

## Jack Rabbit II 2015 trials: preliminary comparison of the experimental results against Drift and Phast dispersion model predictions

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In 2015 and 2016, two sets of large-scale chlorine release experiments were performed at the U.S. Army Dugway Proving Ground in Utah, USA. These experiments, known as the Jack Rabbit II trials, were carried out to improve our understanding of the potential consequences of a release of chlorine from a road or rail tanker. The work was part of a four-year programme and involved releases of 4.5 to 18 metric tons of chlorine with dispersion measurements up to a distance of 11 km from the source. The first set of trials in 2015 consisted of downward-directed jet releases from a 6 inch (0.152 m) diameter orifice, and dispersion through a mock urban array of obstacles. The subsequent trials in 2016 involved chlorine jet releases with a range of discharge angles and dispersion across open unobstructed terrain. The work followed on from the smaller-scale Jack Rabbit I experiments conducted in 2010.

The Health and Safety Executive (HSE) contributed to the Jack Rabbit II Modelling Working Group (MWG) by providing dispersion model predictions prior to the 2015 and 2016 trials, to help select appropriate locations for concentration sensors used in the experiments. Two different integral models were used by HSE: Drift 3.7.2 and Phast 7.11. The developers of these models worked with HSE to provide input and feedback on the predictions.

This paper compares HSE's model predictions of the 2015 Jack Rabbit II trials to the experimental data. The model predictions have been refined to take account of the actual release conditions and weather data, rather than use nominal values that were considered by the MWG prior to the experiments. Results are presented with sensitivity tests to assess the impact of uncertainties in modelling the experimental conditions. This includes tests on the source conditions and the effects of rainout and pool formation.

The dispersion results showed that the Drift and Phast models that incorporated rainout effects gave predicted maximum arc-wise concentrations in better agreement with the experimental data. This finding is consistent with video footage of the trials that showed the concrete test pad to become wetted by a pool of liquid chlorine.

**Keywords:** chlorine, flashing, impinging jet, dense gas dispersion, Jack Rabbit field experiments, consequence modelling

### Background and objectives

In 2015 and 2016, two sets of large-scale chlorine release experiments were performed at the U.S. Army Dugway Proving Ground in Utah, USA. Known as the Jack Rabbit II trials, these experiments were carried out to improve our understanding of the potential consequences of a large release of chlorine from a road or rail tanker. The work was part of a four-year programme led by the U.S. Department of Homeland Security and followed on from the smaller-scale Jack Rabbit I experiments conducted in 2010 (Hanna et al., 2012).

The Health and Safety Executive (HSE) contributed to the Jack Rabbit II Modelling Working Group (MWG) by providing dispersion model predictions for a 9 metric tons release of chlorine prior to the 2015 experiments (McKenna et al., 2016). The purpose of these simulations was to provide predictions of the likely maximum chlorine concentrations in the dispersing cloud, in order to help select the most appropriate locations for concentration sensors. The two integral models used by HSE to model the dispersion of the chlorine cloud were Drift (Tickle and Carlisle, 2008) and Phast (Witlox and Holt, 1999; Witlox and Harper, 2013). The developers of the dispersion modelling software worked with HSE to provide input and feedback on the predictions. GT Science & Software contributed towards the work on Drift and DNV GL Software contributed towards the work on Phast.

The main purpose of this paper is to compare HSE's model predictions of the 2015 Jack Rabbit II trials to the experimental data. Whereas the model predictions previously presented by McKenna et al. (2016) used nominal release and weather conditions, the results presented here take account of the actual release conditions and weather data from the five trials conducted in 2015.

### Jack Rabbit II 2015 experiments

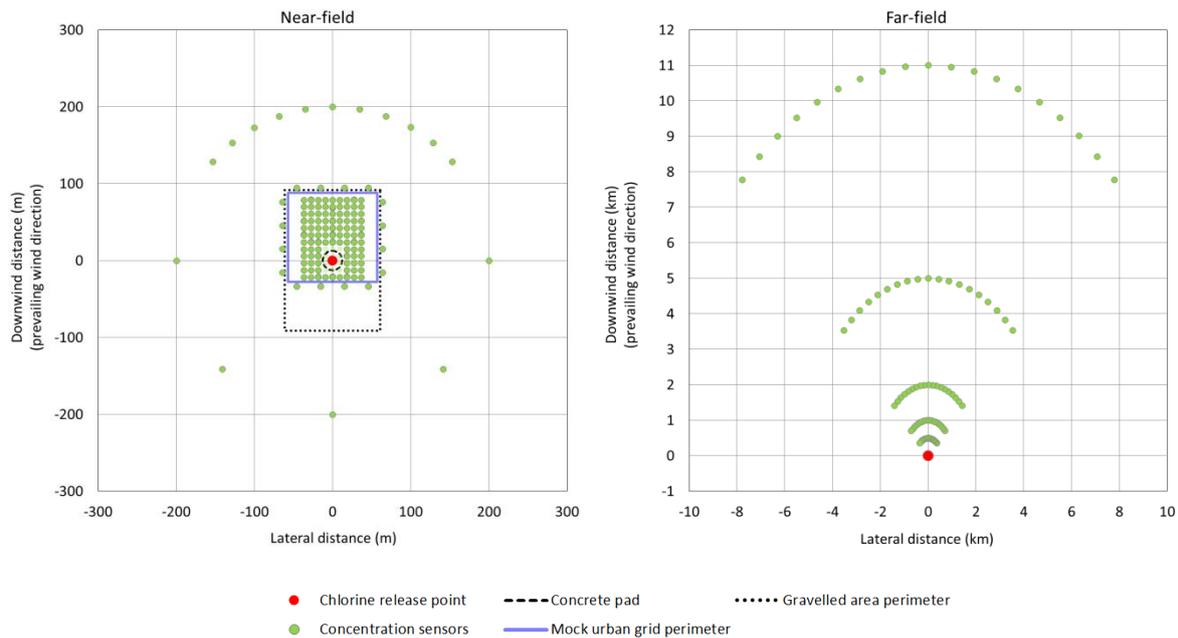
The first round of Jack Rabbit II experiments was carried out from late August to early September 2015 and consisted of five trials. Table 1 provides a summary of the experimental release conditions. Load cells and pressure gauges recorded the mass of chlorine and pressure inside the vessel. In the 2015 trials, chlorine was released vertically downwards through a 6 inch (0.152 m) diameter hole at the bottom of the vessel. The release mechanism involved a blanking plate that was fitted to the end of a short flange (8.3 cm long) using explosive bolts; the discharge was initiated by blowing those bolts. The bottom of the tank was 1 m above a circular concrete pad that was 25 m in diameter. The concrete pad was surrounded by a rectangular gravelled area that measured 183 m long by 122 m wide. An array of Conex shipping containers was

positioned on this gravelled area to represent a mock urban environment. The surface level of the gravelled area was approximately 0.6 m above the surrounding flat unobstructed desert surface (the playa).

**Table 1.** Experimental release conditions

Jack Rabbit II Trials: Dugway Proving Ground, Utah, USA							
Trial	Date	Release Time (local)	Mass of Chlorine (kg)	Initial Tank Pressure (barg)	Jet Release Angle	Release Height (m)	Obstacles
1	24/08/2015	07:35:45	4509	6.50	Directly downwards	1	Mock urban grid
2	28/08/2015	09:24:21	8151	6.06	Directly downwards	1	Mock urban grid
3	29/08/2015	07:56:55	4512	5.71	Directly downwards	1	Mock urban grid
4	01/09/2015	08:38:50	6970	5.16	Directly downwards	1	Mock urban grid
5	03/09/2015	07:28:19	8303	5.87	Directly downwards	1	Mock urban grid

The centreline of the array of Conex containers was aligned with the prevailing wind direction and the chlorine tank was located within the grid of containers, approximately 30 m from the upwind edge. The mock urban grid was approximately 122 m long by 122 m wide with an open area of gravel extending a further 61 m on the upwind side of the grid. The downwind locations for the concentration sensors outside the mock urban grid were along radial arcs at distances of 0.2 km, 0.5 km, 1 km, 2 km, 5 km, and 11 km from the chlorine tank. Figure 1 illustrates the geometric layout of the experiments and the proposed locations for the concentration sensors.



**Figure 1.** Geometric layout of the experiments

The mean obstacle height of the mock urban grid was 2.68 m and the lambda parameter, which is a dimensionless parameter used in many empirical urban boundary layer formulas (Britter and Hanna, 2003), was calculated to be 0.18. Accordingly, the surface roughness length ( $z_0$ ) for the mock urban grid was 0.4 m and, for the surrounding playa,  $z_0$  was estimated to be 0.001 m.

Portable Weather Instrumentation Data Systems (PWIDS) were deployed over the test site to record weather information, which included wind speed, wind direction, temperature, humidity and pressure. The layout of the PWIDS was fan-shaped, similar to the layout of concentration sensors shown in Figure 1, but it also included various other lateral and upwind positions. In total, there were 34 PWIDS mounted on tripods 2 m above ground level. The weather information shown in

Table 2 is taken from an average of all the PWIDS with the exception of Trial 2, which is taken from PWIDS 25 (located about 830 m upwind from the release point).

At present, data presented in Table 2 should be considered only as a preliminary assessment of the weather conditions in the Jack Rabbit II 2015 trials and these values may be updated in the future. There are plans to undertake a more thorough examination of the data from additional sensors that were present at Dugway Proving Ground, including information from weather stations that were mounted on three 32 m high towers. The stability classes given in Table 2 were taken from a Surface Weather Observation Form provided by Dugway Proving Ground. There was no stability class provided for Trial 1, so this was estimated by HSE to be Class F using a flow chart from the U.S. Army Research Laboratory report by Wetmore and Ayres (2000), which provides an estimate of the Pasquill stability class from the wind speed, cloud cover and the time of day.

The weather data and associated Pasquill stability classes are an area of uncertainty, particularly for integral models such as Drift and Phast that assume a fixed set of conditions for the entire duration of the dispersion period. The wind speed and stability changed during the course of the experiments (as indicated by experimental values of the Pasquill stability class in Table 2). It is the authors' intention to examine these uncertainties in future work by carrying out model sensitivity tests.

**Table 2.** Preliminary data for the weather conditions in the Jack Rabbit II 2015 trials

Jack Rabbit II Trials: Dugway Proving Ground, Utah, USA								
Trial	Wind Direction <sup>a</sup> (degrees)	Wind Speed <sup>b</sup> (m/s)	Atmospheric Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (Pa)	Pasquill Stability Class		Notes on physical measurements
						Experiment <sup>c</sup>	Model Inputs	
1	147	2.0	17.7	39.2	87,350	Not provided	F	Mean PWIDS data, 195 s before release
2	158	4.2	22.7	33.6	87,512	C → B	C	PWIDS 25, 441 s before release
3	169	3.9	22.5	30.3	87,097	D	D	Mean PWIDS data, 65 s before release
4	183	2.3	22.5	26.9	86,926	D → C → B	D	Mean PWIDS data, 70 s before release
5	182	2.7	22.2	26.5	86,653	D	D	Mean PWIDS data, 99 s before release
<sup>a</sup> Angle from which the wind was blowing. The urban grid and sensor arcs were aligned at an angle of 165 degrees. <sup>b</sup> Wind speed measurements were taken at a reference height of 2 m. <sup>c</sup> Values for stability class were taken from the Surface Weather Observation Form provided by Dugway Proving Ground.								

## Dispersion modelling tools

The two main software programs used by HSE for modelling the Jack Rabbit II trials were the integral models Drift and Phast. Drift was developed by ESR Technology and is used by HSE to model dispersion of toxic and flammable gases for land-use planning applications. The effect of the short release duration was represented using Drift's finite-duration model. To simulate the 2015 Jack Rabbit II trials, Drift 3.7.2 was used in conjunction with two other models. The first was Stream A.7, which is an outflow model developed by HSE. The second was Gasp (Webber and Jones, 1989), which is a pool spreading and evaporation source model also developed by ESR Technology; Gasp 4.2.12 was used for this work.

Phast is developed by DNV GL Software and is a comprehensive hazard analysis package that contains various sub-models, including vessel discharge, pool evaporation and atmospheric dispersion. The time-varying leak option in Phast 7.11 was used by HSE to model the 2015 Jack Rabbit II trials.

Drift and Phast do not allow variations in  $z_0$  within individual dispersion simulations. To take account of the change in  $z_0$  from the mock urban grid to the playa, two simulations were performed for each trial: a 'near-field' scenario that used a uniform  $z_0$  of 0.4 m, and a 'far-field' scenario using a uniform  $z_0$  of 0.001 m. The results were 'blended' together by matching the centreline concentrations at the boundary between the urban grid and the playa, at a distance of 100 m downwind from the release point.

Neither of the models accounted for dry deposition in the Jack Rabbit II simulations. Drift has the option of accounting for dry deposition, whereas it is not possible to include this effect in Phast. A number of previous studies have suggested that deposition could be important in dispersing clouds of chlorine. Simulations of the Graniteville chlorine railcar incident by Buckley et al. (2007) gave the best agreement with the observed vegetation damage and recorded health effects when a deposition velocity of 1 cm/s was used. Other modelling studies discussed by Hanna and Chang (2008) showed that half of the chlorine gas could be deposited to the ground within a few hundred metres of the source in low wind speeds and stable weather conditions. Since the model predictions presented here do not account for deposition, the concentration predictions might be expected to be higher than the measurements, particularly in the far-field.

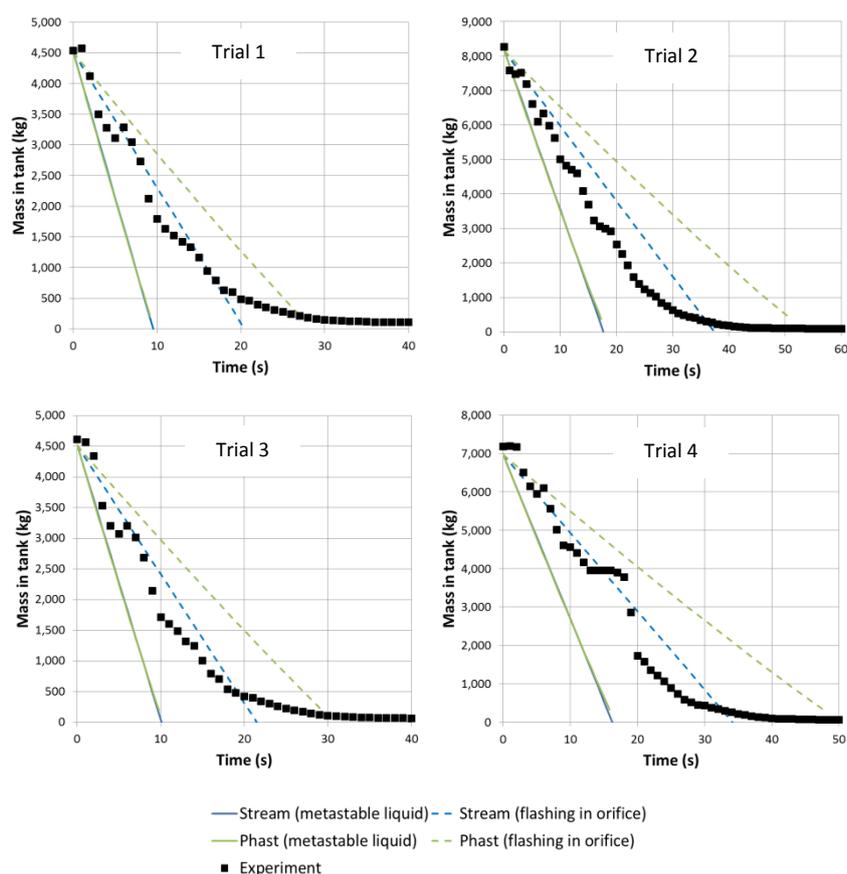
More information on the dispersion modelling methodology, impinging jet source models and evaporating pool source models can be found in HSE's earlier work (McKenna et al., 2016).

## Model comparisons against experimental data

### Discharge

The vessel deployed for the 2015 Jack Rabbit II experiments was mounted on load cells in order to determine the mass release rate of chlorine. The method used to calculate the mass of chlorine in the vessel as a function of time, and to account for the thrust forces from the chlorine jet, was presented by Spicer et al. (2016). Figure 2 compares the experimental data to the predictions from the Stream and Phast discharge models. Stream output data were used as inputs for the Drift model. Two different sub-models were tested in both Stream and Phast: one for metastable liquid outflow and the other for flashing two-phase flow through the orifice.

The review by Britter et al. (2011) suggested that for sharp-edged orifices (less than 10 cm in length—as in the case here), the flow has insufficient time to establish thermodynamic equilibrium and therefore the fluid remains in a metastable liquid state at the orifice. Analysis presented by Babarsky et al. (2016) of the Jack Rabbit II 2015 trials indicated that there was some liquid boiling within the vessel which led to a non-zero vapour fraction in the fluid flowing through the orifice. In contrast, the metastable models in Stream and Phast assume 100% liquid flow through the orifice. The results presented in Figure 2 show that these metastable liquid outflow models over-predict the discharge rate. The Stream and Phast models that assume flashing in the orifice tend to under-predict the measured flow rate, although Stream is in reasonable agreement with the experimental data for Trials 1 and 3. The measurements show that the mass flow rate declined after around 20 s, which suggests that the vapour fraction may have increased as the vessel depressurised. The reasons for the differences between Stream and Phast are currently under investigation. In future work, the authors plan to investigate the potential effect of the predicted release durations on the downwind dispersion model predictions using the analysis presented recently by Hanna and Chang (2017).



**Figure 2.** Comparison of model predictions to measurements of vessel discharge in Trials 1 to 4 (Stream and Phast metastable liquid lines lie on top of each other)

### Chlorine concentration measurements

Three different types of sensors were used in the Jack Rabbit II 2015 experiments. These measured concentrations along the radial arcs, at distances ranging from 0.2 km to 11 km downwind from the release point. There were three Canary sensors located on the 0.2 km arc, which were calibrated to measure concentrations up to 10,000 ppmv. MiniRAE sensors were used

on the arcs from 0.2 km to 2 km, which registered concentrations up to 2000 ppmv. Finally, ToxiRAE sensors were used at the 5 km and 11 km arcs and they measured concentrations up to 50 ppmv. Data from the MiniRAE sensors were corrected to account for calibration tests carried out before and after the trials, which meant that in some cases the maximum recorded concentrations exceeded 2000 ppmv. The experimental values presented for comparison to the model predictions, as shown in Figures 3 to 5a–e, consist of maximum arc-wise concentrations, i.e. the highest recorded concentrations at any of the sensors on a given arc, at any time during the trial. To put these concentrations into context, the Immediately Dangerous to Life or Health (IDLH) for chlorine is 10 ppmv<sup>1</sup>. The IDLH represents a level of toxicity that may pose life-threatening effects to an individual after a 30 minutes exposure, and it is just one of several defined toxicity criteria.

Analysis of the concentration measurements showed that some of the sensors were exposed to chlorine concentrations that exceeded their upper limits of detection. The time-varying concentration recordings in these cases showed a plateau that suggested the sensors became saturated. In other cases, it appeared that the bulk of the chlorine cloud bypassed the sensors, either because it was blown by the wind beyond the edge of the measurement array, or because the cloud was so narrow that most of the cloud passed between sensors. The data points that were affected by these issues are identified by triangular symbols in Figures 3 to 5a–e, which are also coloured according to the key provided in Table 3. Despite being affected by these issues, the data from these sensors are still very useful for model validation, but it should be recognised that concentrations at these downstream distances may have been higher in reality than indicated by these measurements. Unaffected data points are identified by black diamonds in Figures 3 to 5a–e.

It should also be noted that the measured maximum arc-wise concentrations presented here are based on a preliminary analysis of the data and they may subsequently be revised in the future. Although checks have been performed on data quality, the concentration data have not been averaged or filtered over time. These data represent the highest concentrations measured in each trial, as compared to the Drift and Phast integral dispersion models predictions, which represent ensemble-averaged concentrations. In order to be representative of peak concentrations, short averaging times were used in both Drift and Phast.

**Table 3.** Colour key for triangular data points presented in Figures 3 to 5a–e

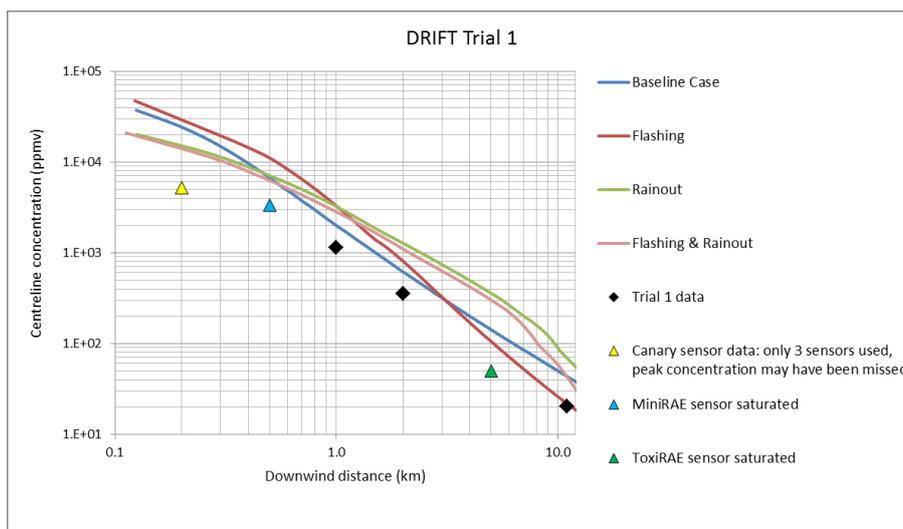
	Canary sensor data: since only 3 sensors were used, peak concentration may have been missed
	MiniRAE sensor saturated
	ToxiRAE sensor saturated
	Plume passed beyond edge of arc: maximum concentration may have been missed
	Narrow plume passed between sensors: maximum concentration may have been missed

## Dispersion

In order to establish reasonably conservative dispersion predictions, a ‘baseline’ case was modelled using Drift and Phast; these predictions assumed metastable liquid outflow and no rainout, i.e. the liquid chlorine droplets impinging upon the ground were assumed to remain in the dispersing cloud as an evaporating aerosol and not form a pool on the ground. However, video footage from the trials clearly showed the formation of chlorine pools on the concrete test pad. For this reason, sensitivity tests were performed using the rainout models in Drift and Phast. These models assumed that all of the liquid in the jet rained out at the point where it impinged on the pad and produced an evaporating liquid pool, which provided a secondary source of chlorine vapour in the dispersion simulations. Further sensitivity tests were carried out for Trial 1 assuming flashing two-phase flow through the orifice (both with and without rainout).

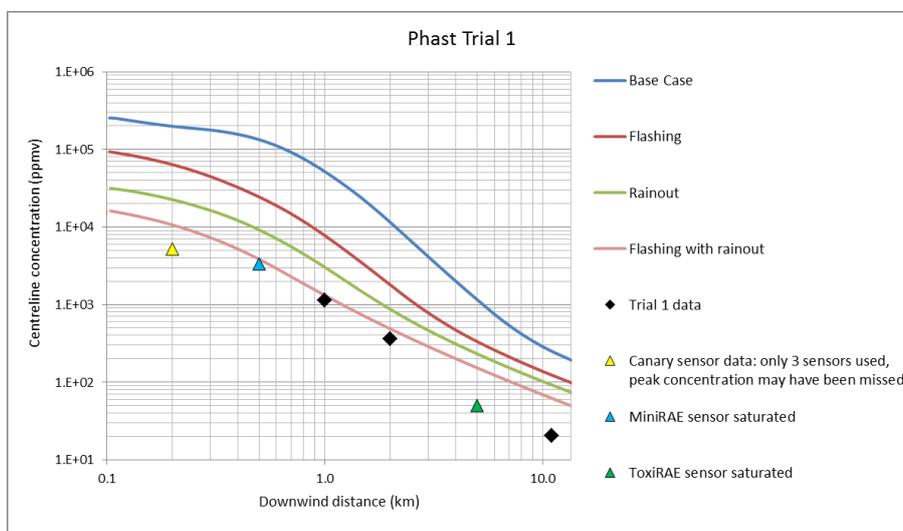
The predicted plume centreline concentrations from Drift are compared against the experimental results for Trial 1 in Figure 3. This trial involved a release of 4.5 metric tons of chlorine in a wind speed of 2 m/s. It is noticeable that the two models with rainout show a more gradual decline in concentration with distance between 0.5 km and 5 km, which may be related to the secondary source of vapour from the evaporating pool. The results previously presented in Figure 2 showed that the metastable liquid model over-predicted the chlorine release rate and the flashing model gave better agreement to the data.

<sup>1</sup> <https://www.cdc.gov/niosh/idlh/7782505.html>, accessed 10 February 2016.



**Figure 3.** Comparison of Drift dispersion modelling against Trial 1 data

The Phast predictions for Trial 1 are compared against the experimental data in Figure 4. The baseline model predictions are significantly higher than the concentration measurements, by at least an order of magnitude. The results from the sensitivity tests show consistent behaviour, with the baseline case being the most conservative (in terms of giving high concentrations) and the concentrations reducing with either the flashing discharge model or with the rainout model. The concentrations are lowest when both flashing and rainout options are combined, and this model follows the experimental results most closely. However, the model with both flashing and rainout still over-predicts the concentration at 11 km by a factor of three. One of the reasons for Phast over-predicting concentrations in the far-field may be that the time-varying model does not account for along-wind diffusion. A planned future release of Phast will address this issue.



**Figure 4.** Comparison of Phast dispersion modelling against Trial 1 data

The following set of graphs (Figures 5a–e) compares the concentration predictions from both Drift and Phast against the experimental data for each of the five trials. Results are only presented for the metastable liquid discharge model (with and without rainout), where the model without rainout has been taken as the baseline case. Flashing discharge models were not plotted here on the basis that metastable liquid outflow models would be the default choice, based on the recommendations of Britter et al. (2011).

Figure 5a shows a comparison of the models against Trial 1 data (that was presented separately in Figures 3 and 4). The most immediately obvious trend shown in this graph is that the Phast baseline case over-predicts the measured chlorine concentrations by an order of magnitude or more. The Phast rainout model performs better in terms of following the experimental data. The Drift baseline case provides the best fit to the experimental measurements out of the four models shown, although it over-predicts the concentrations at 1 km, 2 km and 11 km by around a factor of two. It is worth noting

that the atmosphere may have been less stable than the assumed Pasquill F-class during Trial 1, particularly at the furthest downwind locations (due to the 30–60 min cloud arrival time and increasing solar radiation post-sunrise). This may partly explain why Drift and Phast over-predicted the concentrations at these positions. However, a further complicating factor is that the wind speed increased towards the later stages of Trial 1 as the cloud approached the 11 km arc, and a higher wind speed may increase the predicted concentrations. It is commonly assumed that concentrations in dispersing plumes are higher in stable, low wind speed conditions, but for short duration dense gas releases this is not always the case (Hanna and Chang, 2014).

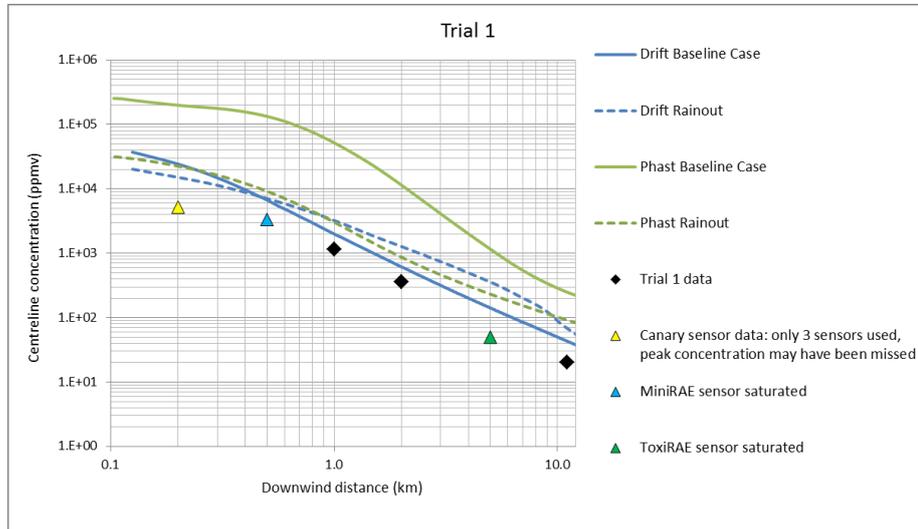


Figure 5a. Model comparisons against Trial 1 data

Figure 5b shows the results for Trial 2, which involved a release of approximately 8.2 metric tons of chlorine in a wind speed of 4.2 m/s. In this trial, the Phast rainout model performs best against the experimental data, with concentrations within a factor of two at 2 km and 11 km. The Phast baseline case again provides the most conservative prediction. The Drift baseline case is also conservative in the near-field, but it under-predicts concentrations at the 5 km and 11 km arcs. The Drift rainout model is within a factor of two at 0.5 km, 1 km and 2 km, but it under-predicts the chlorine concentration at 5 km and 11 km. Sensitivity tests were undertaken with Drift using a lower release rate and longer release duration to match the measured release behaviour (not shown here) which gave slightly higher predicted concentrations at the 11 km arc, but the concentrations were still lower than the measured value.

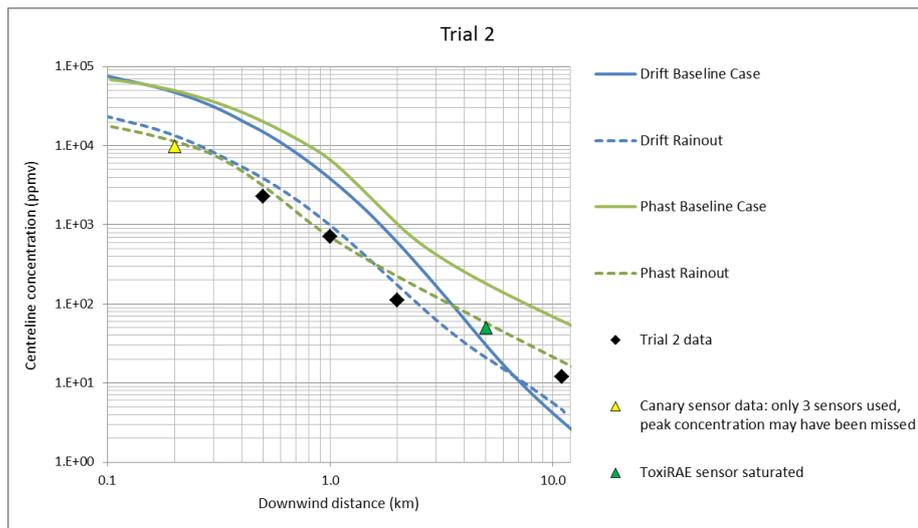
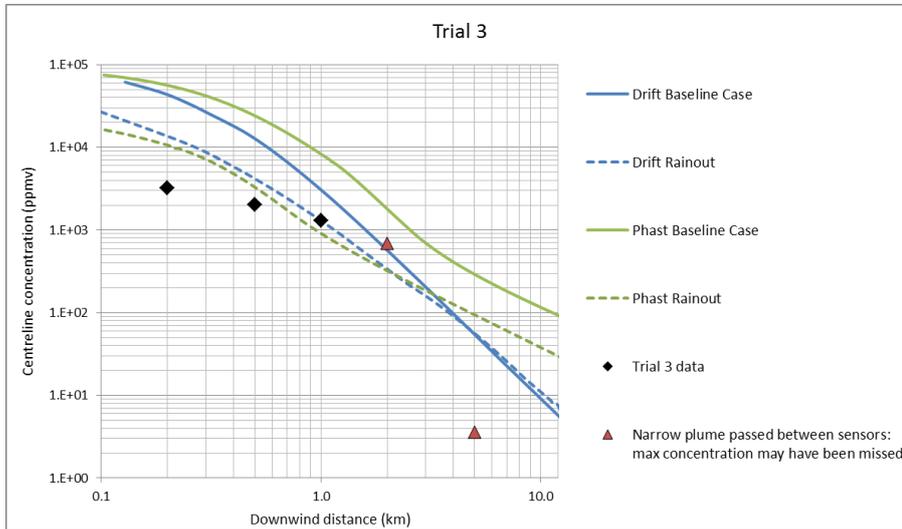


Figure 5b. Model comparisons against Trial 2 data

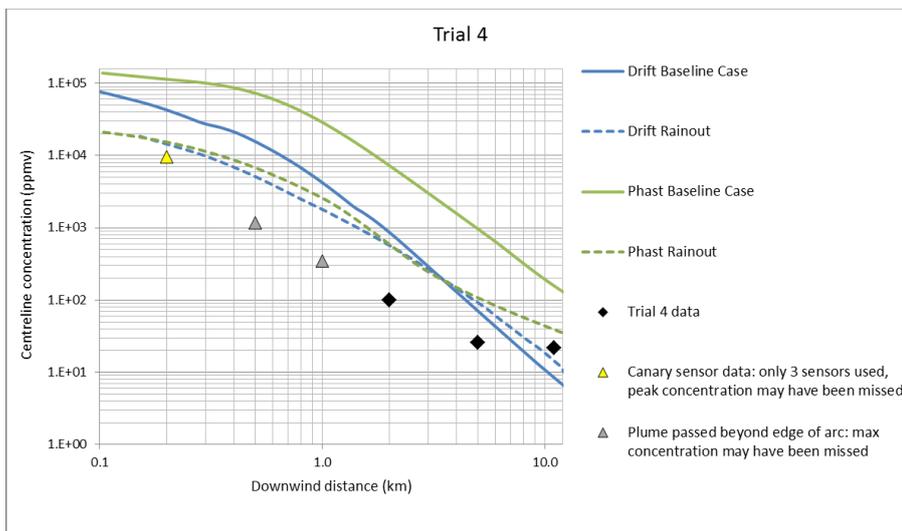
Figure 5c shows the results for Trial 3, which involved a release of 4.5 metric tons of chlorine in a wind speed of 3.9 m/s. Analysis of the experimental data in this case suggests that a narrow chlorine cloud formed that passed between sensors in

the far-field, at positions beyond 1 km. No significant concentrations were recorded by the sensors located at the 11 km arc. It is therefore difficult to draw any firm conclusions about the models' performance beyond 1 km in this case. The Drift and Phast rainout models perform better than the baseline cases for the measured concentrations up to 1 km, although Phast under-predicts the chlorine concentration at 1 km (but is still within a factor of two). Both of the rainout models under-predicted the maximum concentration recorded at 2 km, where the actual concentration at this position was probably higher than the measured value.



**Figure 5c.** Model comparisons against Trial 3 data

Figure 5d shows the results for Trial 4, which involved a release of 7 metric tons of chlorine in a wind speed of 2.3 m/s. It is difficult to draw conclusions about the models' performance in the near-field up to 1 km, due to uncertainty in the experimental measurements. The final two data points at 5 km and 11 km also do not follow the expected exponential decay rate of concentration with distance. The models with rainout appear to perform better than the baseline cases in this trial. The Drift rainout model under-predicts the plume concentration at 11 km, but it is still within a factor of two. The Drift baseline case under-predicts the concentration at this distance to a greater degree.



**Figure 5d.** Model comparisons against Trial 4 data

Figure 5e shows the results for Trial 5, which involved a release of 8.3 metric tons of chlorine in a wind speed of 2.7 m/s. There is only one unaffected data point in this Trial. The wind direction caused the bulk of the cloud to move outside the array of sensors between 0.5 km and 2 km. The cloud then moved back into the sensor array at 5 km, but the ToxiRAE sensors on this arc saturated. Therefore, the actual concentrations were probably higher than indicated by most of the data points on the graph. The four model predictions are higher than the measurements, with the two Drift predictions showing

best agreement with the data at 11 km. The Phast baseline model again predicts noticeably higher concentrations than the other models, while the Phast rainout model over-predicts concentrations at the 11 km position by around a factor of six.



**Figure 5e.** Model comparisons against Trial 5 data

In considering all five trials, the Phast predictions show a similar pattern where the baseline model over-predicts the measured chlorine concentrations at all distances by roughly an order of magnitude. The Phast rainout model is in much better agreement with the measurements, although it under-predicts concentrations in Trial 3 at 1 km and 2 km, and over-predicts concentrations in the far-field at 11 km in the other trials. This trend towards over-prediction in the far-field may be a consequence of the fact that the current time-varying model in Phast does not account for diffusion in the along-wind direction.

For Drift, the baseline results are in better agreement with the measurements than the Phast baseline results, but the model still over-predicts all of the measured concentrations in the near-field, up to a distance of 1 km. The Drift model with rainout provides predictions in closer agreement with the experiments. Drift also under-predicts chlorine concentrations on more occasions than Phast (with or without rainout), notably in the far-field at the 11 km position, where concentrations were close to the IDLH value of 10 ppmv. However, the degree of under-prediction was relatively modest.

There are a number of dispersion modelling input uncertainties that should be kept in mind when reviewing these results. Firstly, regarding the source conditions, the model predictions presented in Figures 5a–e used the metastable liquid outflow model which was shown in Figure 2 to over-predict the release rate. The sensitivity tests in Trial 1 (Figures 3 and 4) showed that this gave rise to consistently higher predicted concentrations in the dispersing cloud with Phast, and a more complex pattern of behaviour with Drift. Secondly, there is uncertainty in the amount of rainout. The models gave predictions that agreed best with the data when it was assumed that all of the liquid in the impinging jet rained out and formed a pool, which was consistent with observations of pool formation in the experiments, although in reality a fraction of the liquid probably remained in the dispersing cloud as an aerosol. Thus, the Drift and Phast models with rainout are expected to over-predict the amount of rainout (and not account for evaporating droplets in the dispersing cloud), which may lead to an under-prediction of concentrations. The source terms in Drift and Phast also do not account for the increased turbulence levels resulting from the impinging jet. A further uncertainty relates to the treatment of atmospheric conditions. The weather data provided as input to the models was based on a preliminary assessment; the conditions may be refined in due course. The wind speed and weather conditions were also assumed to be constant in the models, whereas in many cases the wind speed increased and the atmosphere became progressively less stable in the later stages of the dispersion period, when the cloud was reaching the furthest downwind sensors. None of the simulations took into account the effects of dry deposition, which would tend to decrease the predicted concentrations below the levels shown here, particularly in the far-field.

In addition to these modelling uncertainties, there is uncertainty in some of the data points. These relate to sensors not capturing the cloud centreline concentration and issues with sensors reaching saturation levels. The maximum arc-wise concentrations were not time-averaged or filtered, whereas the model predictions used short averaging times. Averaging of the data would tend to reduce the measured concentrations. In field scale tests such as these with short duration releases, it is also expected that there will be variability between trials, even under nominally identical conditions, due to the effects of turbulence in the atmosphere.

HSE intends to carry out work on the second round of Jack Rabbit II trials which took place in 2016. This involved a range of discharge angles and dispersion across open and unobstructed terrain. It will provide an opportunity to carry out further analysis of model performance for different jet orientations.

## Conclusions

Comparisons have been presented between two integral dispersion model predictions (Drift and Phast) and a preliminary dataset of measurements from the five Jack Rabbit II 2015 trials. These experiments involved releases of 4.5 to 8.3 metric tons of pressure-liquefied chlorine through a 6 inch (0.152 m) diameter hole in the underside of a vessel, at a height of 1 m above the ground. A baseline set of simulations was performed in which the models assumed that chlorine was discharged from the vessel in a metastable liquid state. The jet of chlorine impinging on the ground was assumed not to produce a pool, instead the liquid was assumed to remain in the dispersing cloud as an evaporating aerosol of droplets. Sensitivity tests were also performed with (a) a discharge model that allowed flashing in the orifice, and (b) for the liquid impinging upon the ground to rainout and form an evaporating pool.

Comparison of the models to the discharge measurements showed that the metastable liquid outflow models over-predicted the mass release rate. The Stream discharge model that assumed flashing in the orifice gave results that were in better agreement with the data, whilst the Phast flashing model under-predicted the discharge rate.

The dispersion results showed that the Drift and Phast models that incorporated rainout effects gave predicted maximum arc-wise concentrations in better agreement with the experimental data. This finding is consistent with video footage of the trials that showed the concrete test pad to become wetted by a pool of liquid chlorine.

When the rainout models were used, the predicted concentrations from Drift and Phast were similar to each other up to a distance of approximately 2 km, and sometimes beyond. Further downwind, the Phast concentrations were higher than those predicted by Drift in most cases. This was probably due to the Phast time-varying model neglecting the effects of along-wind diffusion, which were taken into account by Drift. A planned future release of Phast will address this issue.

Both models under-predicted chlorine concentrations on occasion in the far-field, Drift more so than Phast. In two of the trials, Drift under-predicted concentrations at the 11 km arc, where concentrations were close to the IDLH threshold of 10 ppmv. Neither the Phast nor Drift models took into account the effects of dry deposition, which would tend to reduce concentrations below the levels shown here.

It should be noted that the experimental data presented here is only preliminary and it may be subject to change. Furthermore, there are a number of modelling and measurement uncertainties that will be investigated in future work.

## Future Work

HSE's post-processing of the experimental data to determine the maximum arc-wise concentrations was only an initial assessment and further work is needed to examine the impact of averaging times. HSE also plans to compare model predictions to measured values of the toxic load, calculated from the integral of the time-varying measured concentrations. Recent results have been presented for the measured toxic load in the Jack Rabbit trials by the Institute for Defence Analysis (Luong et al., 2016).

The weather data and associated Pasquill stability classes are another area of uncertainty that will be investigated further. This will require analysis of meteorological data from equipment such as the 32 m weather towers and a more thorough examination of Pasquill stability classes. Sensitivity studies will be performed to assess the impact of uncertainties in the wind speed and stability class.

Further work is also planned to investigate the source conditions. Results were only presented for Trial 1 using the flashing discharge models in Stream and Phast. It is planned to investigate the model behaviour for the other trials and to examine in more detail the recent work by Hanna and Chang (2017).

HSE also intends to carry out similar work on the second round of Jack Rabbit II trials which took place in 2016. These trials involved a range of discharge angles and dispersion across open, unobstructed terrain.

## Disclaimer

The experimental data presented in this paper is preliminary, pending further analysis by the Jack Rabbit II Data Quality Working Group.

GT Science & Software contributed towards the work on Drift, and DNV GL Software contributed towards the work on Phast, but the Drift and Phast simulations presented in this paper were performed by HSE and have not been independently checked by the software developers.

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