# Flammable vapor cloud generation from overfilling tanks: learning the lessons from Buncefield

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## Abstract

The Buncefield Incident in 2005 led to a significant change in our understanding of how flammable vapor clouds could be generated from overfilling bulk storage tanks with volatile liquids. Prior to that incident, it was widely thought that an overfilling tank would produce a pool of liquid in the bunded area around a tank that would evaporate relatively slowly. However, in the Buncefield Incident, the release of liquid through vents in the tank roof led to waterfall-like cascade of fine gasoline droplets that produced flammable vapor at a much faster rate. It took only around 25 minutes for the dense current of flammable vapor to fill an area roughly 500m by 400m to a depth of between 2m and 4m. The wind speed was very low during the incident and the way in which the vapor cloud dispersed was affected by the slope of the ground and presence of obstacles. The resulting explosion was severe, even across open unobstructed areas. Fortunately there were no fatalities, but the total damage from the incident was estimated to have cost around $1.5 billion. Since the Buncefield Incident took place, several incidents with striking similarities have taken place at Jaipur (India), San Juan (Puerto Rico) and the Amuay Refinery (Venezuela).

This paper presents the findings of the Buncefield Incident investigation team and further research that has been carried out on tank overfilling releases over the last seven years at the Health and Safety Laboratory (HSL). The work has involved a combination of unique spill experiments and Computational Fluid Dynamics (CFD) modeling, and has resulted in a simple methodology for predicting the rate of flammable vapor production from overfilling tanks. This paper takes the opportunity to present for the first time a unified narrative, starting with the key findings of the incident investigation and culminating with the description of a workbook method for predicting which substances and storage tanks could create significant vapor clouds.

## Introduction

At 06:01:31 on Sunday December 11th 2005 a powerful explosion devastated the fuel depot at Buncefield, some 40 km Northwest of London. Nineteen storage tanks containing gasoline, aviation fuel and diesel were immediately set on fire. The fire subsequently spread to a small number of additional tanks and was not fully extinguished for several days.

Investigative work began immediately after the explosion, despite the on-going fire-fighting operation. Damage to the site and surroundings was extensive and the initial thoughts of the investigating authorities were that the explosion might have been caused by a large bomb. A substantial area was affected by the blast (approximately 150,000 $m^2$) and much of this was strewn with debris. Examination of the scene by the security services yielded a valuable set of early photographs documenting damage to a range of around 500m from the site.

Police helicopters were used for several days to monitor the area and numerous high quality aerial photographs were taken, allowing the damage to be appreciated as a whole. Early police involvement also provided the resources to interview a large number of eyewitnesses in the immediate aftermath of the explosion i.e. before they were exposed to media reports of the comments of others. Eyewitness descriptions of events before during and after the explosion provided valuable inputs to the investigation.

Within a few days it became clear that the damage could not have been caused by a bomb; although the severity of damage over a wide area and seismic records from all over the UK indicated a very significant explosion event, there was no sign of a crater. Primary responsibility for investigating the explosion and fire passed to the UK Health and Safety Executive (HSE) and Environment Agency.

Detailed and systematic photographic records were made of blast and heat damage to buildings, vehicles, trees, masts, tanks etc. It became clear to investigators that a large area, well away from the site, had been affected by flash burning as well as blast. The evidence for burning included scorched leaves and rubbish, such as paper and plastic film. A large continuous area surrounding the site was uniformly affected by both blast and heat i.e. all vegetation was scorched and all pressure sensitive objects were affected. The area powerfully affected by blast (e.g. vehicles crushed) did not extend more than a few tens of meters beyond the edge of the burned zone.

Aerial photographs confirmed the observations on the ground: the site was surrounded by a blackened area (all plant leaves scorched) extending to a distance of up to around 250m (Figure 1). All of this ground had been exposed (briefly) to a vapor flash and contained crushed cars and severely damaged buildings. Outside the area affected by the flash, damage to vehicles was minimal; buildings were affected only by damage to vulnerable elements such as windows and cladding. The idea that the incident had been caused by a vapor cloud spreading out in all directions from the site began to be discussed by the investigation team. The burned area would correspond to the area covered by the vapor cloud – or at least that part of it that burned.

It took some time for CCTV records to be recovered from the site and the surrounding buildings that lay within the area covered by the cloud. This typically involved retrieving hard discs from broken computer systems within ruined (collapsing) buildings. As investigators began to recover and view the data it became clear that these images held the key to understanding what had occurred.

It was dark at the time of the release but the areas covered by CCTV were well lit. Conditions were clear but the temperature was close to the dew point. About 25 minutes before the explosion, cameras close to Bund A (containing 3 large gasoline tanks) captured a current of dense white mist flowing westwards out of the bund; outside the bund the mist continued to spread smoothly in all directions at a speed of order 1 m/s. After a few minutes cameras in the large car parks of nearby buildings showed the mist initially flowing in a very shallow, smooth topped layer. In one location around 200m West from Bund A, there are remarkable pictures of a worker arriving by car for an early shift. He successfully parked the car and then walked away out of a cloud that extended to around his knees but no higher. Over time, the depth of this layer increased until it reached about 2m over most of the areas covered by cameras (Figure 2). Around the source in Bund A the cloud depth had increased to 4-5 m.

The upper surface of the vapor cloud was visible over large distances and it was apparently undisturbed by any vortices. This, and the symmetry of the spreading cloud, confirmed that the incident had occurred in nil wind conditions, with the spread of vapor being driven by buoyancy forces.

Before process data could be recovered from the site, witness statements started to give clues about the source of the vapor. A tanker driver had seen the vapor current as it reached the tanker loading gantry: alerted to the fact that something unusual was occurring he looked around for a possible source and was able to see what looked like a weak spray coming from part way down the wall of a tank in the distance. Significantly, he also reported seeing mist further up near the top of the tank. All of this suggested that the tank in question (Tank 912) might have been the source; if liquid spilled out of the top of the tank and ran down the side, it would strike a wind girder and be projected out, forming a spray and mist trace at high level that would both correspond to the witness description. When the tank level and supply pipe pumping rate data became available, this overflow hypothesis was confirmed (Buncefield Major Incident Investigation Board, 2007).

At the time of the incident, Tank 912 was being filled with winter grade gasoline at a rate of 550 $m^3$/hr. The level reached the top of the tank and liquid began to run out of the vents in the fixed tank roof. The overflow continued for around 25 minutes with the flow rate being increased to 960 $m^3$/hr about 8 minutes before the explosion. In parallel with efforts to uncover the root causes of the loss of containment, the investigation team began to consider how the outflow could have produced such a large cloud. The volume of the visible cloud formed in 25 minutes was approaching 300,000 $m^3$, corresponding to a rate of production of order 200 $m^3$/s. Where did this cloud come from?

Examination of the CCTV images and blast damage levels convinced the investigation team that there was very little entrainment into parts of the cloud further than about 20m from the tank. Explosion severity (and therefore presumably gas concentrations) appeared to be close to uniform over more than 95% of the area covered by the cloud. The conclusion was that all of the air (as well as the gasoline vapor) was entrained into the vapor current very close to the tank and thereafter the vapor cloud spread out in a buoyancy current with minimal further increase in volume flux.

Previous assessments of vapor risks around bulk tanks had focused on pool evaporation in a range of wind speeds: nil wind conditions were not considered as there would be no movement of contaminated vapor away from the surface of a pool in a bund. It became clear that a crucial aspect of the source term had been overlooked – of particular significance for low wind speeds.

In a tank overfilling release, such as that from Tank 912, a stream of liquid from the top of a tank breaks up into a cascade of small droplets. As these droplets fall through the air, there is a transfer of momentum from the liquid to the air; the droplets are retarded by the air and the air is driven into downward movement. This was not a previously unknown phenomenon; many people must have noticed that large waterfalls drive a strong current of air outwards from the area where the cascade impacts the ground at the foot of the waterfall. However, the significance of this effect for industrial safety had not been appreciated.

The entrainment of large volumes of air by freely falling cascades of a volatile liquid produces a large and continuous flow of vapor. For overfilling releases from tanks of the size typically found on fuel storage sites, the initial speed in the vapor current is of order 5-8 m/s. The shear between this current of vapor and the surrounding air produces some initial mixing and dilution – depending on the extent of recirculation in the immediate vicinity of the tank. Moving further away from the tank, as the velocity of the cold, heavy vapor current falls, mixing is progressively reduced (due partly to stable stratification which suppresses turbulent mixing). In very low wind speeds, the amount of dilution on the top surface of the spreading vapor cloud may vanish completely, with only a small degree of mixing at the front of the gravity current. Under these conditions, the vapor current may run for very large distances without diluting significantly. If the (constant) concentration of this extensive flow is in the flammable range, there is potential for the production of a very large, hazardous cloud which could sustain an explosion throughout.

The challenge facing the investigation team was therefore to develop a quantitative understanding of the physical processes involved in the formation of the Buncefield cloud. The team was well aware that tank overflows and other elevated releases could occur at other sites and that the risk profile of a range of other sites might have to be re-examined.

## Initial Modeling Work

From the outset, the HSL team working on vapor dispersion used a combination of methods to tackle the problem: full scale testing, fluid mechanics and thermodynamic analysis, and CFD. In the end, each of these elements made crucial contributions to the development of HSE's Vapor Cloud Assessment (VCA) method.

Large scale models were built of sections of the tank at Buncefield (see Atkinson and Gant, 2012). The character of the liquid flow from the vents and over the edge of the tank is illustrated in Figure 3a. Tank 912 was fitted with a "deflector plate" around the rim of the tank top which would redirect cooling water running down the roof onto the walls (in the event of an engulfing bund fire). Flow rates from the vents in the event of an overflow are large compared with this cooling water flow and about half of the liquid overflow would have overtopped the deflector plate and fallen as a free cascade from tank top to ground level. The remainder would have fallen as a dense shower close to the wall before hitting a wind girder part way down and being thrown out as a spray (Figure 3b).

At the time, during the incident investigation, there was some speculation that this liquid impact on the wind girder might be a pre-requisite to the formation of a large vapor cloud. It has subsequently been shown that that this is not the case – all elevated releases have the potential to form vapor clouds, even if they fall freely to the ground.

Preliminary observations of the cascade width and droplet size spectrum were made (at close to full scale). For water cascades, droplets were large and irregular in size; most of the mass was contained in droplets 4-6mm in diameter. For gasoline cascades, typical droplet sizes were around 2mm diameter; anything much larger than this seemed to readily break up (the surface tension of gasoline is normally less 30% that of water). Droplets much smaller that 2mm diameter seemed to disappear rapidly due to evaporation.

The extent of spread of the cascade (perpendicular to the tank wall) is crucial in calculating the air entrainment and hence cloud size and concentration. Reliable measurements in the open require flat calm conditions and low turbulence levels in the outflow liquid. The first HSL large scale experiments were done using an existing facility and arrangements for settling the large pumped flows of liquid were rudimentary. Instability in the liquid outflow and the effects of air currents led to significant overestimates of the extent of cascade spread; early modeling used a figure of 1.5m for the cascade width after a 15m drop whereas subsequent experimental project work with a purpose-built rig in very stable conditions showed that the cascade spread is much less. The cascade width increased rapidly as the primary breakup of the liquid streams into a droplet cascade occurred, a few meters below the release height, but thereafter the rate of increase in width was very slow.

During the incident investigation estimates of mass entrainment were made based on momentum conservation principles. If it is assumed that the momentum flux associated with gas and vapor is concentrated within the area covered by the liquid spray, then this analysis is possible without use of empirical constants (Atkinson *et al*., 2008). In this respect, entrainment of air into a cascade is very different to that in a gas jet or even the low mass, high momentum sprays studied, for example, by Ghosh and Hunt (1998). The key difference is that in the cascade both liquid and gas phases are accelerating towards the ground. Contaminated air that spills out of the cascade, because of vortices in the shear layer at the cascade edge, is likely to be immediately re-entrained because of the suction effect of drag on droplets. Thermal images of large scale cascades support the assumption that there is relatively little air flow outside the area covered by the droplet spray.

Although the basic entrainment analysis was correct (and was eventually used in the VCA method) errors were made in its early application to the problem of overfilling. Firstly, it was assumed that the air entrained would only depend on the fall as a spray i.e. after the liquid streams had fully broken up into a liquid spray. Since it takes some time for the liquid stream to break up into a spray of droplets, the effective tank height in the entrainment calculations was reduced.

In addition, the investigation team had seen images of a 4-5 m deep vapor layer around Bund A. It was assumed the downward vapor current within the cascade would disappear into this accumulated layer and any subsequent mixing would not involve entrainment of fresh air. The effective height over which entrainment could occur was further reduced in the entrainment calculations.

Both reasons for reducing the effective drop height turned out to be spurious, so the early analyses substantially and inappropriately underestimated the rate of entrainment. On the other hand, the basic width of the cascade had been overestimated. Errors associated with both the width and fall assumptions largely (and fortuitously) cancelled. The early estimates of vapor cloud size developed in the initial investigation and subsequently published by HSL and Shell (Atkinson *et al*., 2008) were reasonably close to the results of much more detailed studies, which were backed up by extensive large scale tests on a range of volatile liquids.

Estimates of cloud volume production and concentration were used as inputs to a CFD dispersion model developed by Gant and Atkinson (2011). This model represented the overflowing tank as a source of vapor that welled up and out of the bund with minimal momentum. Once the vapor had overtopped the bund wall, the model predicted it to spread out across the site as a gravity current. Studies were performed to investigate the sensitivity of the model predictions to various physical and numerical input parameters: the computational grid resolution, initial turbulence levels, surface roughness, presence of porous barriers (e.g. hedges) and slopes. These showed the dispersion behavior was strongly affected by relatively modest slopes in the terrain and the presence of obstacles. As a consequence, a detailed CFD model of the Buncefield site was constructed using topographical data from a site survey. The resulting detailed CFD model predictions were then compared to the CCTV records, in terms of the vapor cloud arrival times at various locations (Figure 4). The movement of the vapor front was well predicted but the total cloud volume was somewhat under-predicted. Most of the discrepancy was probably traceable to errors in the early estimates of the source term volume flux as the entrainment fell away.

These initial developments of the CFD model allowed rapid progress to be made subsequently on the dispersion analysis, once improved methods of modeling the source term had been produced. Rather than model the source as a prescribed upwelling flow of vapor from the floor of the bund, the later model calculated this flow rate of vapor using a coupled Lagrangian-Eulerian approach to track the trajectory of spray droplets and account for the transfer of heat, mass and momentum between the spray droplets and the air within the liquid cascade.

By the time of the Hazards XX Conference in November 2008, the basic elements of a scoping method for tank overfilling incidents could be published (Atkinson *et al*., 2008). The purpose of this method was to determine whether a particular liquid (e.g. a solvent, gasoline blend or volatile crude oil) could generate a large flammable cloud if overfilled at a given rate.

Early results from CFD modeling of vaporizing sprays were available at that time, but some elements of the problem were still intractable: especially the width of the cascade (which needed to be taken from experiments) and the effect on heat and mass transfer of splashing droplets (at the base of the tank, where the cascade hits the ground). Understanding of the near- and far-field dispersion, in terms of the interaction between the vapor flow and the bund walls, was also incomplete. The scoping method adopted a number of conservative assumptions where technical issues remained unresolved. For example, it was assumed that droplets and the co-flowing air would reach a state close to equilibrium as the vapor flowed out of the impact zone. Later experiments have shown that this is in fact a remarkably good approximation. Similarly, it was assumed that if a vapor current is flammable as the vapor emerges from the impact zone it may produce a large flammable cloud – i.e. near-field entrainment may be completely suppressed by an overlying accumulated layer. This turned out to be overly conservative and it has been corrected in the more recent VCA method.

## Experimental and CFD development work

The uncertainties remaining in the HSE/Shell scoping method (Atkinson *et al*., 2008) prompted further experimental and CFD research on tank overfilling releases, using the test rig shown in Figure 5. The objectives were to re-examine some of the assumptions underpinning the scoping method and to replace conservative assumptions with more fundamental models and data. The key areas for experimental work were:

1. Measurements of cascade dimensions and air entrainment

2. Analysis of the effects of splashing on heat and mass transfer

3. Analysis of the effects of fine splash products carried into the vapor current

4. Provision of data in and beyond the cascade to allow the development and testing of CFD models.

The key areas for CFD development were:

1. Appropriate representation of droplets in the cascade

2. Accounting for the effects of splashing

3. Investigating effects of tank bunds and other obstructions on entrainment.

**Key Findings in Experimental Studies**

**A.) Flow characterization in the cascade**

Figure 6 shows typical measurements of liquid temperatures across a free cascade about 10m below the release height. Substantial temperature drops are observed because of the vaporization of droplets. These results illustrate the difficulties associated with such measurements in the open air: The cascade is only about 400mm wide – exceptionally stable conditions are required to resolve its internal structure. Figure 7 shows a collection of such measurements for a range of volatile liquids. Temperature drops are divided by the temperature drop to be expected if liquid and vapor reach full equilibrium. The results show that the extent of vaporization in the cascade is normally only about 70% of that which would be possible if full equilibrium with entrained air was reached.

One interesting finding from both experiments and modeling was that the average liquid temperature at the base of the cascade was a little higher than the co-flow of vapor. At first sight this is difficult to understand, since evaporative cooling should produce a fall in the droplet temperatures below ambient. The observed effect only occurs because droplet breakup produces a range of fragment sizes. Smaller droplets cool very rapidly and the whole fragment may evaporate completely into very cold vapor. Larger droplets that hold the bulk of the mass cannot vaporize quickly enough to match the rate of vapor cooling.

**B.) Liquid and vapor flow after impact**

Measurements of liquid temperatures are much more straightforward to make in the outflow of liquid running along the floor away from the impact point. This material is naturally mixed and the temperatures recorded are not particularly sensitive to slight movements of the cascade trajectory. Comparison of temperatures in this flow and in the liquid approaching impact show that the temperature of the liquid drops rapidly and significantly during the impact process. Figure 8 shows the post-impact temperatures for the experiments shown in Figure 7. Little additional air is entrained in the impact zone but the generation of fine splash fragments during the impact and the high slip velocities between droplets and vapor lead to greatly enhanced rates of heat and mass transfer. The liquid/vapor system is therefore pushed much closer to equilibrium. The amount of liquid vaporized typically rises to around 90% of the maximum possible (equilibrium level). A relatively large proportion of the liquid (around 50%) forms finely divided droplets in the impact zone but most of these are immediately driven back into the liquid flow on the ground – a few are snatched away from the surface by strong eddies and carried out of the impact zone by the vapor flow.

**C.) Splash evaporation zone**

As vapor flows rapidly away from the impact point it entrains fresh air. In the absence of droplets, the vapor temperature would rise rapidly as warm air enters the vapor current. However, thermocouples outside the splash zone showed that temperatures remained low, which indicated that fine droplets were present in the vapor flow for several meters from the impact point. The vaporization of these droplets produces a cooling effect that offsets the inflow of warm air. Measurements of the vapor temperature just after the droplets disappeared suggested that for hexane the total amount of extra vaporization associated with these fine splash products was about 10-20% of the total. Overall, the rate of vaporization tends to be around 100-110% of that which would have been predicted on the basis of the entrainment into the cascade (only) and attainment of full equilibrium.

To summarize: spray vaporization (post-impact) makes a small but significant contribution to the total vaporization rate. The effect on vapor temperatures is much more pronounced because spray evaporation occurs where the heat capacity of the flow is not dominated by the liquid flow.

**D.) Near-field dispersion**

Figure 9 shows measurements of gas concentration where the vapor currents from various hexane cascades pass over either vertical or sloping bunds that are located at different distances from the impact point. Vertical bund walls direct the primary vapor current upward leading to recirculation and accumulation of vapor in the bund. The primary vapor current tends to run straight over sloping bund walls and there is minimal recirculation of this forwards flow. However, part of the gas flow away from the impact point is backwards or sideways and much of this vapor does accumulate in the bund. Overall, the concentration in the bund is much reduced compared with a vertical wall of the same height.

On the other hand, the flow of vapor out of a bund with vertical walls can reach a substantial height and it entrains air strongly as it slumps down out of the bund. In contrast, the flow over a sloping bund entrains moderately throughout rather than at the edge of the bund. Systematic studies of dispersion in a range of geometries over long periods of time have been carried out with CFD (Coldrick *et al*., 2011). Further details of experimental work can be found in Atkinson and Coldrick (2012a, 2012b).

**Key findings of CFD work**

The CFD model used to investigate the production of vapor from tank overfilling releases is shown in Figure 10. A coupled Lagrangian-Eulerian approach was used to simulate the dispersion of liquid droplets in the cascade and their evaporation into vapor. The exchange of momentum, mass and heat between the vapor and droplets was two-way. Droplets falling through the air were subjected to drag forces, and their trajectories are affected by turbulent perturbations in the air. The air was also affected by the drag of the droplets and entrained into the spray.

Although CFD sub-models have been developed to predict the primary breakup of a liquid sheet into droplets, these models were developed for devices such as high-pressure fuel injectors and were not found to be suitable to model gravity driven cascade flows. Instead of trying to predict the droplet breakup, an empirically-based approach was taken in developing the HSL model in which the post-breakup droplet size spectrum was specified to provide a good representation of measured vapor and liquid temperatures in the cascade. The mean size of the larger droplets (where mass is concentrated) was adjusted to match the measured (mass weighted) liquid temperatures, and the proportion of smaller droplets was adjusted in order to match the measured vapor temperatures. The smaller droplets have a minimal effect on average liquid temperature but strongly affect the vapor temperatures.

Satisfactory fitting of the CFD predictions to measurements in hexane cascades was achieved using a Rosin-Rammler droplet size distribution with a mean diameter of $\bar{x}$ = 2 mm and index of $\gamma$ = 3:

$$1 - v = \exp\left(\frac{x}{\bar{x}}\right)^{\gamma} \tag{1}$$

where (1-$v$) is the volume fraction of liquid contained in droplets larger than $x$. This fit was tuned to a particular set of experiments, and the model was then applied separately to simulate further experiments under different conditions (i.e. different liquid release rates). The agreement between the model predictions and measurements in these independent tests was good, which indicated that the droplet size spectrum could be applied more generally, rather than on a case-by-case basis with tuning necessary for each experiment.

The experimental work suggested that splashing droplets were significant in promoting heat and mass transfer in the impact region, and that there was some additional vaporization of fine spray carried into the vapor current. Potential methods of representing the effects of splashing droplets were examined by Coldrick *et al*. (2011). Attempts to directly model the splashing and fragmentation process were not successful and, instead, splashing at the base of the cascade was accounted for by a secondary injection of particles with a prescribed size, mass flow, temperature and velocity. Again these parameters were adjusted to reproduce the measurements made in the near-field part of the vapor current.

More details of the CFD model can be found in the works of Coldrick *et al*. (2011) and Atkinson and Coldrick (2012a). Further background to the development and validation of the CFD model for sprays and tank overfilling cascades can be found in the works of Gant and Atkinson (2012) and Gant *et al*. (2007).

The CFD model predictions showed that if the vapor flow away from the tank is constrained in some way by either the presence of a nearby bund wall or distant changes in ground level (or buildings etc.) then there will be some re-entrainment of vapor into the cascade. In these circumstances, the vapor concentration in the bund and the dispersing cloud increases with time, until the pattern of re-entrainment is established. The higher the bund or constraints, the deeper the final vapor layer and the lower the proportion of fresh air that dilutes the vapor flow from the tank before it joins the cloud.

Results of studies of re-entrainment and the effect on vapor dilution using CFD were reported by Atkinson and Coldrick (2012a) and some typical results are shown in Table 1. The dilution factor in this table refers to the ratio of the vapor concentration in the cascade to average concentration of the vapor in the cloud within the bund.

Table 1: Dilution factors for constrained vapor flows

| **Barrier height (m)** | **Cloud depth (m)** | **Distance to barrier (m)** | **Dilution factor** |
|---|---|---|---|
| 4 | 5 | 30 | 1.5 |
| 2.5 | 3.6 | 30 | 2.1 |
| 2 | Not recorded | 5 | 1.8 |
| 2 | Not recorded | 10 | 2.0 |
| 2 | Not recorded | 15 | 2.0 |

All of the barriers in Table 1 were vertical but the effect of different (sloping) bund profiles has been investigated and for long duration releases the bund shape makes little difference. Similarly, the data show that the dilution factor is insensitive to the location of bunds or other constraints.

The reason for this convenient and somewhat surprising result is that entrainment is normally dominated by air drawn rapidly into a very small area immediately surrounding the impact zone. Back-flow of vapor from the bund is too sluggish to prevent fresh air being drawn into the vapor. The situation is analogous to the final stages of draining a bath: at some point water from the shallow layer cannot drain back quickly enough to prevent air being entrained into the plug flow.

A vertical bund, close to the tank, establishes a deep layer that suppresses some near field dispersion but such a bund also introduces additional dilution as vapor flows out of the bund. These effects are illustrated in Figure 11 which shows multiple cascades discharging into a bund. Vapor immediately surrounding the cascades is displaced by the entrained air and further entrainment occurs as the vapor spills over the bund. The CFD analyses show that the net effect of changing the bund is actually very small: it makes very little difference to the total dilution rate if the bund is close or distant, vertical or sloping or even absent.

These are useful general results that have been adopted in HSE Vapor Cloud Assessment (VCA) method to provide basic guidance on cloud development on fairly flat uncluttered sites. CFD has a vital role to play in further development of low wind speed vapor cloud assessment in circumstances where topography or structures have an important effect on vapor flow, or where more accurate results are required because of the proximity of vulnerable targets to potential sources of vapor. HSL is actively engaged in a range of such specialized dispersion studies, where the results are being used to develop various mitigation strategies. This work has contributed to developing an understanding of the extent to which vapor barriers can be used to control risk.

## HSE Vapor Cloud Assessment (VCA) method

HSE's Vapor Cloud Assessment (VCA) method (Atkinson and Coldrick, 2012a) provides a means of calculating the rate at which the volume of a vapor cloud increases during an overfilling incident. The analysis also gives the concentration of hydrocarbons in the cloud.

Of more practical significance is the extent of the area covered by the vapor cloud. In general, this depends on the specific site topography, i.e. slopes and obstacles that may impede, encourage or redirect the flow of vapor. If the site is fairly flat and open (like Buncefield or Jaipur) the cloud tends to spread symmetrically (at least initially). The VCA method can be used in these circumstances to estimate the time at which a vapor cloud will extend to engulf a particular location (e.g. a site control room or tanker filling gantry). If assumptions are made about the maximum duration of the overfilling incident then the method can also be used to estimate the maximum extent of the cloud.

The method can be used to carry out assessments for a specified grade of winter gasoline without the need for additional thermodynamic analysis. Application to other volatile liquids requires the user to determine the equilibrium state when the fluid is mixed with various amounts of air. A number of worked examples are provided in the report (Atkinson and Coldrick, 2012a).

**FABIG Technical Note 12 (Atkinson and Pursell, 2013)**

This document extends the scope of the VCA method. Parameterized thermodynamic analyses are available for hexane, acetone, ethyl acetate, benzene, MEK, toluene, methanol, ethanol and a range of mixtures with defined compositions: naphtha, winter grade gasoline, raw gasoline, F3 condensate, stabilized Brent Crude, reformate and heavy reformate. The assessment method is also suitable for other liquids but a simple thermodynamic analysis is required.

This document also provides some preliminary advice on the integration of cascade vaporization into the source term for the assessment of windy conditions.

The risks associated with spray releases, as opposed to tank-overfilling releases, were exemplified by the Jaipur incident (MoPNG Committee, 2010) in which gasoline was forced from an upward facing opening at the foot of the tank, simply by the hydrostatic pressure exerted by fluid in the tank. The loss of containment continued for more than an hour and a very large flammable vapor cloud was formed extending to more than 500m from the source in some directions.

Many of the physical processes that apply in such a release are common with the overfilling tank problem. Entrainment of air into the liquid spray occurs on the way up and on the way down. For relatively low-pressure, high-volume releases, the area covered by the liquid spray is larger on the downward part of the trajectory, and this is where most air is entrained.

The vertical extent of the drop is often comparable with that in a tank overfill cascade and for hydrocarbons it would be expected that the droplets to be sufficiently fine to bring the liquid fairly close to equilibrium with the entrained gas – as was the case for overfill cascades. There is also an impact zone in which enhanced heat and mass transfer after splashing brings the liquid and vapor phases even closer to equilibrium.

A wide range of hole shapes and sizes are possible and the distribution of liquid in the spray can vary much more widely than was the case for cascades of liquid during overfills. Normally, failure of a pipework system is a very unlikely event and may involve corrosion or complex third-party actions such as damage from mechanical excavators, dropped objects or collisions. The geometry of such breaches is not normally known in advance although some common faults such as flange leaks should be considered. The normal method of risk assessment is to assume a series of characteristic hole sizes and frequencies. A simple hole-geometry is then assumed to allow the hazard range to be assessed.

FABIG TN 12 (Atkinson and Pursell, 2013) presents an analysis of the cloud characteristics for a range of sprays. These results suggest that, as a rule of thumb, a spray of gasoline can produce a cloud capable of powerful explosion (i.e. stoichiometric concentration) at a rate approximately 1200 times the volume outflow rate of liquid gasoline. For very diffuse sprays a flammable cloud can be produced at a rate up to approximately 3500 times the liquid outflow rate – the fuel concentration in such a cloud would be close to the Lower Explosive Limit (LEL). A range of examples are also given on the use of the method for hazard assessment in the case of tank overfilling and spray releases.

## Conclusions

Buncefield and other recent major incidents at Jaipur (India), San Juan (Puerto Rico) and Amuay Refinery (Venezuela) have highlighted the risks associated with very large explosible vapor clouds developing in calm conditions. Such clouds may continue to grow for as long as the release continues and distances well in excess of 500m have been observed. Source terms in all of these cases involved liquid releases at elevation, either from tank overflowing releases or pressurized sprays. In all of the cases, the entrainment of air into the spray produced a continuous source of dense vapor that, under the low wind speed conditions, led to the accumulation of a large flammable cloud. The Amuay Refinery explosion appears to provide a particularly clear illustration of the fact that low wind speeds represent a worst case. In this incident, a long-duration release was initially dispersed by a light breeze. Only when the wind decreased did the flammable cloud extend to around 700m from the source.

Dispersion in very low or nil wind speeds is likely to be the worst case for many loss of containment events and it should be routinely included in risk assessments. Although not covered by established risk assessment tools, such as PHAST (DNV, 2013), a variety of new methods of analysis are now available for use.

## Acknowledgement

This publication and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

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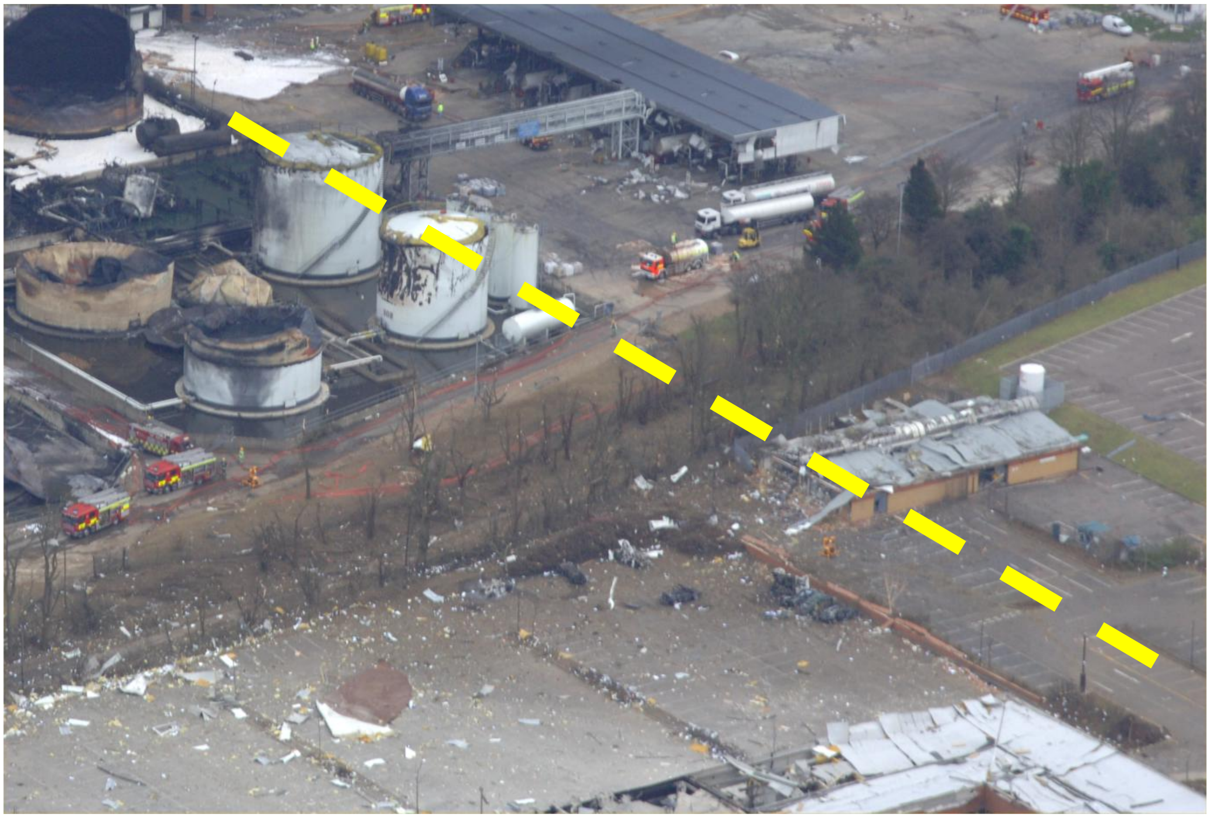

Figure 1: Part of the southern edge of the vapor cloud at Buncefield. Vegetation within the cloud (to the left) is all burned.


Figure 2: Off-site areas at Buncefield before and after the accumulation of vapor

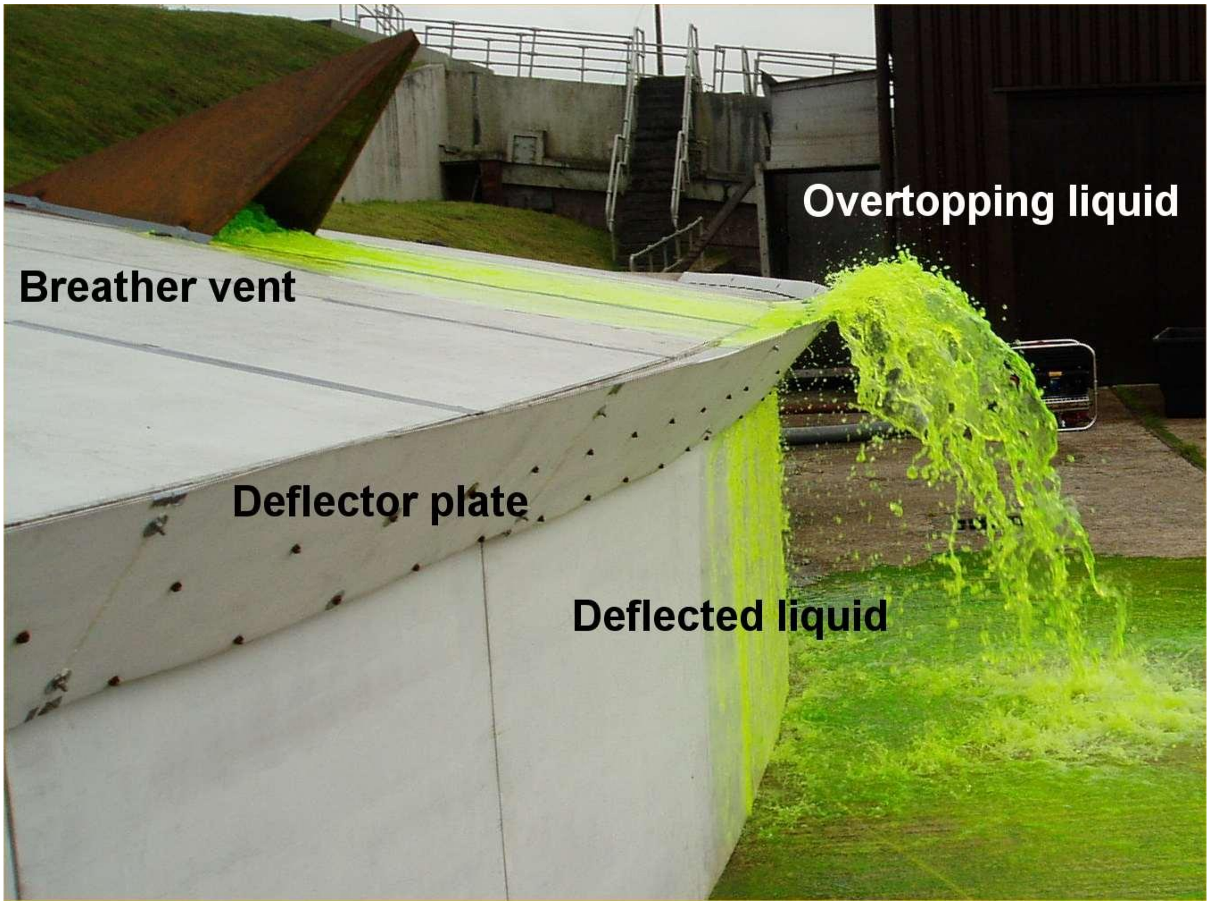


Figure 3a: Reconstruction of liquid flow from the top of the tank

Figure 3b: Reconstruction of flow down the tank wall. Some liquid falls freely from the top and some runs down the wall, impacts a wall girder and is projected outwards as a spray.

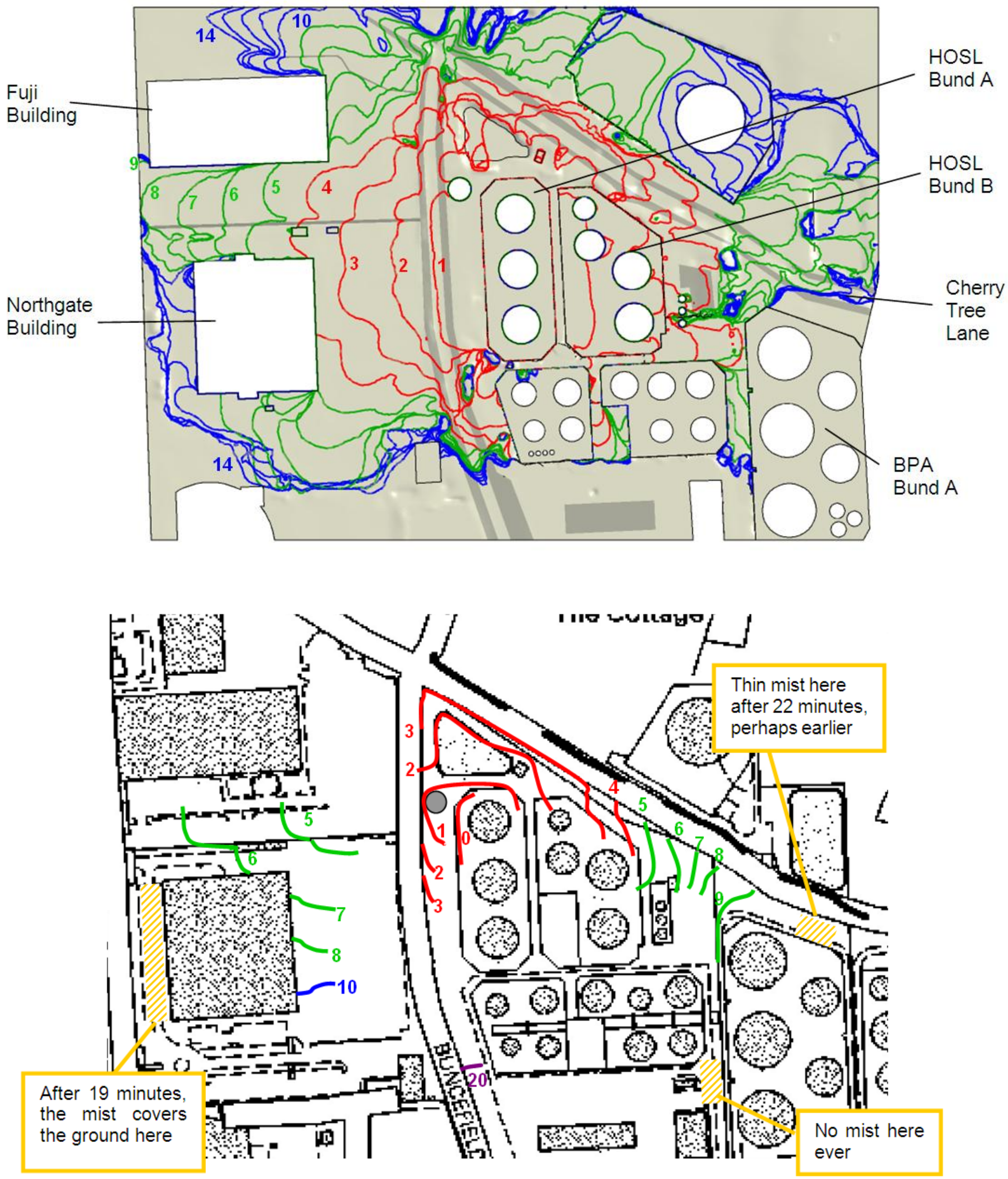


Figure 4: Comparison of CFD predictions (top) and CCTV observations (bottom) for the progress of the vapor cloud or mist across the Buncefield site. Times shown are in minutes from the moment the mist appeared over the wall of Bund A

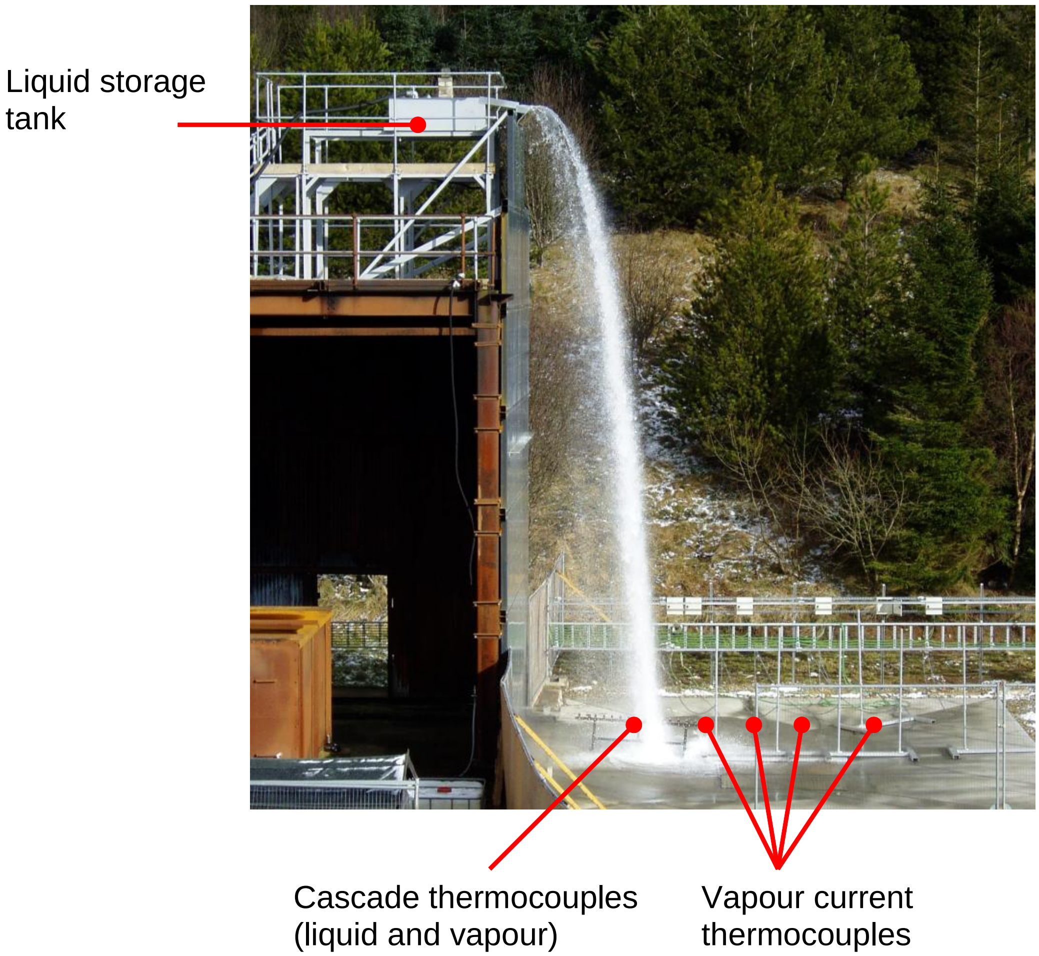


Figure 5: HSL tank-overfilling test facility showing location of measurement equipment

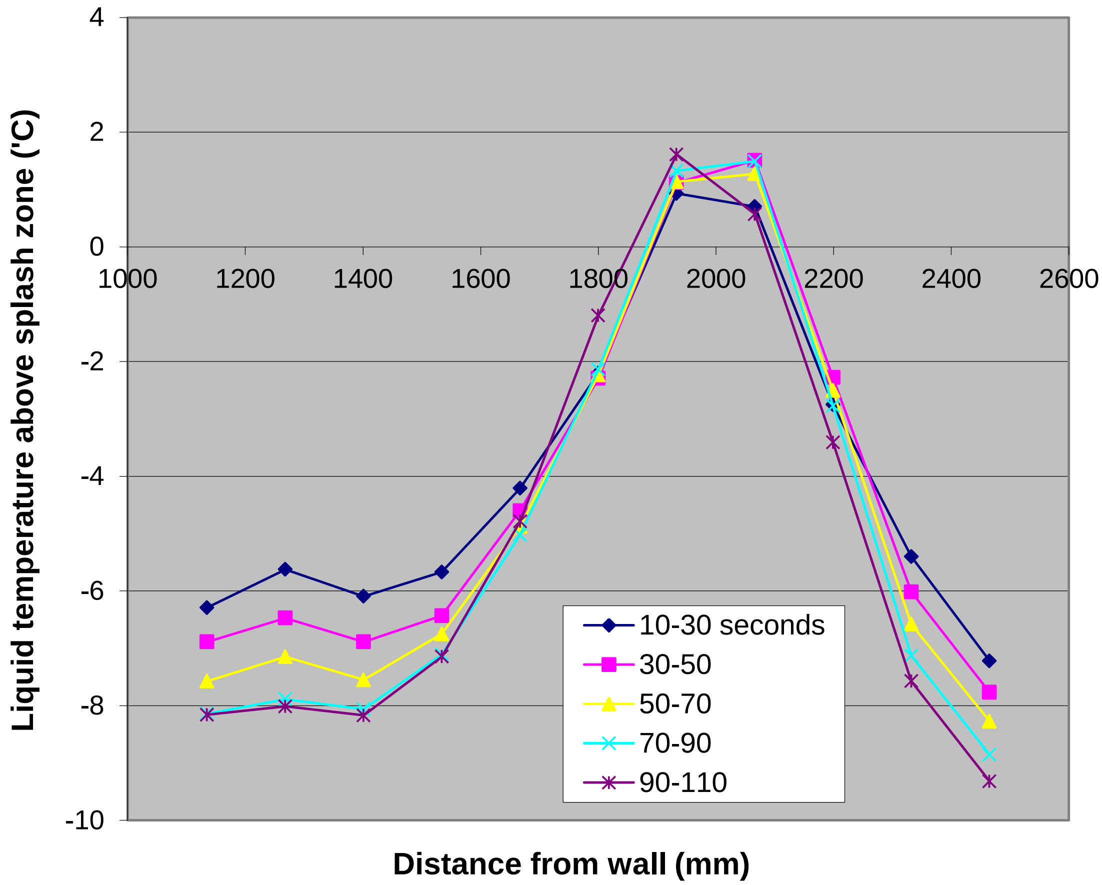


Figure 6: Liquid temperatures in a 10m high hexane cascade just before impact.

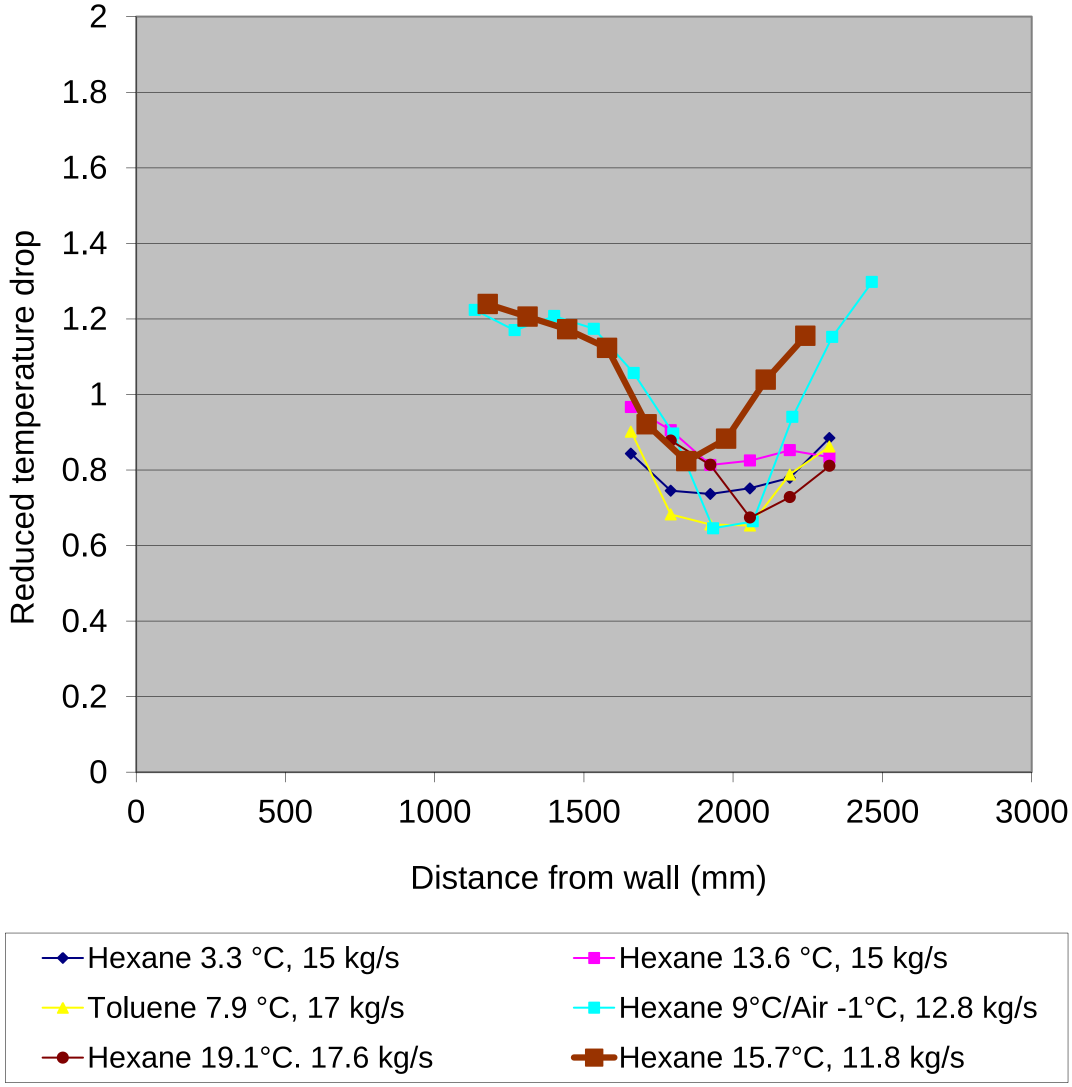


Figure 7: Temperature drop in liquid cascades just above the impact zone

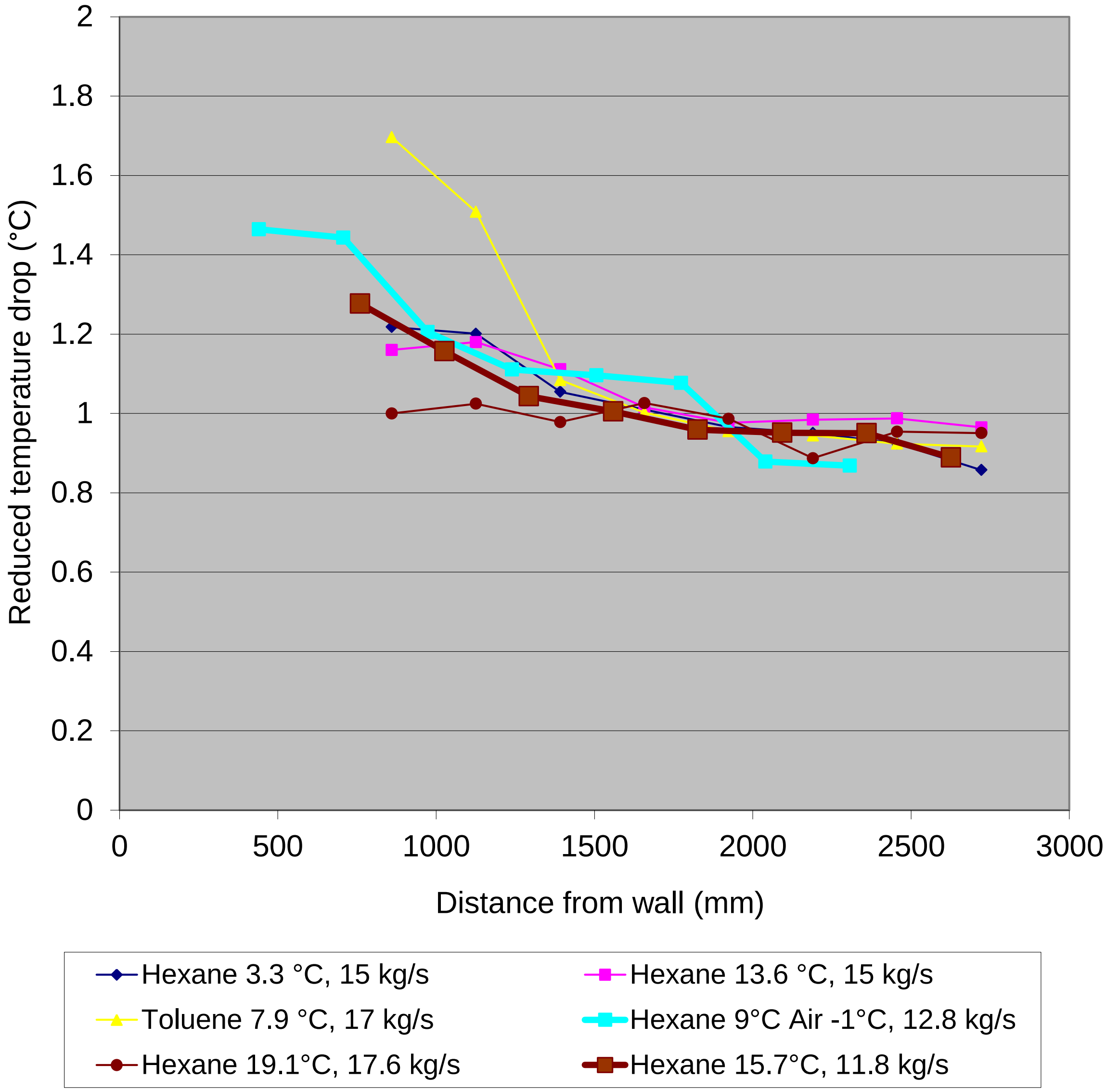


Figure 8: Temperature drop in liquid running away from the impact zone

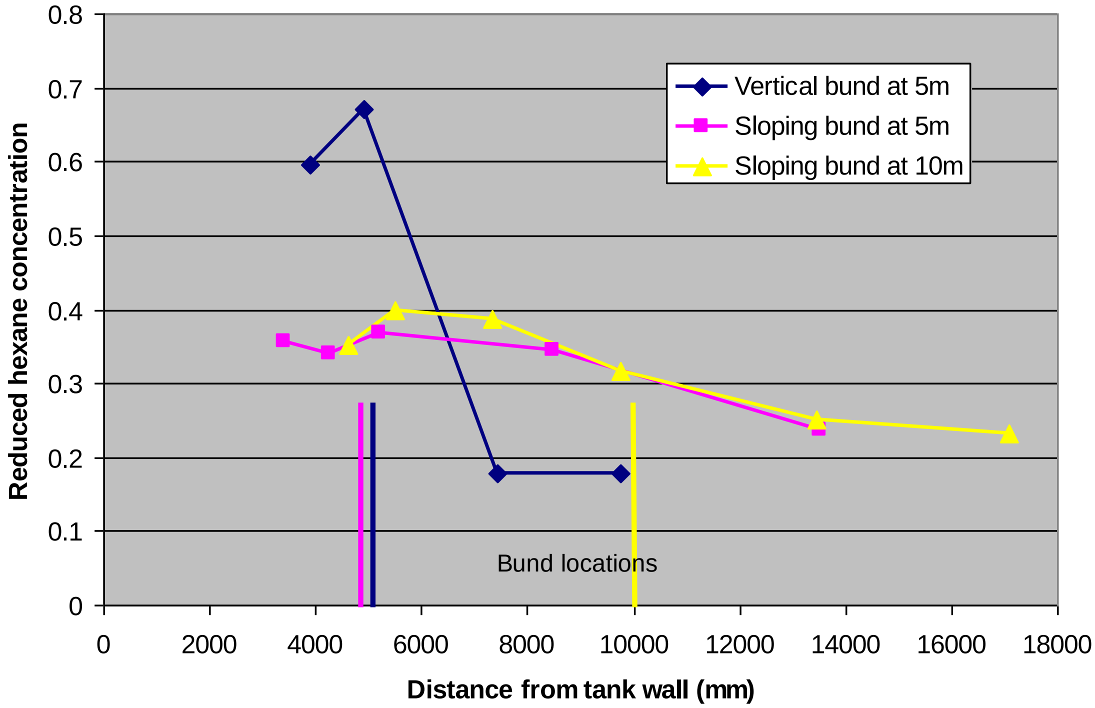


Figure 9: Gas concentration measurements for various bund shapes and locations

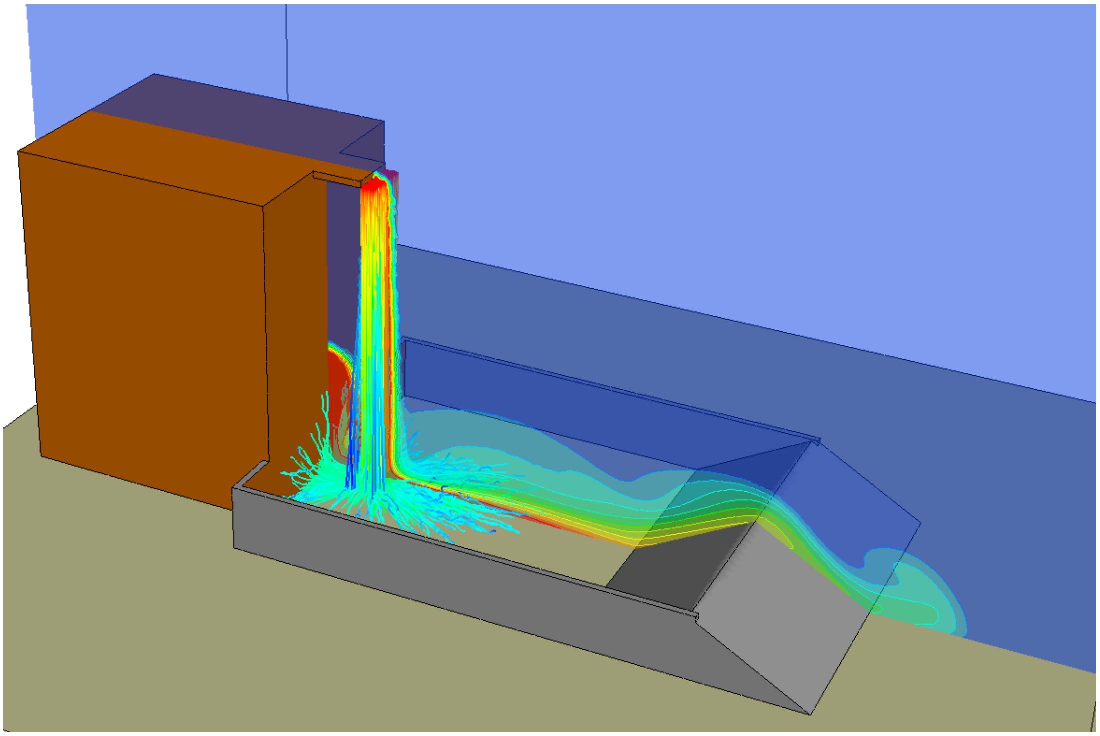

Figure 10: CFD model of one of the HSL tank overfilling experiments involving a sloping bund. This snapshot is taken 20s after the start of the release. Trajectories of spray droplets are colored according to the droplet temperatures and contours show the predicted vapor concentrations.

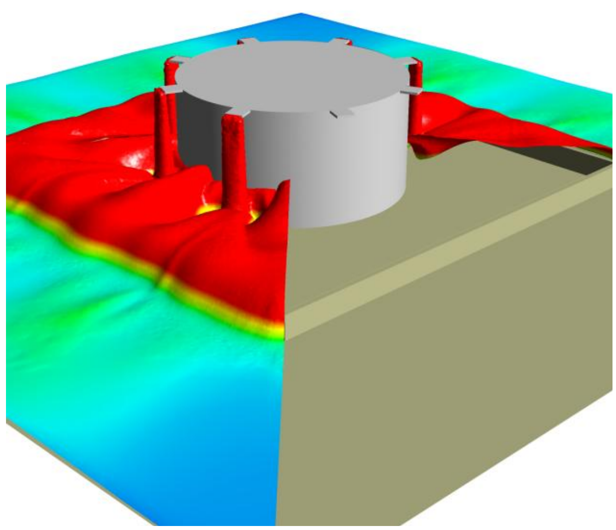

Figure 11: CFD model of an accumulating vapor layer within a bund. The plot shows a surface of the LEL concentration colored with height from the ground.