Characterisation of a vehicle fire on a 7 tonne LPG road tanker

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INTRODUCTION

Since 2013, there have been two incidents involving 7 Te LPG road tanker vehicle fires in the UK. The first event occurred in 2013 on the A1 in Northumberland near Belford; several Fire and Rescue Services attended the scene and an area of 1000 m radius was cordoned off with an exclusion zone resulting in long delays on the main route between the North East of England and Scotland. The Fire and Rescue Service attempted to keep the tank cool to reduce the likelihood of the 7 Te LPG tank failing and resulting in a Boiling Liquid Expanding Vapour Explosion (BLEVE). A second tanker was involved in an incident in August 2015, this incident occurred on the M56 near Chester resulting in a 1600 m exclusion zone being put in place around the vehicle. The exclusion was put into place as the Fire and Rescue Service could not approach the tanker due to safety concerns. As the Fire and Rescue Service could not tackle the vehicle fire it was allowed to burn out before approaching, this caused the M56 and the nearby railway line to be closed for 6 hours in both directions[2]. On both occasions there were no casualties and neither incident lead to a BLEVE event. However, in both cases the Fire and Rescue Service had to put into place large exclusion zones as little is known about the possible consequences of the vehicle fire impinging on the 7 Te LPG vessel.

More information is required by the Fire and Rescue Services to help best tackle similar incidents in the future. Statistics show that incidents like these, while uncommon, do occur. In March 2016, Bolton News reported that a road tanker carrying a flammable liquid had a near miss when the brakes stuck and caught fire whilst driving along the A666 in the Midlands. This could easily have led to a similar incident as the two LPG tankers and set the entire vehicle alight[3]. While the news article does not state that the tanker was carrying LPG, it highlights that these incidents have an increasing probability as more vehicles use the roads to transport hazardous products such as LPG[9].

The worst-case scenario resulting from a road tanker crash would be for the vessel on the back of the vehicle to fail and for BLEVE to occur. The exact definition of a BLEVE is often debated in research papers. The general description is that the event is a sudden, almost instantaneous, opening of a vessel and the explosive release of the contents[4]. BLEVE events can have catastrophic consequences which, in over 80 separate events, have claimed more than 1000 lives between 1940 and 2005. Not only have these events caused a large death toll they have also left thousands more people seriously injured[5]. Studies into previous incidents show that a fire heating the outside of the vessel, known as ‘hot BLEVEs’, caused 36% of BLEVE events. This is considerably higher than the second most common cause of failure that is mechanical damage to the skin, causing 22% of vessel failures, or ‘cold BLEVEs’. The fatalities and injuries recorded were caused by; rocketing fragments from the failure of the vessel, the blast wave from the initial explosion and thermal radiation from the ignited fireball.

RESEARCH METHODOLOGY

The vehicle was located on a remote test pad of the Spadeadam Testing and Research Centre in Cumbria, UK. The vehicle was positioned on a concrete pad with a steel bund under the wheels of the road tanker. Within this outer bund, an inner bund contained fuel to represent spilled fuel in a real event. The fuel bund was water filled, with a layer of diesel on the top to simulate a full fuel tank spill under the chassis, an additional volume of diesel was included to be representative of the propane contained in the pipework under the vessel. The diesel was poured into the bund under the road tanker to stop an unplanned BLEVE of the fuel tank or rupture of the propane pipework, the fuel tank was left without the fill cap and all pipework was drained prior to testing. The vehicle was ignited at three locations; in the engine bay, in the cab and in the diesel filled bund. The engine bay was ignited first and when fully engulfed the cab and the bund were simultaneously ignited to try to create the worst-case fire by gaining the highest heat fluxes concurrently. The fires were ignited using an electronic ignitor, petrol soaked rags and magnesium filings.

The instrumentation was set up to record the heat flux around the outer surface of the vessel using water-cooled calorimeters. Thermocouples were used to measure the vessel wall temperature and the flame temperature.

The calorimeter locations were chosen to provide information on the heat load distribution on the vessel from the vehicle fire. The fire from the chassis and cab provide a heat load at one end of the vessel and under the entire length of the vessel. The aluminium crash bars protect the hose boxes and fill points under the centre of the vessel; the LPG contents of these components are all potential fuel to the vehicle fire. As the majority of the fuel for the fire is below the centreline of the vessel the 20 calorimeters were all located on the bottom half of the vessel. A line of calorimeters ran along the bottom dead centre (BDC) line of the vessel, a second row were located along a line 25 % of the way up the height of the vessel and a third row along a line 50 % of the height up the vessel, Figure 1.

Type K stainless steel sheathed thermocouples, 3 mm diameter, were fitted into the vessel wall to a depth of 3 mm off the outer surface of the vessel to measure the temperature of the wall material. The wall temperature measurements help to understand the heat gain from the fire and with the characterisation of the fire when commissioning the burner array. These wall temperature thermocouples were located adjacent to all calorimeter locations and designated the same reference number.

At eight locations along the BDC of the vessel, a 1.5 mm diameter hole was drilled through the wall. 1.5 mm diameter stainless steel sheathed Type K thermocouples were inserted through the wall with the tip protruding 1 mm from the outer surface. These thermocouples measured the temperature immediately outside the vessel during the test. These thermocouples were located adjacent to all calorimeter locations and designated the same reference number.

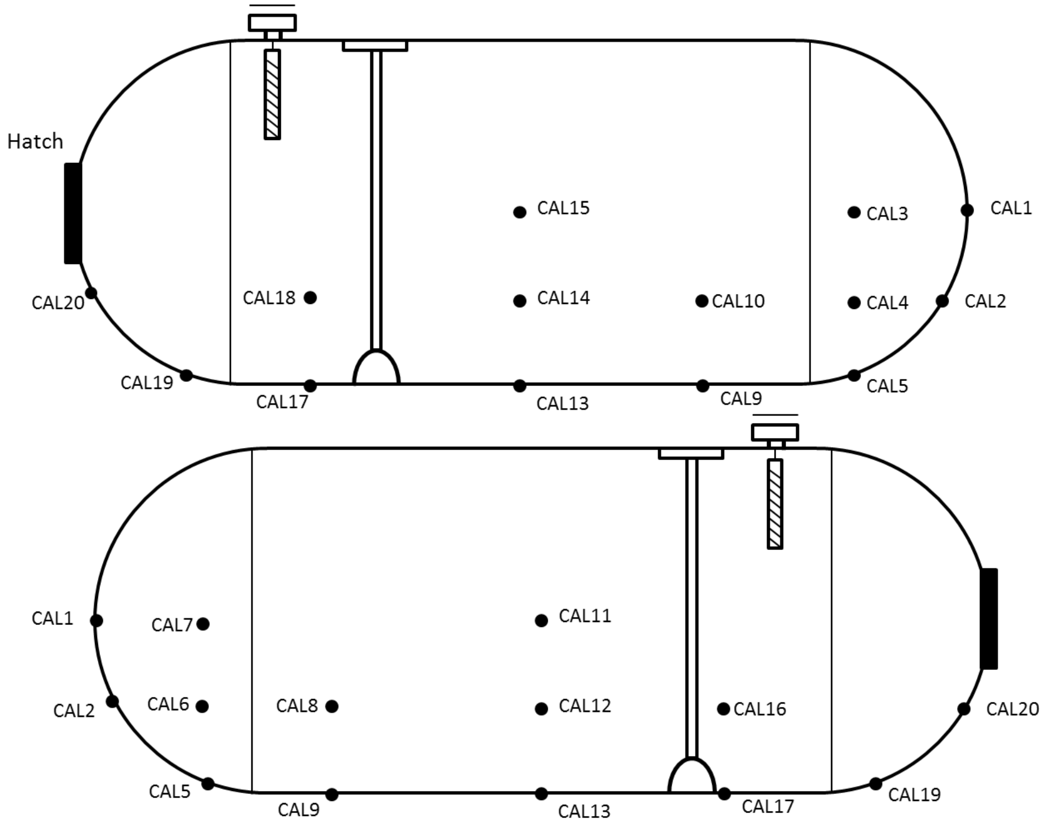

Figure 1- Locations of calorimeters, wall temperatures and flame temperatures

The vehicle was setup in a large bund, 6 m x 6 m, to capture any diesel or oil spills. A secondary 1.5 x 1.5 m bund was located under the centre of the vehicle by the diesel fuel tank. The bottom 150 mm of the bund was filled with water to prevent buckling from the heat during the fire and 300 litres of diesel was poured on top. The volume of diesel was calculated based on the volume of the fuel tank, engine pipework and the volume of the hoses under the vessel, which are usually filled with propane during normal transportation of the vehicle. The volume of propane was replaced with the same volume of diesel for ease of testing. It was expected that over the 2.25 m^2 area of the bund the diesel would burn at a regression rate of 1.5 mm.min^{-1}, this gave a predicted burn time of 40 minutes. The mass burning rate was calculated using Eq. 1.

$$\dot{m}'' = \frac{\rho_l \times R \times 10^3}{60} \qquad \text{Eq. 1}$$

Eq. 1 gives a mass burning rate of 0.022 kg.m^{-3}.s^{-1} using the density of diesel (ρ_l) as 885 kg.m^{-3} and the regression rate (R) of 1.5 mm.min^{-1}.

In the interest of safety prior to the test, all of the tyres on the vehicle were depressurised and holes drilled into the sidewalls to prevent an accumulation of pressure and subsequent explosion during the fire. The tyres provide high heat flux to the sides of the vessel so it was important to ensure this was directed onto the vessel walls by keeping the tyres attached to the vehicle. The batteries were removed from the vehicle to prevent harmful acids being released once engulfed in the fire. All of the fuel, coolant and oil tanks had caps removed to prevent the build-up of pressure and limit the likelihood of an explosion.

Three ignition devices were located around the vessel to ensure that all parts of the vehicle and the diesel pool fire ignited at the same time to generate the highest heat flux levels. The first device ignited was located inside the engine bay. This used a container of petrol and rags ignited using a remotely activated spark, the container was located beneath hoses and cabling to ensure the engine bay fully ignited. The second device was located inside the cab of the vehicle under the driver’s steering wheel, this too was a petrol-filled container ignited in the same way as the engine bay. Once the engine bay and the cab were fully engulfed, the diesel pool fire was remotely ignited from outside the exclusion zone and upwind of the fire.

RESULTS AND DISCUSSION

Vehicle Fire

The vehicle fire took place on 26th August at Spadeadam Testing and Research Centre. The vehicle was set up on the remote Test Site West location to allow for an exclusion zone of 50 m to the immediate area to protect personnel from the radiative heat from the fire, and a larger 200 m exclusion zone downwind of the fire was imposed due to the smoke hazard from the diesel pool fire and the burning vehicle.

A large plume of black smoke formed from the diesel pool fire and from the large volumes of rubber and plastic on the vehicle, Figure 2. The downwind exclusion zone allowed the smoke to disperse safely from the area.

Figure 2- Fully engulfed cab and diesel pool fire under vehicle

The wind was predominantly from the west throughout the test pushing the flames to the east side of the vehicle.

Figure 3 shows the difference between the downwind and upwind sides of the vehicle and vessel post-experiment. The downwind side was covered in a layer of soot up the entire vessel with the paint burnt, while the upwind side of the vessel shows far less damage with hazard signs still visible on the side. The heat from the diesel pool fire and the chassis fire has completely melted the aluminium crash barrier on the downwind side of the vehicle, which shows the temperatures experienced here were more than 660 °C, the melting point for aluminium. The diesel tank located on the downwind side of the vessel also burst during the fire and all of the plastic housings for the batteries entirely melted away. The tyres on both sides of the vehicle were left with only the wire inserts as the rubber had burnt away during the experiment.

The roller-shutter boxes containing 80 m of hose were left closed on both the upwind side of the vessel and the back of the vessel prior to the experiment. Both of these boxes and hoses remained intact during the fire and the hoses remained visibly undamaged. The hoses on the downwind side under the vessel were also still in place at the end of the experiment however they had suffered a large amount of damage from the flames.

Figure 3- Downwind (LHS) and Upwind (RHS)

The cab of the vehicle and the engine bay burnt out during the experiment. The windscreen melted during the experiment and flowed down the front of the engine. All of the seats and the fabric around the cab burnt. All of the flammable parts of the engine ignited and the heat of the fire caused aluminium parts to melt, including the steps up to the cab on the downwind side of the vehicle.

At the time of experiment initiation, the ambient air temperature was 15°C with a relative humidity of 77%. The wind was in a West North West direction at 20.4 km/h (5.7 $m.s^{-1}$).

The temperature measured in the flame in Figure 4 shows that the peak measured temperature was 540 °C at location FLT_17. FLT_17 was located to the south edge of the diesel bund and in close proximity to the two rear inner tyres. The videos show that the rear inner tyres were alight within 10-15 minutes of the ignition of the diesel pool fire which is prior to the time of peak temperature measurement. FLT_09 also saw a peak temperature of over 500 °C, this thermocouple was located close by the front set of tyres indicating that the peak temperature is from a combination of the diesel pool fire and the burning tyres. During the experiment the diesel in the 1.5 m x 1.5 m bund spilled out into the larger bund, this meant that the majority of the diesel had burnt after 30 minutes. The chassis and the tyres were still smouldering under the vessel until around 90 minutes when the tyres on the upwind side of the vehicle caught fire causing a series of flame temperature peaks in the data at FLT_09 and FLT_05, both close to the front tyres.

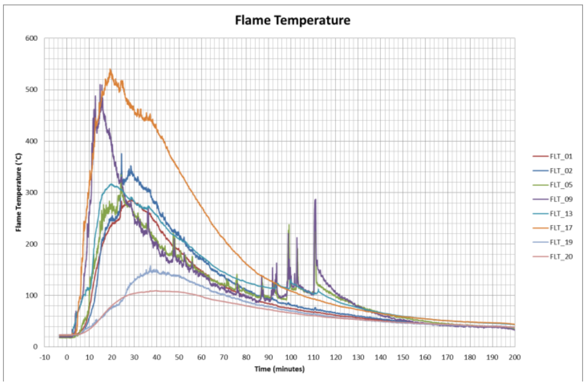

Figure 4- Flame Temperature

The wall temperature of the vessel peaked at 803 °C at thermocouple WT15 located on the mid-height line of the downwind side of the vessel, see Figure 5. The next three highest wall temperature measurements were WT10, WT14 and WT18, which are below WT15 on the downwind side of the vessel at one quarter of the vessel height. All three of these thermocouples measured temperatures in the steel of greater than the 600 °C. The ultimate tensile strength of the vessel would begin to diminish significantly past this temperature[8]. This implies that when the tank is at a lower fill level such as the 50% or 25% it is possible that the metal temperatures will be sufficiently high to result in a BLEVE of the vessel.

After around 16 minutes, the initial peaks from the diesel pool fire begin to the decrease. This is due to the diesel spilling out of the initial bund and covering a larger area increasing the rate at which the fuel was burning. Due to the slope of the bund all the fuel funnelled to the downwind side of the vehicle; this reduced the amount of flame around the vessel. After 40 minutes, much of the downwind vessel was at nominally 200-300 °C.

After 90 minutes, the temperature in the vessel increases again due to the front tyres, hoses and cables burning under the vessel.

The average temperature measured in the flame at each location shown in Table 2. The average temperature taken between 7.5 minutes and 8.8 minutes from the start of the test; where the heat flux was nominally steady on the calorimeters. The temperature measured in the flame continued to increase and peaked at around 27 minutes after the rear tyres started to burn.

Table 1 Temperature within the Flame at Steady State

Position	Temperature (°C) at steady state
FLT_01	42.1
FLT_02	35.6
FLT_05	52.7
FLT_09	148.5
FLT_13	103.0
FLT_17	238.8
FLT_19	33.9
FLT_20	28.9
Average	85.4

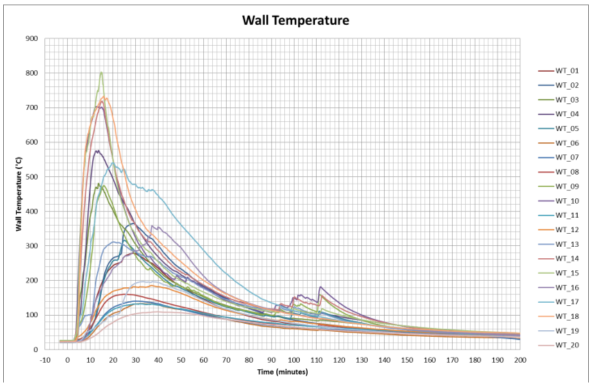

Figure 5- Wall Temperature

The average wall temperatures at each location are shown in Table 2. The average temperature was taken between the same nominally steady state heat flux region of 7.5 minutes and 8.8 minutes from the start of the test. These wall temperatures continued to increase and peaked at around 13.5 minutes, after this point the majority of the diesel pool, engine bay and drivers cab had burnt away, only the underside of the chassis and tyres continued to burn. WT_10 which was located above the front tyre on the downwind side of the vessel began to show temperatures that are close to the 600°C threshold.

Table 2 Wall Temperature Average Values at Steady State

Position	Temperature (°C) at steady state
WT_01	43.48
WT_02	35.60
WT_03	269.16
WT_04	294.54
WT_05	40.43
WT_06	29.73
WT_07	36.06
WT_08	44.58
WT_09	142.79
WT_10	569.78
WT_11	36.77
WT_12	56.48
WT_13	98.67
WT_14	458.91
WT_15	562.34
WT_16	36.30
WT_17	202.44
WT_18	586.29
WT_19	47.39
WT_20	27.28
Average	181.0

The calorimeter data shows a spike in the heat flux readings of over 650 kW.m^{-2}, see Figure 6. This is likely an anomaly as it is higher than could be reasonably expected in a pool fire or vehicle fire. This could be due to the instrument cabling being exposed to high radiative heat and being damaged. After 80 minutes all of the calorimeters return to zero, the calorimeters do not show a spike in the heat flux around 90 minutes as seen on the thermocouples when the tyres ignite downwind. The data for each location has been analysed focusing on the first 80 minutes.

Generally, the peak heat flux on the vessel is around 200 kW.m^{-2} and occurs in the first 10 minutes from the start of the experiment. This is consistent with previous published values for surface emissive power from pool fires on land[7].

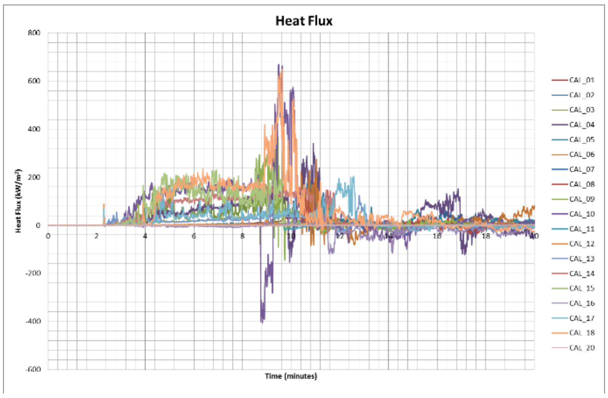

Figure 6- Measured heat flux for first 40 minutes

The calorimeters along the BDC of the vessel recorded negligible readings in comparison to those further up the vessel wall. The most likely cause of the comparatively low temperatures measured at some calorimeter locations is much of the material underneath the vehicle is metal and non-flammable. This material is acting as a protective barrier to radiant heat from the pool fire and tyre fire. The air gap between the vessel and the chassis is also allowing the wind to flow between the fire and the vessel wall, which could also be reducing convective heat flux on the centreline of the low parts of the vessel.

The upwind calorimeters show limited heat flux on the vessel. At the time of testing the wind speed was 5.7 m.s^{-1} in a WNW direction. The wind was pushing most of the flame to the east side of the vessel. The peak in heat flux registered on some sensors at around 20 minutes onwards coincides with the front tyres taking fire. In a lower wind speed the flame from a diesel spill, or in this experiment from the diesel bund, would be more evenly distributed up both sides of the vessel.

The downwind side of the vessel saw much higher heat flux in the first 20 minutes of the fire compared to the upwind side. The heat flux on the downwind side of the vessel was around 200 kW.m^{-2} this is around the expected value for a pool fire. If there was no wind during a vehicle fire then the total heat gain of the vessel could be higher as the flames will be more uniformly distributed across the vessel. More of the flame would be in contact with the vessel wall and this would transfer more heat into the vessel increasing the wall temperature and increasing the likelihood of failure. This must be considered when developing a propane burner to replicate the vehicle fire.

The average heat flux over the entire vessel during the nominally steady state period between 7.7 minutes and 8.5 minutes is shown in Table 3. The average heat flux across the vessel was 44.3 kW.m^{-2} over all measurement locations, this heat flux could have been greater if the test had been carried out with a lower wind speed. During test three, calorimeters, CAL 13, CAL 17 and CAL 19 were damaged due to the heat damaging the instrument cables, for the table below these results have been removed. CAL 06 and CAL 16 were removed due to electrical noise.

Table 3 Calorimeter Averages at Steady State

Calorimeter	Heat Flux (kW.m^{-2})
CAL_01	6.2
CAL_02	2.8
CAL_03	72.6
CAL_04	97.0
CAL_05	6.3
CAL_07	0
CAL_08	0.8
CAL_09	33.1
CAL_10	159.9
CAL_11	0
CAL_12	4.6
CAL_14	108.1
CAL_15	122.8
CAL_18	160.1
CAL_20	0.0
Average	44.3
Total	768.2

The results from the vehicle fire have been used to build a representative propane burner system to produce similar heat flux onto the vessel. Propane is a good source of fuel to replicate the vehicle fire as the surface emissive power of LPG on land according to Table 6.2 (from Ref. 2) is 48 kW.m^{-2} which is similar to the average value seen in the vehicle fire. Commercial propane was used as the fuel in the propane burner, this has a small butane content.

Propane Burner Commissioning

The data collected from the vehicle experiment was used to create a burner array to replicate the vehicle fire to conduct further tests into the possibility of a BLEVE without the need to set fire to a vehicle and to make the tests more repeatable, with the advantage that experiments can also be stopped and started at will. Only the calorimeter data is used for comparison between the two arrays as the wall temperature is time dependent and the flame temperature is related to the fuel. The initial burner array was fabricated with 40 nozzles in four rows of 10 spaced 600 mm apart. The centre two rows of nozzles were pointed directly upwards and the outer row of nozzles were angled at 45° to the vertical. All of the nozzles were positioned to be inside the footprint of the original chassis. See Figure 7. To fuel the burner array liquid propane was used at saturation pressure (nominally 7.5 barg) resulting in an average propane flow rate of around 125 l/min.

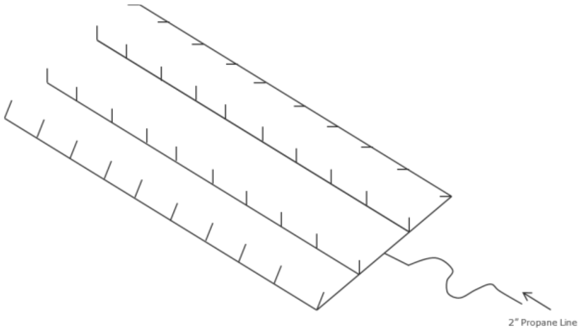

Figure 7 Schematic of Initial Burner Array

The nozzles were fabricated from a 6.35 mm (¼”) OD stainless steel, with an internal diameter of 3 mm and a length of 200 mm. Each nozzle was welded onto 25 mm (1”) OD stainless pipe which in turn was connected to a 50 mm (2”) NB propane supply line.

The initial burner array trials produced more heat flux on the vessel than was seen in the vehicle fire and therefore not representative; see Table 4. Photographs showed that the ends of the vessel were subjected to almost constant flame coverage not seen in the vehicle fire. The calorimeters around the centreline of the vessel also saw large heat fluxes. In the vehicle fire, the majority of the underside of the vessel and the front end of the vessel were shielded from the pool fire and the cab fire by the steel wall of the cab and the pipework and hoses on the chassis.

For the second commissioning run the two end rows of nozzles were welded closed and the centre two rows of nozzles had alternate nozzles welded closed, see Figure 8. A steel mesh was also fitted above the nozzles under the vessel to try to limit the flame thickness on the underside of the vessel.

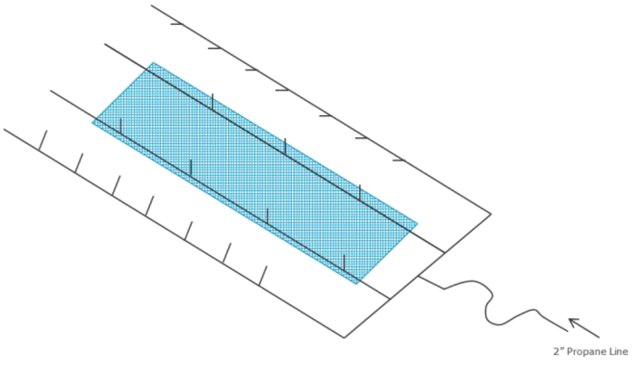

Figure 8 Schematic of Burner Commissioning Run 2

The steel mesh was welded in place using steel tubes secured into the ground. The mesh was positioned 100 mm from the top of the centre nozzles.

Figure 9 Modifications to the Burner Array Commissioning Run 2

The photograph from Commissioning Run 2 shows that the ends of the vessel are no longer totally engulfed by the flames, this reduced the heat flux on the ends of the vessel. However, the total heat flux on the vessel increased due to the mesh helping to spread the flame to cover both sides of the vessel. The centreline of the vessel still showed heat flux readings far greater than the initial vehicle fire, see Table 4.

Figure 10 Commissioning Run 2

For Commissioning Run 3 a solid steel plate was welded on top of the mesh to create a solid barrier between the nozzles and the vessel as shown in Figure 11, this was used to reduce the level of heat flux on the bottom of the vessel. The sheet used was 3 mm thick plate, the plate was thin enough to deflect the flame away from the vessel whilst still allowing some heat to be transferred through the steel.

Figure 11 Steel Plate for Commissioning Run 3

Commissioning Run 3 was much more comparable to the vehicle fire, again summarised in Table 4.

Table 4 Comparison of calorimeter readings for burner commisioning trials

Calorimeter	**Vehicle**	**Commissioning Run 1**	**Commissioning Run 2**	**Commissioning Run 3**
CAL_01	6.2	100.4	DNR	DNR
CAL_02	2.8	107.5	DNR	DNR
CAL_03	72.6	142.2	218.9	33.3
CAL_04	97.0	91.4	239.5	93.3
CAL_05	6.3	146.3	256.7	1.9
CAL_06	DNR	87.4	234.8	81.3
CAL_07	0	43.4	108.7	84.8
CAL_08	0.8	72.8	199.7	1.3
CAL_09	33.1	105.5	DNR	DNR
CAL_10	159.9	125.5	251.5	123.7
CAL_11	0	3.8	37.4	65.4
CAL_12	4.6	31.5	117.4	81.3
CAL_13	DNR	DNR	DNR	DNR
CAL_14	108.1	140.0	301.2	11.3
CAL_15	122.8	DNR	DNR	DNR
CAL_16	DNR	43.6	97.3	13.8
CAL_17	DNR	DNR	DNR	DNR
CAL_18	160.1	108.1	261.9	3.5
CAL_19	DNR	DNR	DNR	DNR
CAL_20	0.0	121.1	DNR	DNR
Average	**44.3**	**91.9**	**193.7**	**49.6**

The average of the steady state calorimeter measurements across all calorimeters is used to compare between the vehicle fire and commissioning runs. The vehicle fire and Commissioning Run 3 are similar. The propane burner gives a more uniform heat flux across the vessel when compared to the vehicle fire with localised high heat flux.

The temperatures measured in the flame around the bottom of the vessel on Commissioning Run 3 are, in the majority, similar to those seen in the vehicle fire at around 500 °C, see Figure 12. The wall temperatures in Figure 13 are also similar to those seen on the vehicle fire with two measurement locations reaching the failure threshold of around 600 °C, the test was stopped after a short period of time, however it is likely that the other thermocouples would reach similar temperatures. If this propane burner arrangement was allowed to run for 25 minutes as was the duration of the significant heat flux seen in the vehicle fire then it is likely, depending on the fill level of the vessel that the material of the vessel could fail leading to a rupture or BLEVE of the vessel.

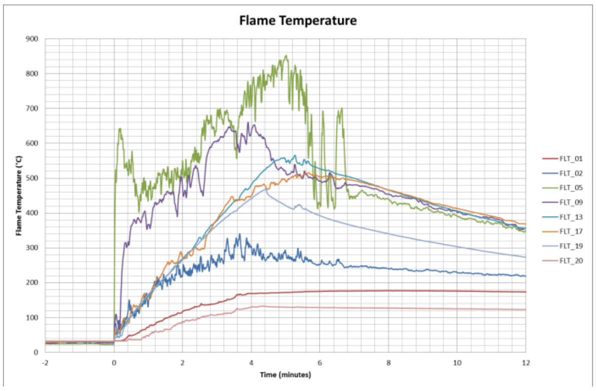

Figure 12 Flame Temperatures on Commisioning Run 3

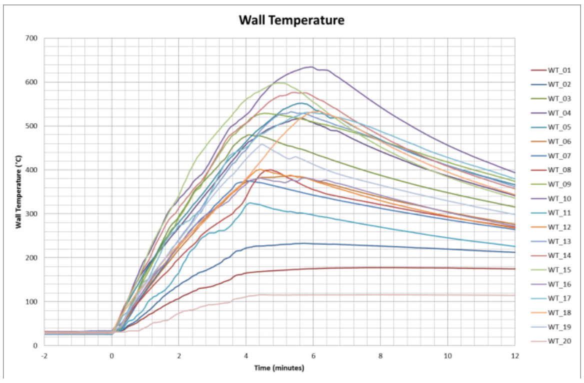

Figure 13 Wall Temperatures on Commissioning Run 3

The heat flux graph for all the measurement positions shows that while the highest heat fluxes are lower than the peaks seen in the vehicle fire it is much more uniform across the vessel than in the vehicle fire, see Figure 14. As the table of results and the graphs of heat flux and temperature show similar values to the vehicle fire, it can be concluded that the propane burner arrangement in Commissioning Run 3 is suitable, with the findings of this paper to replicate the vehicle fire and for use in the continuation of the test program into the possibility of a BLEVE event with 7 Te road tankers when subjected to fire.

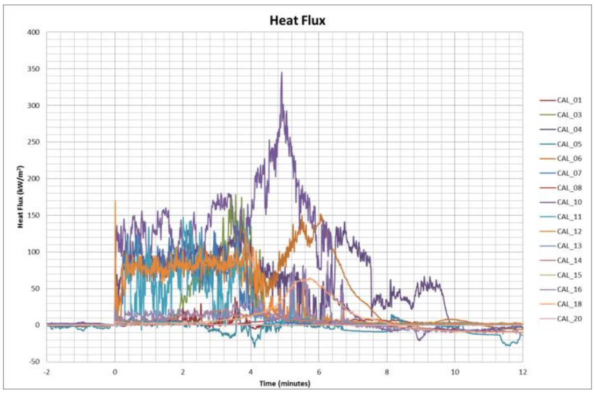

Figure 14 Calorimeters in Commissioning run 3

Concluding Remarks

This paper concludes that there is a strong possibility that a road tanker fire on a LPG road tanker could cause a BLEVE event. The literature surrounding the possibility of a BLEVE incident has been reviewed and shows the consequences of a BLEVE event could be catastrophic. A road tanker fire has been characterised and shows temperature rises in the vessel steel up to the region of 600 °C where it is known that vessel failures will occur in pressurised vessels. A propane burner system has been built and optimised to replicate a vehicle fire and the associated heat flux observed on the walls of the vessel and will be used to confirm if LPG vessel failure can occur in simulated vehicle fires in future work in 2017.

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