of the spray nozzles is given as a table of discharge angle versus stand-off distance from the vessel. Protection of the ends is provided for, by increasing by one the number of spray nozzles per row indicated by the table for the desired vessel length. The two outer spray nozzles are arranged so that half their output sprays back to cover the vessel end (flat or curved) and half sprays on the vessel shell. For curved vessels above $\geq$ 3.5 m in diameter, an additional spray nozzle onto the centre of the vessel end is required. Where the plinths supporting the vessel interfere with the water distribution, additional spray nozzles should be provided on the bottom rows of spray nozzles. Further spray nozzles of, for example, 6 mm bore size will be required for the vent, manholes, inlet and outlet points, pumps etc., "*unless the items are well protected by sprayers protecting the vessel surface"*.

With respect to the actual water coverage, the Tentative Rules stress in a note that "*it is not acceptable to establish total flow requirements for protection of a vessel by simply adding a given percentage to the theoretical figure obtained by consideration of required density and surface area of vessel and then determining the number of sprayers by dividing the total flow by the output for one spray nozzle*". However, study of the original derivation of the recommended rates suggests that the rate that is quoted is the **delivery rate** to the nozzles divided by the vessel surface area and ***not*** the amount of water actually delivered to the surface of the vessel.

HSL EXPERIMENTAL DELUGE SYSTEMS

A commercial organisation designed two directed water deluge systems for use in the experimental programme. The first was designed to deliver the minimum recommended application rate of 9.8 $dm^3\ m^{-2}\ min^{-1}$, and the second to provide a range of configurations within the parameters permitted in accordance with the Tentative Rules. The systems were designed for installation on nominal 2 te LPG vessels, details of which are given below.

SYSTEM DESIGNED TO GIVE THE MINIMUM RECOMMENDED RATE

The system comprised 9 stainless steel, medium velocity, hollow cone (impact type) nozzles (see Figure 1) that were specially made with a nominal 4.7 mm bore and 95^o spray angle nozzles, and quoted K factor of 10, arranged in three rows around the vessel (see Figure 2). Four additional nozzles were fitted to prevent formation of dry spots on the vessel behind the supporting legs. The stand-off distance of the nozzles from the vessel surface varied between 0.5 m and 1.0 m as shown in Figure 2. To produce the required coverage, the manufacturer specified a water pressure of 2 barg at each nozzle, Figure 4 shows the spray pattern.

SYSTEM NOMINALLY DESIGNED TO THE TENTATIVE RULES

The system comprised three rows of four stainless steel, medium velocity, hollow cone nozzles (nominal bore 6.8 mm, spray angle of 95°, K-factor 28) with a 1.50 m longitudinal spacing (c.f. 1.57 m specified in the Tentative Rules) and a 0.65 m stand-off distance. For the experimental set-up, the end nozzles were ***not*** directed half onto the parallel section and half onto the end cap as recommended in the Tentative Rules, nor were the pressure relief valve or top and bottom outlet valves specially protected by dedicated nozzles. Additional nozzles were not required to prevent the formation of dry spots on the vessel behind the legs. Figure 3 shows the positions of the spray nozzles and Figure 5 the spray pattern.

CHARACTERISATION OF DELUGE SYSTEMS

For each type of nozzle, at least 3 were randomly selected and checked by collecting and measuring the amount of water delivered to the nozzle in a specified time at the minimum and maximum water pressures used. The overall flow through the system was measured using a calibrated flow meter. For the non-standard 4.7 mm bore nozzles, the measured K factor was 13.2 compared to 10.0 quoted by the manufacturer. This may have been a calculated, rather than a measured value. The K factor for the 6.8 mm nozzles was found to be the 28.0 stated by the manufacturer.

A key element of the work was to characterise not only the water leaving the nozzles but also the amount of water covering the surface of the target vessels. Davies and Nolan[9, 10] (South Bank University) were tasked with:

- performing a more detailed characterisation of the spray (e.g. trajectories, droplet size and velocity); and
- characterising the water coverage of the vessel (e.g. water film thickness, surface water flow rate).

The measured (contact probe) film thicknesses for the minimum recommended rate system were slightly higher, 1.20 mm compared to 0.95 mm, than the Tentative Rule system but this is probably a function of the measuring technique used. In the early use of the film thickness instrumentation, measurements were made when the probe left the water film rather than when approaching it (as used in other deluge system measurements) and there may have been surface tension effects. The results suggest that, within the limits of experimental error, there was very little difference in water film thickness between the systems. Hence putting more water on the surface of the vessel will lead to an increased flow rate across the surface rather than an increased depth of water film.

The results from the water coverage experiments, measured by sealing a collection device to different points of the vessels surface, are summarised in Table 1. The surface water flow rate values varied considerably across the surface of each of the vessels. In most cases, the surface water flow rate was lowest over the bottom surface of the vessels, suggesting that water running down the tank was falling from the surface of the vessels just after passing the tank equator. The results from the systems where the top and bottom rows were not staggered (as recommended in NFPA 15 but not the Tentative Rules) indicated that the surface water flow rates were generally higher at positions between nozzles, where the spray patterns overlapped. This was confirmed by a series of later, detailed experiments by Davies and Nolan[9, 10]. The effect of increased water concentration between nozzles appears to increase with increasing pressure. The deluge system designed to provide the minimum recommended rate (9.8 $dm^3\ m^{-2}\ min^{-1}$) actually gave a mean surface water flow rate well below this. The deluge system designed in accordance with the Tentative Rules gave a mean surface water flow rate nominally in excess of the recommended rate. However, the rate varied significantly across the surface of the vessel.

Table 1. WATER COVERAGE

System	Between (B) or Opposite (O) nozzles	Water pressure (barg)	Surface water flow rate ($dm^3\ m^{-2}\ min^{-1}$)			
			Top front	Front centre	Lower front	Mean
Minimum recommended rate	O/B *	2.0		4.2	4.8	5.1
	O/B *	2.0		7.1	5.5	
	O/B *	7.0		5.0	9.8	8.1
	O/B *	7.0		11.6	6.4	
Tentative Rules	B	1.4		13.7	14.9	10.0 ±4.4
	O	1.4	10.8	8.4	4.3	
	B	2.0		16.4	16.3	10.6 ±4.7
	O	2.0	11.5	8.0	2.8	

* Top and bottom nozzles staggered

EXPERIMENTAL SET-UP

TARGET VESSELS

Two target vessels were used. The first vessel (see Figure 4) was similar to those used in failure mode trials[11] and was used unpressurised in case it was weakened in the fire trials. The second vessel (see Figure 5) was used from new for validation trials in which it was filled with propane and where the deluge system was expected to prevent the shell temperature from significantly exceeding 100 ^oC. The dimensions of the vessels are summarised in Table 2.

Each target vessel was mounted on a steel I-beam frame located in a pit in a concrete pad. This pit was filled with water during the trials to protect the support frame.

Table 2. TARGET VESSEL DIMENSIONS

Parameter	Vessel used for phase 1 to 4 trials	Vessel used for phase 5 trials
General shape	Horizontal bullet	Horizontal bullet
End caps	1.9 : 1 Semi-ellipsoidal	2 : 1 Semi-ellipsoidal
Overall length	4064 mm	4064 mm
Length of parallel sections	3276 mm	3370 mm
Outside diameter of parallel sections	1200 mm	1240 mm
Surface area	15.6 m^2	16.3 m^2
Thickness of parallel sections (minimum)	7.1 mm	10 mm
Thickness of end sections (minimum)	7.2 mm	8.5 mm

JET FIRE

The jet fire consisted of a 2 kg s^{-1} flashing-liquid propane discharge from a 80^o basic fan nozzle with the long axis of the elliptical opening in a vertical orientation. The supply system consisted of six 1.7 tonne propane storage vessels, which were over- pressurised with nitrogen (nitrogen is slightly soluble in propane but this had only a marginal effect on the flame characteristics) to maintain the propane at just above its vapour pressure at the point of discharge. Since the nitrogen control system was relatively crude and the trials duration short, the same nitrogen start pressure (11 barg) was used for each experiment. The point of discharge was 1.30 m above the ground and aimed at the centre of the vessel, 0.05 m below its base. The distance between the point of discharge and the target vessel was varied between 1.0, 2.5, 3.0, 3.5 and 4.5 m. The set-up was chosen to expose the vessel to the most onerous conditions of the jet-fire. Discharge 4.5m from the vessel resulting in almost complete fire engulfment (at least 85% of the vessel surface was engulfed, the fall off occurring at the two end caps). Previous work has shown that this is sufficient to bring an unprotected vessel to failure within 5 minutes[11]. At shorter discharge distances to the target vessel, the fire is not so developed, but the force of the discharge is greater.

INSTRUMENTATION

As the primary measure of the success or failure of the deluge systems was the shell temperatures, only details of the type K thermocouple positions on the shell are given here. The metal temperature was measured at a number of points using 3 mm, stainless steel-sheathed, type K thermocouples attached to the surface of the vessel. In each case, a 60 x 12 x 3 mm steel plate was grooved 2.5 mm deep using a 3 mm diameter spherical milling tool. The plate, with the thermocouple in place, was clamped to the vessel and then metal-sprayed in position. The spray coating and plate were ground to a smooth finish. This held each thermocouple tightly to the vessel surface and protected it from direct flame impingement. The thermocouples were positioned as shown in Figures 6 and 7 in terms of their horizontal position left or right of the central weld and the angle from the top around the circumference of the vessel. It was not possible to place the thermocouples symmetrically at the top and bottom of the vessel because of the positions of the valves and support legs.

EXPERIMENTAL PROCEDURE

Before each series of trials, the system was flushed and clean nozzles were fitted in the appropriate pattern. The water pressure was set and checked for correct operation. After starting the deluge and allowing the spray pattern to be established, the propane supply valves were opened and propane ignited. Thereafter, the flame pattern and its effect on the tank were observed and recorded. For the delayed deluge initiation trials, the flame was first established and after the required delay time the water was started and observations made on whether the vessel was adequately cooled. The delay times quoted are the times from ignition of the propane to full water pressure being achieved. The water deluge target tank was heated until one of the following conditions prevailed:

(i) The tank shell temperatures stabilised at close to 100 ^{o}C or less, and no dry spots were observed on areas of the vessel surface remote from the thermocouple locations, showing that the water deluge was effective in protecting the tank;

(ii) One or more of the tank shell or support feet temperatures exceeded 200 ^{o}C and continued to climb, showing that the water deluge was not effective in protecting the tank; or

(iii) Dry spots were seen to develop on areas of the tank surface remote from the thermocouple locations, showing that the water deluge was not effective in protecting the tank.

In order to minimise any damage to the vessel, the tests were stopped as soon as the temperatures had stabilised or it was clear that they were not going to stabilise. The deluge was continued after the flame was extinguished until the vessel returned to ambient temperature.

For the validation trial on the 20% full propane vessel, before the vessel was filled, the plastic and aluminium level gauge (in the top of the vessel) was replaced by a steel blanking plate in order to prevent premature failure. The water spray was started and set to 2 barg water pressure. The water deluge system was established and stabilised at the required settings before application of the jet fire. The criteria used for the deluge system being effective in protecting the vessel were that the shell temperatures should not exceed 100 ^oC and no dry spots should develop. The test would be terminated if:

(i) Dry spots were formed.
(ii) Any of the measured temperatures exceeded 120 ^oC.
(iii) Any of the fittings, e.g. pressure relief valve, showed signs of failure.

Towards the end of the trial, the water deluge was turned off for one minute and then restarted to ascertain if the vessel temperatures would recover. Approximately 5 s was required for the water pressure to build from 0 barg to 2 barg or decay from 2 barg to 0 barg. One minute was chosen as the interval for interruption of the water supply. This was the time required for the vessel surface to reach 300 ^oC and was considered sufficient to observe any dry spots, which might have been obscured from the monitoring cameras by the steam and flames. The nominal temperature of ca. 300 ^oC was chosen because, above this, damage to the target vessel was expected to occur. The water deluge was allowed to continue after the flame was extinguished until the vessel surface returned to ambient temperature.

For the nominally empty vessel trial, the vessel was emptied of propane and the pressure transducers and emergency dump line were removed. A plug was removed from the top of the vessel to prevent pressure build up. The plastic and aluminium level gauge was re-inserted in the top of the vessel to determine if the deluge provides sufficient protection of the gauge. The same operating procedure was used as for the filled vessel except that the test was terminated if the shell temperature exceeded 300 ^oC rather than 120 ^oC.

EFFECTIVENESS OF THE MINIMUM RECOMMENDED RATE

The effectiveness of the deluge system designed to give the minimum recommended rate was assessed using five different propane release stand-off distances (1.0, 2.5, 3.0, 3.5 and 4.5 m). In order to help avoid damaging the vessel, these trials were performed with the vessel 20% full of water. The initial trials, at a water deluge pressure of 2.0 barg, indicated that the system was not capable of protecting the vessel. The most severe effects to the vessel occurred at a propane stand-off distance of 1.0 m, giving most heat input to the back of the target vessel, and at 3.0 m giving most heat input to the front. The water pressure was then increased in steps to determine if, at higher flow rates, the vessel could be protected using the original nozzle arrangement. Water pressures of 2, 3, 4, 6 and 7.3 barg (the maximum available at the time) were used. The maximum temperatures (over 100 ^oC) at each circumferential angle are summarised in Table 3, and the maximum temperatures for each pressure are plotted in Figure 8.

At higher water discharge pressures of 6 barg and above), the recorded maximum temperatures fell broadly within the conditions (i) specified for the tests. However, the variation in temperature profiles indicated that the deluge system was not fully controlling the jet fire. The tank temperatures below the water fill level only exceeded 100 ^oC at the right hand end of the vessel and on the legs. This confirmed that the vapour space wall of the vessel is that which is most vulnerable to excessive heating.

Table 3. MAXIMUM TEMPERATURES FOR TRIALS WITH 3.0 M STAND-OFF

Test No.	Water pressure (barg)	Temperatures over 100 ^oC (angle at each circumferential position*)								
		A	B	C	D	E	F	G	H	Leg
W26	2				210 (045)	250 (045)	325 (022)	440 (045)	160 (180)	500(R)
W25	3						132 (022)	380 (045)		390 (R)
W24	4				230 (045)	375 (045)	360 (022)	275 (045)		235 (R)
W23	6							125 (045)		170 (R)
W22	7.3					220 (045)	130 (022)	170 (045)		170 (R)

* 0^o = top, 090^o = front, 180^o = bottom and 270^o = back

EFFECTIVENESS OF SYSTEM NOMINALLY DESIGNED TO THE TENTATIVE RULES

The effectiveness of the deluge system designed to give the minimum recommended rate was assessed using five different propane release stand-off distances (1.0, 2.5, 3.0, 3.5 and 4.5 m). As the trials on the deluge system designed to give the minimum recommended rate indicated that the maximum heat transfer to the target vessel occurred at 1.0 and 3.0 m propane release stand-off distances, these were used for the trials on the deluge system designed to the Tentative Rules. The system was run at water pressures of 1.4, 2.0, 2.7 and 3.5 barg; i.e within the range permitted by the Tentative Rules. As noted above, due to the effect that the water fill has, it was decided to use the target vessel empty for subsequent trials in order to be able to detect any hot spots at the base of the vessel.

No temperatures over 100 ^oC were recorded and no dry spots were observed in any of the trials performed with a water pressure of 2.0 barg or more. Even at 1.4 barg water pressure, there were no temperatures of more than 112 ^oC recorded, although visual observation indicated a dry spot in the trial with a 3.0 m stand-off distance. The results of the trials at 1.4 and 2.0 barg water pressure and with a 3.0 m stand-off distance are compared in Table 4.

Table 4. MAXIMUM TEMPERATURES FOR TRIALS WITH 3.0 M STAND-OFF

Test no.	Water pressure (barg)	Time (min)	Maximum temperature (Celsius) at measurement time (angle at circumferential position - see Figure 6)								
			A	B	C	D	E	F	G	H	Leg
W84	1.4	6	93 (000)	98 (045)	112 (045)	101 (045)	95 (000)	98 (022)	91 (045)	76 (000)	80 (L)
W85	2.0	6	71 (180)	100 (045)	96 (045)	99 (045)	93 (090)	95 (045)	94 (045)	52 (180)	66 (L)

The results suggest that, for the 3.0 m jet-fire stand-off distance, a water deluge pressure of 1.4 barg does not prevent formation of dry spots but pressures of 2.0 barg or more are effective.

EFFECT OF BLOCKED NOZZLES

A survey by Blything[12] of LPG installations fitted with water deluge systems suggested that at least one blocked nozzle was likely to be found on every installation and a reasonable probability of two. Given the relatively high risk of such an occurrence, it was considered advisable to investigate the effects of blocked nozzles. The triangle of nozzles 1.5 m from the right end of the frame were chosen for the trials as any wind tended to skew the flames in this direction. Hence, to determine the effect of blocked nozzles, nozzles 11 (top), 3 (front) +11 (top) and 3 (front) + 7 (back) +11 (top) (see Figure 3) were blocked off in turn. A 2.0 barg water pressure was used with propane jet release point stand-off distances of 1.0 and 3.0 m.

With the top nozzle (11 - see Figure 3) blanked-off, a large dry spot, which extended down the front of the vessel at the F band and towards the E and G bands, started to form after 2 minutes. The maximum temperatures in the E, F and G bands are illustrated in Table 5 with temperatures over 100 ^{o}C highlighted.

Table 5. MAXIMUM TEMPERATURES (^{o}C) WITH ONE TOP NOZZLE BLOCKED

Position	Front	E	F	G	Back	E	F	G
Top	**0^{o}**	231	379		**0^{o}**	231	379	
	22^{o}	136	438		**337^{o}**	-	165	
	45^{o}	93	423	94	**315^{o}**	92	95	92
	67^{o}				**292^{o}**	93		
Middle	**90^{o}**	92	91		**270^{o}**	85	88	
	112^{o}				**247^{o}**		88	
	135^{o}	80	82	85	**225^{o}**		83	
Bottom	**180^{o}**	80	85		**180^{o}**	80	85	

In the trial (W72) with the top (11) and front (3) nozzles blocked (see Figure 3), dry spots developed within 20 s and the temperatures exceeded 300 ^{o}C in the E, F and G bands. The maximum temperatures recorded are indicated in Table 6 with temperatures over 100 ^{o}C again highlighted.

Table 6. MAX. TEMP. (^{o}C) WITH ONE TOP & FRONT NOZZLE BLOCKED

Position	Front	E	F	G	Back	E	F	G
Top	**0^{o}**		386		**0^{o}**		386	
	22^{o}	221	488		**337^{o}**		192	
	45^{o}	199	499	95	**315^{o}**	94	98	95
	67^{o}				**292^{o}**	94		
Middle	**90^{o}**	392	447		**270^{o}**	86	91	
	112^{o}				**247^{o}**		90	
	135^{o}	277	323	372	**225^{o}**		87	
Bottom	**180^{o}**	133	118		**180^{o}**	133	118	

With three blanked-off nozzles(3, 7 and 11 - see Figure 4), dry spots were first noted after 25 s on the F band. The dry spot increased in area around the front of the vessel and then extended round to the back of the vessel. The temperature reached 400 ^{o}C at the F 22^{o}, E 90^{o} and G 135^{o} positions in less than 3 minutes. The maximum temperatures are illustrated in Table 7 with temperatures over 100^{o}C again highlighted.

The results from the single blocked nozzle trials suggest that the water film breaks-down in the region of the blocked nozzle, resulting in a dry patch. The shell temperature in the dry patch can reach a temperature at which there is a significant reduction in steel strength. Hence, even with a single blocked nozzle, there is a real risk of vessel failure in a jet fire, although whether that would inevitably lead to catastrophic failure is unknown at this time.

Table 7. MAX. TEMP. (^{O}C) WITH 1 TOP, FRONT & BACK NOZZLE BLOCKED

Position	Front	E	F	G	Back	E	F	G
Top	**0°**	255	438		**0°**			
	22°	290	488		**337°**		292	
	45°	224	483	193	**315°**	96	173	96
	67°				**292°**	97		
Middle	**90°**	468	470		**270°**			
	112°				**247°**		232	
	135°		371	413	**225°**	342	226	
Bottom	**180°**	226	314		**180°**	226	314	

With two or three adjacent blocked nozzles, large dry patches are formed. This would almost certainly allow the shell to reach the temperature (ca. 650 °C) where the vessel would fail. However, though large dry patches are formed, there is still a reduction (by at least a factor of two) compared to the corresponding unprotected tank trial[10] in heat transferred to the vessel. This suggests that additional time would be available, for example, to direct water from a portable fire pump onto the dry patch. It is not clear from the available data as to how effective this would be.

EFFECT OF DELAYED DELUGE INITIATION

Deluge systems may be triggered automatically by gas or flame detection or manually. In most cases, it is likely that a vessel may be enveloped in fire before the deluge system comes fully into action. Accordingly, a series of trials were performed in which the target vessel was enveloped in flame prior to the application of water. The delay time was progressively increased from 17 s to 160 s. The nominal 2 kg s^{-1} propane jet fire used will cause some regions of an unprotected vessel wall[10] to reach temperatures of ca. 650 °C in 160 s. At this temperature, there is a significant risk of catastrophic vessel failure.

Lev and Strachan[13] suggest that 120 °C is the critical steel substrate temperature at which there is breakdown of a water film. The results suggest that the unprotected vessel shell needs to be heated for about 25 s to reach this temperature. Hence, as might be expected, there was full recovery (all shell temperatures at or below 100 °C) with a 17 s and, initially, a 24 s delay. However, in the 24 s delay trial, the temperature started rising after 3 minutes at the F 45° position and reached 208 °C after initially cycling between 100 and 120 °C. In general, dry patches were difficult to see through the flames. However, in this case, visual observation suggested that there was a small dry spot immediately downstream of the thermocouple housing. This may imply that small protrusions on the vessel surface, e.g. from a type approval plate, can have a significant effect on the water film and hence the degree of protection. This effect was not observed in the 32 s delay trial. However, in this case, the temperature at the E 180° position (bottom of vessel) reached 120 °C after two minutes and stayed at this temperature until the flames were extinguished. It is possible that any "shadow" effects are magnified if the vessel is heated above 120 °C before applying the water. In the trial with 44 s delay, all the temperatures recovered to 100 °C except at the 45° position at the centre/front of the vessel where they reduced to 120 °C. However, in the 63 s and 100 s delay trials, all the temperatures recovered within 75 s of applying the water. In the final delay trial (160 s), the vessel was taken to over 600 °C before applying the water. Even under these extreme conditions, where an unprotected vessel would fail[9] within another 90 s, the temperature fell to 100 °C at most, although not all, measuring points. At one position, the temperature reached 299 °C and the temperature was still increasing at about 0.7 K s^{-1}. Hence the vessel was kept at temperatures below which there was no loss in steel strength for delayed deluge application times up to 100 s. It was found, therefore, that recovery (i.e. all temperatures $\leq$ 100 ^{o}C) was possible for delay times up to 100 s but this could not always be relied upon.

EFFECT OF THE VESSEL CONTENTS

The previous phases of the experimental work utilised an unpressurised vessel as the jet-fire target. In addition, most of the trials described in the open literature involved using, either water filled or empty, unpressurised target vessels and, therefore, it was considered that validation trial(s) on a vessel filled with propane should be performed. The trials were designed to demonstrate that a water deluge system, shown to protect an unpressurised vessel against a ca. 2 kg s^{-1} flashing liquid propane jet fire, will be effective when applied to a 20% full propane vessel. Two trials were performed:

(a) A remote controlled long duration trial on a 20% full propane vessel to determine the effectiveness of the system developed;
(b) A long duration trial on the empty vessel to determine if the vessel contents influenced the results and to allow close observation of the system behaviour.

Each trial incorporated a one-minute period, with the water diverted away from the vessel, to determine if recovery (i.e. all shell temperatures decreasing to 100 ^{o}C or below) occurred.

20% FULL VESSEL

The temperatures at bands B, C, D, E and F were reasonably stable, remaining under 100 ^{o}C whilst the water deluge was on (for example, see the band D temperatures in Figure 9). The highest shell temperatures experienced by the vessel during the deluge were at the 45^{o} and 90^{o} circumferential positions (on all bands) and the lowest were at the bottom-back of the vessel. All the temperatures of the shell and fittings remained below 100 ^{o}C until the water was diverted away from the vessel for one minute after 40 minutes. A photograph showing a typical fire engulfment is shown in Figure 10.

At 40 minutes, whilst the water deluge was diverted for one minute, temperatures around the bottom of the vessel rose typically by about 25 ^{o}C. This was true for bands B, C, D, E and G particularly at a circumferential position of 315^{o}. Temperatures around the top of the vessel stayed around 100 ^{o}C except at the B and F 90^{o} positions. Here, a hot spot developed and a temperature of 163 ^{o}C was recorded at 41 minutes, just before the water deluge was restored. For the next minute, the temperature continued to increase to 235 ^{o}C (though the water deluge had been reapplied) but, within a further minute, this had returned to under 100 ^{o}C. Thermocouples on or between the valves also recorded temperatures over 100 ^{o}C whilst the water deluge was off. These results were consistent with the results from the 63 s delay time trial but not with the 24 s trial where a significant temperature excursion occurred.

At 41 minutes, the combination valve registered a temperature of 157 ^{o}C and the vessel shell adjacent to the combination valve registered a temperature of 105 ^{o}C. Over the next minute, both increased in temperature to 231 ^{o}C and 153 ^{o}C, respectively, recovering to below 100 ^{o}C when water was reapplied.

The pressure relief valve (PRV) opened after nearly 20.7 minutes at a pressure of 18.2 bara (see Figure 11). It remained open for about 40 s before closing at 15.1 bara. The pressure then rose to 17.9 bara when the PRV opened again. The PRV cycled open and shut 5 times during the trial with the opening pressure slightly lower each time but the closing pressure staying fairly constant. The cycling rate reduced in frequency as the trial progressed but increased again whilst the water was off.

The results suggested that the water deluge system had given 40 minutes fire protection and that this would be maintained as long as water could be supplied at the required rate.

EMPTY PROPANE TANK

The temperatures at bands B, C, D, F and G were reasonably stable, remaining under 100 ^oC until the water deluge was first turned off at 24 minutes. The only exception was at the band E 45^o position (see Figure 12). At this position, the temperature rose above 100 ^oC after 9.9 minutes and reached 163 ^oC after a further 30 seconds and then decreased to 100 ^oC before beginning a major temperature excursion. The temperature reached a maximum of 359 ^oC at 14 minutes and then reduced to below 100 ^oC after a further 3 minutes and remained below 100 ^oC until the water was diverted at 24 minutes.

When the water was diverted at 24 minutes, the shell temperatures rose rapidly reaching a maximum of 410 ^oC at the C 45^o position. The maximum temperatures at each band were all close to the 45^o position. When the water was restored to the spray nozzles, the temperatures at all positions, except the 180^o positions, were reduced to below 100 ^oC. At the C, D and E bottom (180^o) vessel positions, the temperature reached 185, 237 and 240 ^oC respectively, by the times the flames were extinguished. This corresponded to observed dry spots. Similar behaviour, with the 180^o position temperatures exceeding 100 ^oC was observed in the 32 s and 160 s delay time trials. Hence it appears that, with the deluge system used, hot spots that do not recover on application of water can develop along the bottom of an empty vessel.

The top fittings reached a maximum temperature of 91 ^oC before the water was diverted at 24 minutes. The bottom fittings and legs reached a maximum of 88 ^oC. The front of the PRV reached 328 ^oC when the water was diverted and the front left leg reached 195 ^oC. All the top and bottom fittings, and the legs, recovered to below 100 ^oC when the water was restored. The level gauge, made from aluminium with a plastic lens and Viton seal, was subjected to the empty vessel test (W90) and a subsequent 10 minute demonstration trial (W91) included a total of two minute fire engulfment without water deluge protection. The plastic lens melted but both the aluminium body and the Viton seal remained undamaged. It is likely that it would have continued to hold the pressure if the vessel had contained propane. During the empty vessel trial (W90), the brass pressure relief valve on top of the vessel was subjected to the full protected period of the test and one minute of fire engulfment. Shortly after the jet flames were extinguished and whilst the water deluge was still operating, the PRV spring popped and fell on the floor allowing the valve to remain open. The brass retaining / adjusting ring had distorted causing the threads to disengage.

COMPARISON OF FULL AND EMPTY VESSEL

It would be expected that the biggest differences in temperature would be at the bottom of the vessel since, at this position, the shell of the vessel containing propane will be cooled by the liquid propane inside the vessel as well as the water on the surface. The mean temperatures at the 180^o position were nearly 20 ^oC lower for the 20% full vessel than for the empty vessel.

COMPARISON WITH DELUGE SYSTEM DESIGNED IN ACCORDANCE WITH NFPA 15

HSE had sponsored work (Bennett[14] et al.) to investigate the fire protection afforded by a water deluge system designed to NFPA 15 on a LPG vessel. The vessel had the following dimensions: length of parallel section 7.50 m; depth of end caps 0.64 m; diameter of tank 2.17 m; and area of tank 61.3 m^2. The deluge system was nominally designed for an offshore facility (Shirvill and White[15]) to achieve a minimum application rate of 10.2 $dm^3\ m^{-2}\ min^{-1}$ over the whole exposed surface of the vessel. The deluge system comprised four rows of six stainless steel nozzles (7.4 mm bore, 110^o spray angle, K factor 34) with ca. 0.65 m stand-off distances. The total water delivery rate was 1064 $dm^3\ min^{-1}$. A 2.4 barg inlet line pressure was used to give a pressure of 1.4 barg at the furthest nozzle. The calculated mean pressure for the system was 1.57 barg. The application rate was therefore nominally 1064 / 61.3 = 17.4 $dm^3\ m^{-2}\ min^{-1}$. Subsequent characterisation of the system by Davies and Nolan[9, 10] indicated that the actual coverage varied widely over the surface of the vessel, with spot readings as low as 2.6 $dm^3\ m^{-2}\ min^{-1}$ recorded at the top of the vessel. A photograph showing the deluge system in operation is presented in Figure 13.

The tests involved a wider range of propane jet sizes, extending up to 9 $kg\ s^{-1}$. The results with a ca. 2 $kg\ s^{-1}$ propane jet, at 1.0, 3.0 and 5.0 m propane release stand-off distances (the jet was aimed at the centre of the vessel), were similar to those obtained in the HSL trials using the water deluge system designed to deliver the minimum recommended rate when run at 4 barg. This, with a calculated application rate of 16.6 $dm^3\ m^{-2}\ min^{-1}$, most closely compares with that for the NFPA system of 17.4 $dm^3\ m^{-2}\ min^{-1}$. In both, hot spots (temperatures above 120 ^oC) were observed near to the top of the vessel. Similar results were obtained using a 6 $kg\ s^{-1}$ propane jet. With the 9 $kg\ s^{-1}$ propane jet hot spots were recorded in the region of the centre/front of the vessel.

The 17.4 $dm^3\ m^{-2}\ min^{-1}$ calculated application rate was considerable lower than the 31 $dm^3\ m^{-2}\ min^{-1}$ shown by HSL to be required to protect an empty shell against a 2 $kg\ s^{-1}$ jet fire.

CONCLUSIONS

The overall conclusions were as follows:

- Existing industrial directed water deluge systems cannot be relied upon to maintain a water film over the whole of the surface of a vessel in an impinging jet scenario. However, by using additional water (up to double) to the amount normally applied, protection can be provided against at least a ca. 2 $kg\ s^{-1}$ flashing liquid propane jet fire. Protection might be achieved with lower amounts of water if the deluge system was optimised to give the greatest and most uniform surface water flow rate. At present, no guidance or design tools appear to exist, which allow such optimisation.
- The evidence suggests that industrial deluge systems may be designed to the Tentative Rules or NFPA 15 or to an ad hoc design. Systems designed according to NFPA 15 have fewer restrictions on the nozzle specification and spacial arrangement and, in practice, are likely to deliver less water than a system designed according to the Tentative Rules.
- The apparent current practice of designing directed water deluge systems on the basis of the water exiting the spray nozzles masks the variation in water coverage of the vessel that occurs and is therefore considered to be a poor measure. It is recommended that, instead, the amount of water actually flowing over the surface of the vessel should be used in the design specification.
- The successful performance of directed water deluge systems has been found to be critical upon all the spray nozzles functioning correctly and the deluge system coming fully into action within 100s.
- Indications are that careful attention needs to be given to the provision of additional spray nozzles to protect vessel fittings and where obstructions, such as gantries are present, to ensure they do not disrupt the required flow of water over the vessel surface.

- The above conclusions suggest there is clear need for improved validated guidance on the design of directed water deluge systems.
- The conclusions given above relate to deluge systems for horizontal, cylindrical vessels. Whilst guidance is given in the Tentative Rules for spherical vessels, there is no validation of the requirements. There appears to be no United Kingdom guidance at all on vertical, cylindrical vessels.

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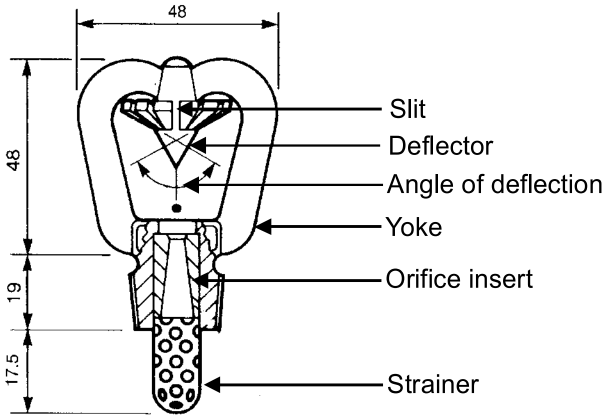

Figure 1. MEDIUM VELOCITY NOZZLE

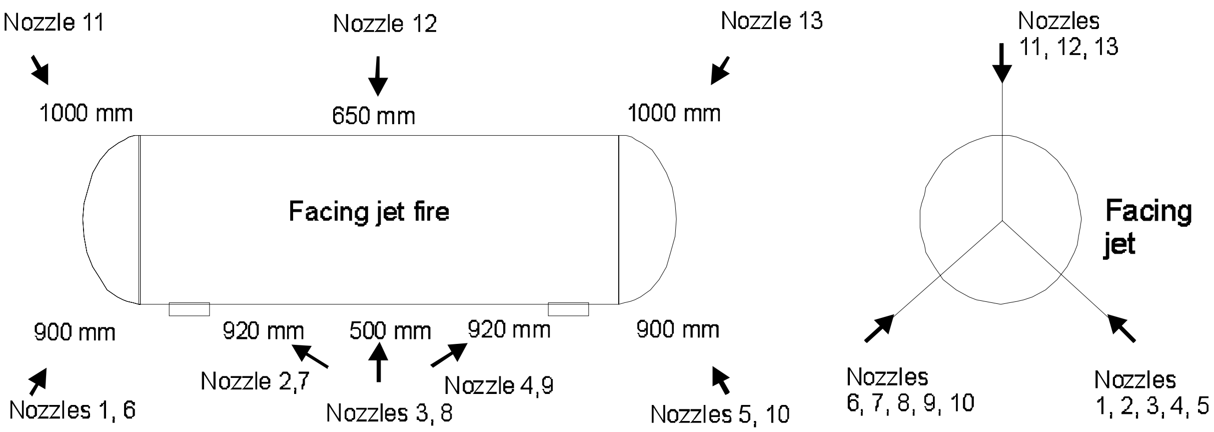

Figure 2. NOZZLE ARRANGEMENT TO GIVE HSE MINIMUM RATE

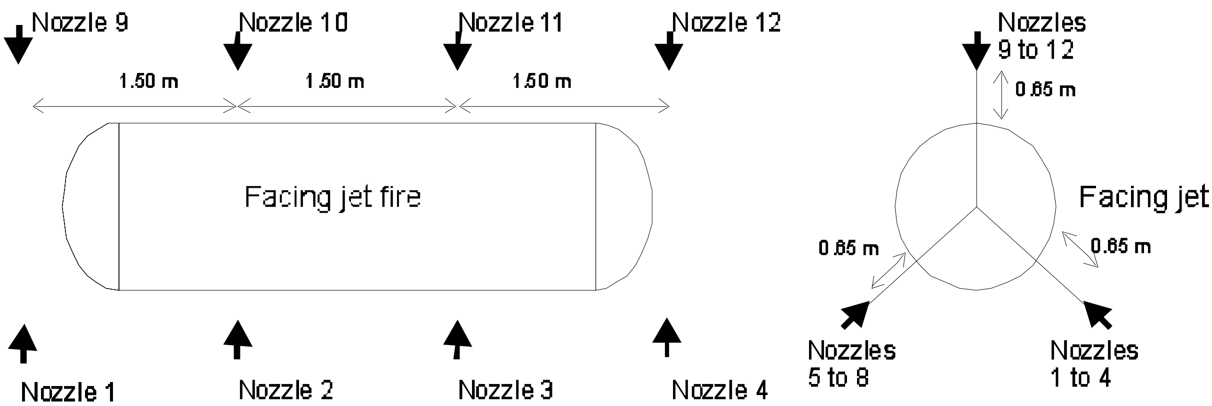

Figure 3. NOZZLE ARRANGEMENT TO GIVE TENTATIVE RULE RATE

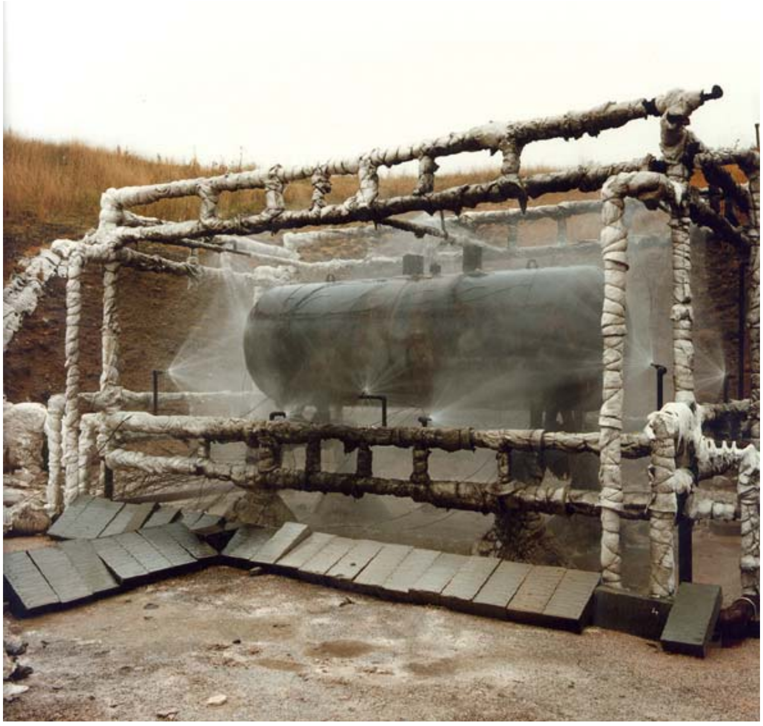

Figure 4. MINIMUM RATE SPRAY PATTERN ON UNPRESSURISED VESSEL

Figure 5. TENTATIVE RULE SPRAY PATTERN ON 20% FULL PROPANE TANK

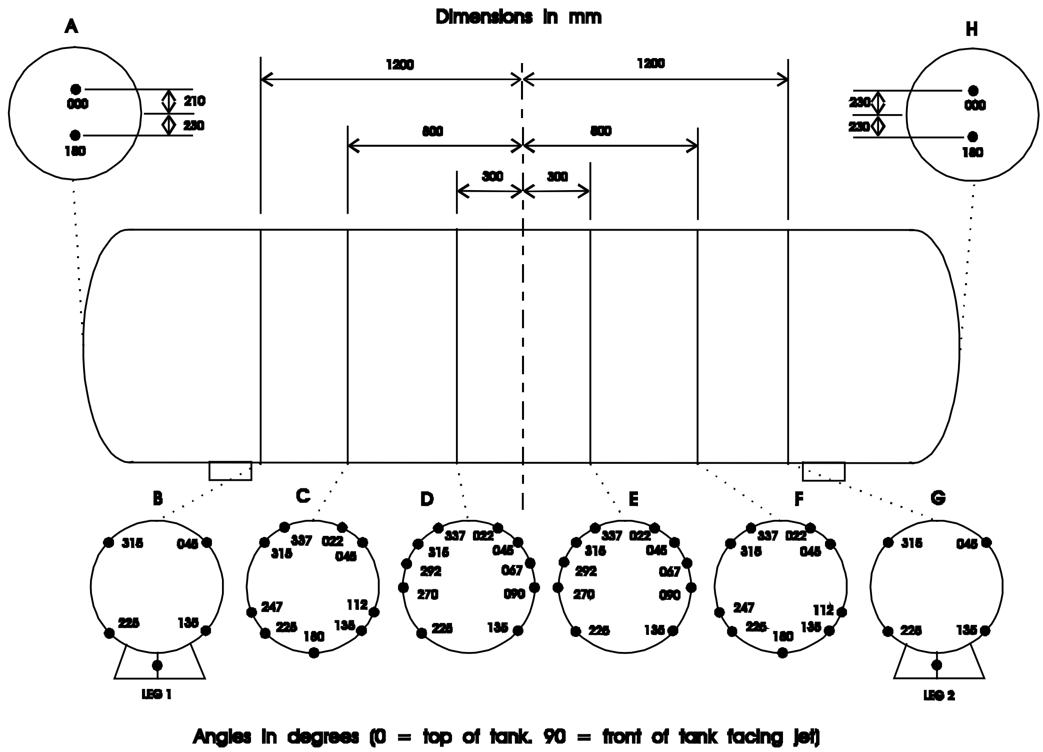

Figure 6. THERMOCOUPLE POSITIONS ON UNPRESSURISED VESSEL

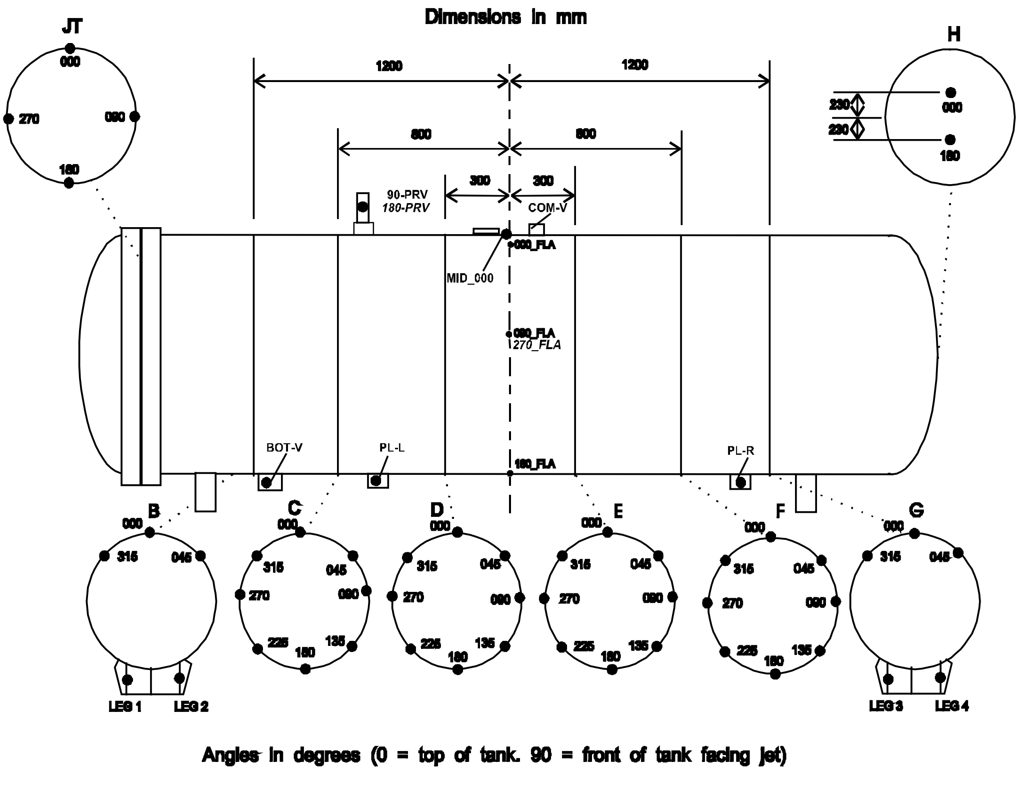

Figure 7. THERMOCOUPLE POSITIONS ON PROPANE TANK

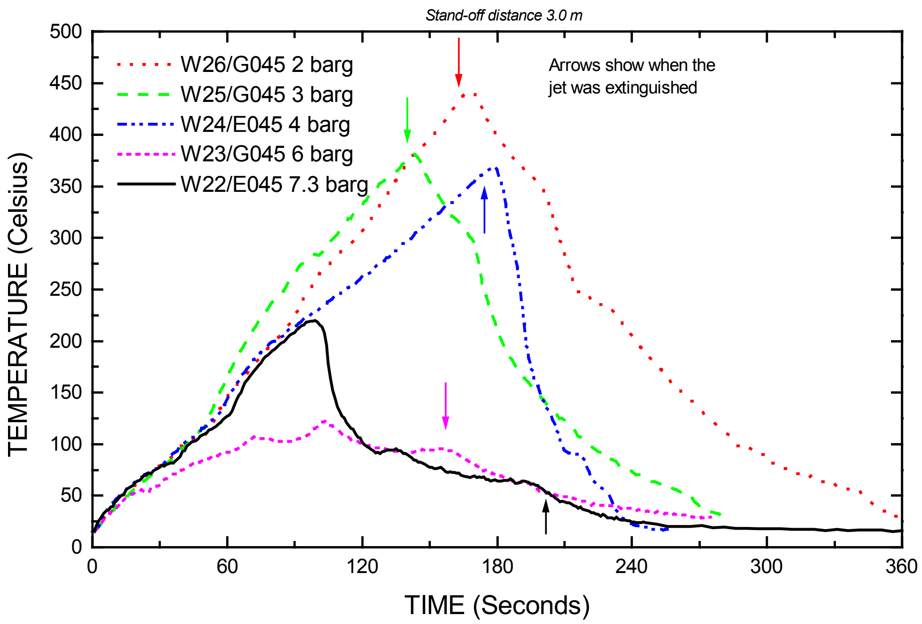

Figure 8. MAXIMUM SHELL TEMPERATURES VS. WATER DELUGE PRESSURE (Recommended minimum rate system with 3.0 m propane stand-off)

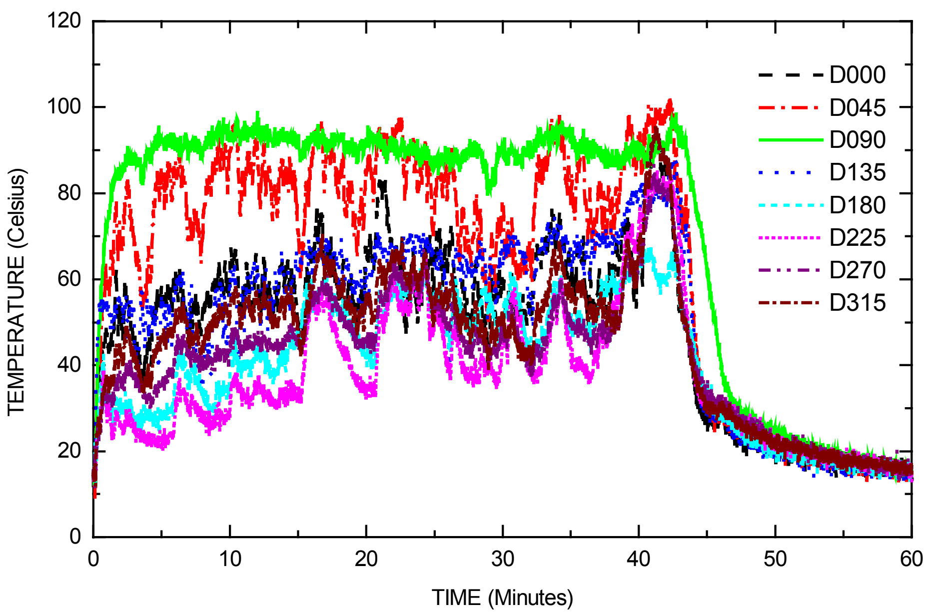

Figure 9. 20% FULL PROPANE TANK: MAX. BAND D SHELL TEMPERATURES (Tentative Rule system with 3.0 m propane stand-off)

Figure 10. FIRE ENGULFMENT OF 20% FULL PROPANE TANK

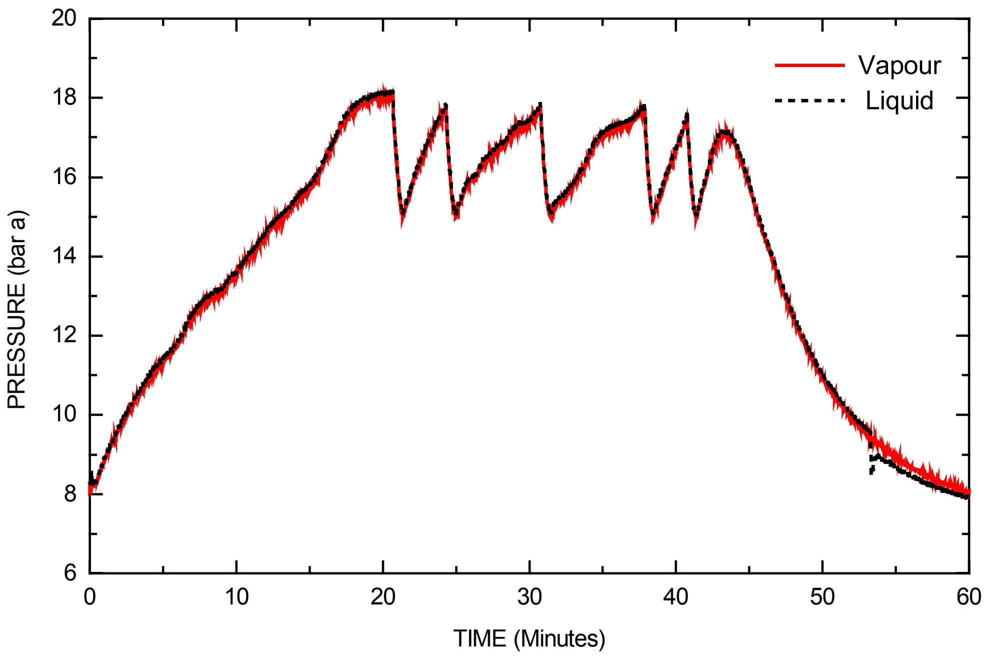

Figure 11. PROPANE VAPOUR AND LIQUID PRESSURES

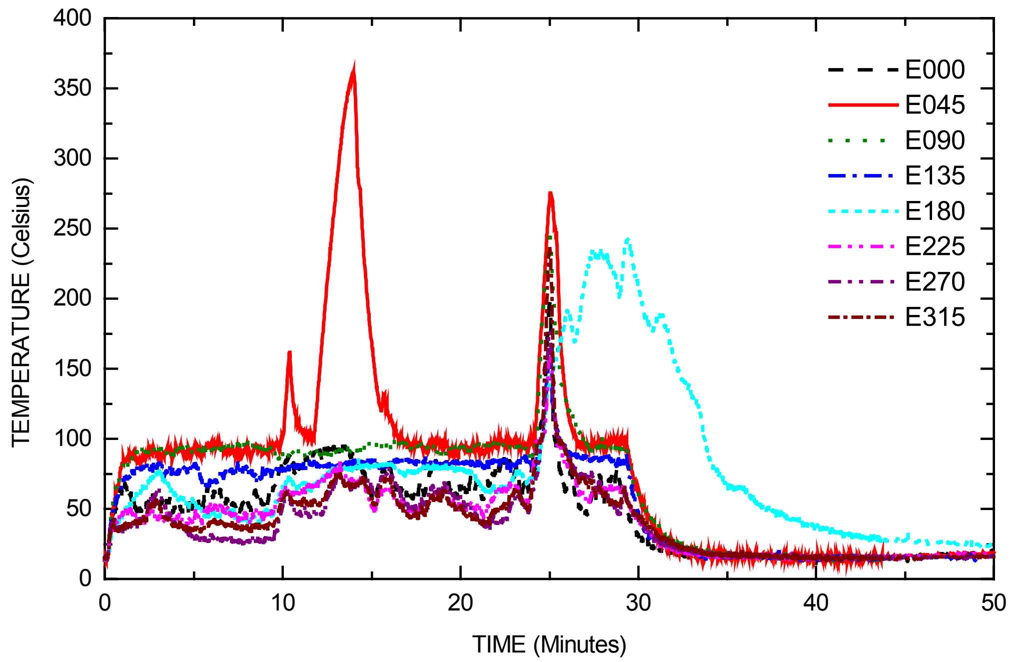

Figure 12. EMPTY TANK BAND E SHELL TEMPERATURES (Tentative Rule system with 3.0 m propane stand-off)

[Courtesy of J Bennett, Shell Global Solutions]

Figure 13. SHELL DELUGE SYSTEM: FLAMES FROM 2 KG S^{-1} PROPANE JET