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The Jack Rabbit chlorine release experiments: Implications of dense gas removal from a depression and downwind concentrations

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ABSTRACT

The Jack Rabbit (JR) field experiment, involving releases of one or two tons of pressurized liquefied chlorine and ammonia into a depression, took place in 2010 at Dugway Proving Ground, Utah, USA. The releases, of duration about 30 s from a short pipe at a height of 2 m, were directed towards the ground. The dense two phase cloud was initially confined in a depression of 2 m depth and 50 m diameter. With wind speeds < about 1.5 m s^{-1}, the cloud stayed in the depression for 30–60 min, during which it was slowly detrained and moved downwind. At wind speeds > about 1.5 m s^{-1}, the initial cloud was not well-confined in the depression and moved downwind. Formulas suggested by Briggs et al. in 1990 in this journal satisfactorily predict the time durations of confinement. Sensitivity runs with the SLAB dense gas model show that the effect of a long confinement on maximum downwind concentrations is strongest near the depression. The model-predicted and observed maximum 20 s chlorine concentrations agree within a factor of two most of the time, as long as the release times based on Briggs' theory are used.

1. Background and objectives

Large amounts of chlorine are transported around many countries in railcars and trucks, and are stored in fixed tanks at industrial facilities and at end-user sites. Most is stored as a pressurized liquefied gas at near-ambient temperatures. In a chlorine railcar accident, as much as 50–100 tons of chlorine can be released in a time period of a few minutes or less [1]. Other types of chlorine release scenarios are also of concern, such as a hole in a pipeline [2], a valve failure on a one-ton "bullet" [3], and a leak from a chlorination facility [4].

Due to three effects—the high molecular weight, the cold temperature of the release, and the high concentrations of small aerosol drops—the chlorine aerosol cloud can have an effective initial density as much as 20 times that of ambient air. Thus the initial cloud behaves as a dense gas after the initial mass release and the associated momentum jet become insignificant.

Chlorine is known to be quite toxic and hence a large release from a railcar has the potential to have a significant effect on the nearby population. Six widely-used dense gas models were applied [1] to three accidents during the past decade involving large (30–60 tons) releases of chlorine from railcars (Festus, MO; Macdona, TX; and Graniteville, SC). The six models had previously been shown to agree fairly well with each other and with the observed concentrations at several research-grade dense gas field experiments [5]. The six models also agreed fairly well with each other on their predictions for the three railcar accidents [1]. There were no observations of chlorine concentrations during the initial large release period at the sites of the accidents, but there were records of casualties. There were only a few casualties and all within a few hundred meters of the release. If the current accepted relations between concentrations and health effects were assumed to be correct, then the predicted concentrations would imply many more casualties than observed and over a broader area.

Several possible reasons for the difference between observed and expected casualties have been suggested. The relation between exposure and health effects is under investigation [6]. The possibilities of removal of chlorine gas and aerosol by chemical reactions [7], by dry and wet deposition [8,9], and by collection on vegetation are being studied. The uncertainties regarding the very large source emissions term and the aerosol properties are being assessed [10], as well as possible removal due to the impaction of the aerosol jet on the ground. Another concern, and the subject of the Jack Rabbit (JR) field experiment studied here, is the possible "hold-up" of the large dense aerosol cloud formed around the source, especially

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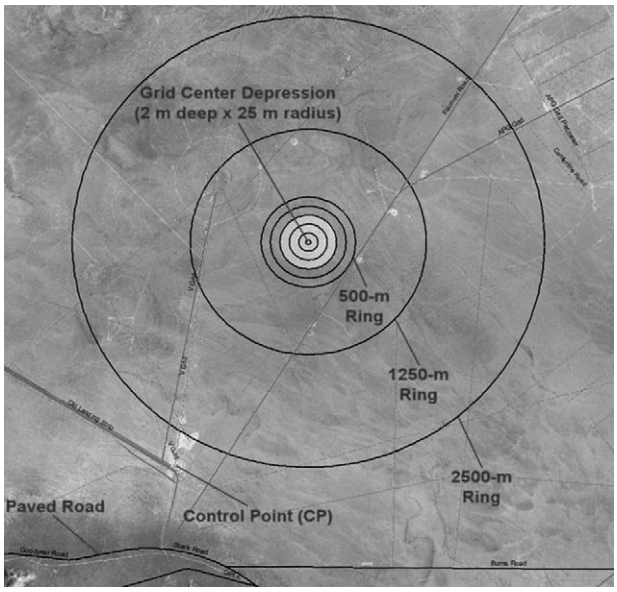

Fig. 1. Jack Rabbit field site, showing source location (grid center depression) and rings of samplers. Figure courtesy of Dugway Proving Ground.

Fig. 2. Jack Rabbit chlorine release site, showing the 50 m diameter by 2 m deep depression and the tank set-up. This is the one-ton pilot release (Trial 2, see Table 1). The photo was taken about 2 s after the chlorine release began. Photo courtesy of Dugway Proving Ground.

during light wind stable conditions and with a natural depression in the area [11]. With a larger "hold-up" time (i.e., release duration), there is expected to be smaller downwind concentrations, at least near the source, since the mass release rate (g/s) is inversely proportional to release duration.

No research-grade field experiments have been conducted with a full scale chlorine release of 60–90 tons from an actual railcar. That experiment would be difficult and dangerous. However, as described in this paper, one or two tons of chlorine were released during each trial of the Jack Rabbit field experiment, providing fundamental data that can be used to develop a universal understanding. It is hoped that the results can be scaled to a full size railcar release.

2. Overview of Jack Rabbit field experiment

The Jack Rabbit field experiment took place at a flat desert location in Dugway Proving Ground, Utah, USA, in April and May of 2010 [12]. The desert surface was modified by construction of a 50 m diameter by 2 m deep bowl-shaped depression, with the release occurring at the center. The central area of the depression was flat with radius about 12 m. One ton releases of both anhydrous ammonia and chlorine were initially conducted as a test of the release mechanism and measuring systems. These were called Trials 1 and 2 under the "pilot test" category. They were followed by the "record tests" consisting of four two ton anhydrous ammonia releases (Trials 3, 4, 9, and 10) and four two ton chlorine releases (Trials 5, 6, 7, and 8).

The JR field site is shown in Fig. 1, where the source location and some of the sampling rings are indicated. There were several types of concentration samplers and meteorological sensors employed, as well as many video and still cameras. The control point (CP) in the lower left part of the figure, about 2700 m SW of the release, is where the field experiment personnel were located during each trial.

This paper focuses on the chlorine releases. The JR chlorine was stored as a pressurized liquefied gas at ambient temperature, with high enough pressure that the two-phase release (a mixture of about 20% gas and 80% liquid, by mass) generated small aerosol drops (about 10 μm) which did not settle out (i.e., rain-out) appreciably. The videos of the JR releases show a large volume of two-phase cloud, with a characteristic yellow-green color.

By using a short downward-pointing pipe at the bottom of the storage tank elevated 2 m above the bottom of the depression, the chances of the dense cloud remaining in the depression were optimized. The pipe and valve were designed to minimize flashing in the pipe prior to release from the aperture, and therefore maximize the mass release rate. The jet impacted a steel plate on the ground. Although some of the chlorine aerosol was deposited on the surface by impaction and some of the chlorine was also absorbed into the ground (packed desert sand), the magnitude of this removal appeared to be only a small fraction of the total mass released. Nevertheless, due to degassing of chlorine from the ground after the major part of the cloud moved away, it was not safe to allow personnel back to the site for an hour or so afterwards.

Fig. 2 is a photo from JR Trial 2, showing the depression, the chlorine disseminator, the flashing chlorine jet, and the radial-moving chlorine cloud at about 2 s into the test. The time duration of the flashing chlorine jet was about 30 s. Fig. 3 shows the cloud at later times for the same trial. Because of the light ambient winds (0.6 m s^{-1} at a height of 2 m), the doughnut-shaped dense wall jet is nearly axisymmetric in the left photo, when the two-phase jet is still evident at the release point. After the initial source ceases (see the right photo), a nearly still dense cloud, of depth about 1 m, fills most of the depression. The dense cloud was observed to be

Table 1
Meteorological conditions observed at a height of 2 m for the five Jack Rabbit chlorine release trials.

Trial	Mass Released	Date	Release time (local time)	Wind speed (m s^{-1})	Wind direction (°)	Temperature (°C)
2-PC	1 ton	04/08/10	0745	0.6	84	−0.3
5-RC	2 tons	05/03/10	0720	1.6	346	3.5
6-RC	2 tons	05/04/10	0740	6.2	20	6.1
7-RC	2 tons	05/05/10	0705	1.4	235	6.3
8-RC	2 tons	05/07/10	0650	1.2	160	−2.9

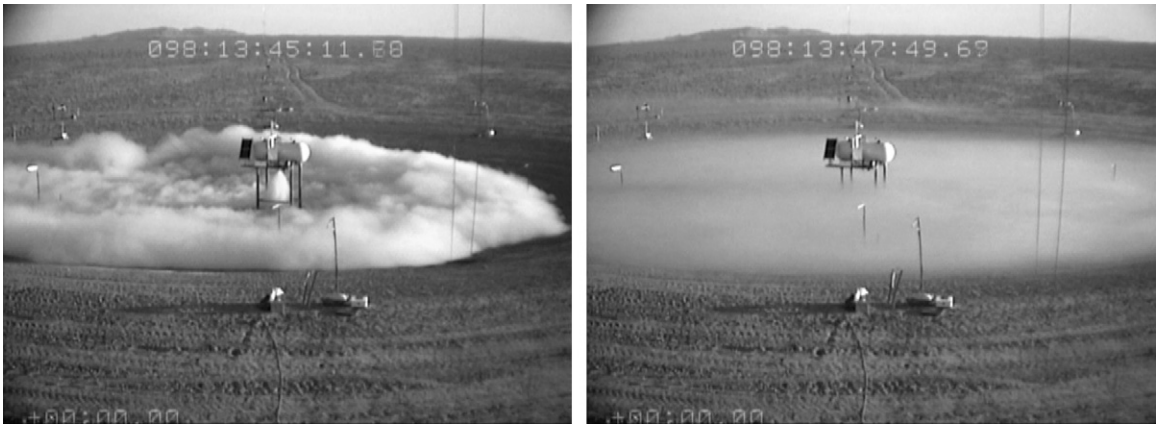

Fig. 3. Jack Rabbit Trial 2 (see Table 1) chlorine cloud, at 22 s (left) and 180 s (right) after the release began. This is the same one-ton pilot release shown at 2 s after release in Fig. 2. Photos courtesy of Dugway Proving Ground.

held-up for a relatively long time (30–60 min) in the depression due to the very light winds.

Table 1 provides a summary of the meteorological conditions for the five JR chlorine tests. The target JR test conditions were steady low speed winds and a stable boundary layer; therefore, the tests were conducted in the early morning, as soon after sunrise as possible. In four of five chlorine tests, low wind conditions were achieved, with wind speeds of 0.6–1.4 m s^{-1} (at a height of 2 m), allowing the dense chlorine cloud to persist in the depression for many minutes after the release stopped. However, for JR Trial 6, with the largest (6.2 m s^{-1}) wind speed, there was no significant chlorine cloud persistence beyond the 30 s release duration period (see Fig. 4). The cloud does not extend across the entire depression but is seen to be swept downwind with minimal hold-up.

Concentrations were measured by several types of samplers, including those that reported rapid-response concentrations every second, and others that reported concentrations integrated over a prescribed time period (i.e., dosages) covering the entire time of cloud impact, such as 30 min to 2 h. Many fast-response MiniRAE samplers were set out at positions around the circles at distances (such as 50, 100, 200, 300, and 500 m) shown in Fig. 1. Remote sampling of the cloud also took place. Extensive meteorological measurements were taken; e.g., winds were observed by a network of standard anemometers as well as by several sonic anemometers.

3. Source release rate from tank and initial momentum jet behavior

Calculations of hazard effects are dependent on good inputs of the source release rate and the chemical and physical properties of the release. Some formulations for estimating source emissions from tanks containing pressurized liquefied gas are available [10] and these have been used in the JR planning and analysis. The characteristics of the pipe were specially designed to assure a release time of a few tens of seconds at most and to avoid flashing inside the release pipe [12]. Thus the designed (and actual observed) mass emission rate is in the range of about 30–40 kg s^{-1}. For the one ton (908 kg) and two ton (1816 kg) tank inventories in Trials 2 and 6, respectively, the release time (duration) is estimated using the so-called Omega method [10] to be in the range from about (908 kg)/(40 kg s^{-1}) = 23 s to about (1816 kg)/(30 kg s^{-1}) = 60 s, which is fairly close to the observed range of release times (durations).

After the two-phase jet ceased, there was a period of gas release from the pipe aperture lasting a few more seconds but with much less mass flux. This gas mass emission rate is much less than that for the two-phase release.

Most transport and dispersion models cannot handle the above source inputs defined at the release aperture, since they are not able to account for the subsequent depressurization and expansion, the thermodynamic effects in the strong momentum jet, the uncertain angle of the jet, the possible impactions of the jet on the underlying surface and nearby obstacles, and a host of other factors. Most of these models prefer to receive their inputs at some point after the significant momentum effects are no longer evident. Recently, models such as SCIPUFF [13] have been modified to better treat the flashing momentum jet, but these models do not account for all of the complicating factors mentioned above.

The momentum flux dominated the flow near the source when the chlorine was being released from the bottom of the tank. The buoyancy flux (negative in the case of a chlorine release) dominated the flow in the region after the momentum jet was no longer clearly evident. During JR, the downwards-directed momentum jet impacted the hard pad constructed beneath the tank, and turned (without energy loss) to travel radially. The resulting radial wall jet would have radial momentum equal to the previous vertical momentum. The radial jet during Trial 2 can be seen in Figs. 2 and 3. The cloud height h is proportional to the radial distance from the source and the leading edge may have a larger h, leading to a doughnut-shaped cloud. The flow in the radial wall jet "looks" highly turbulent, as seen in Fig. 2 through 4. Using the knowledge that the bottom of the pipe aperture under the tank in the figures is 2 m above the basin (depression) floor, the average height, h, of the radial wall jet can be estimated by eye to be about 1 m. However, it is difficult to simulate this accurately with a model because of the many uncertainties (angle of jet, local topography within 50 m, surface hardness of the ground at the point of jet impaction, etc.).

The JR videos and still photographs show that, for wind speeds less than about 1.5 m s^{-1}, the radial jet extended to the edge of the depression. For higher winds (6.2 m s^{-1}) in Trial 6 (see Fig. 4), the radial jet was distorted in the direction of the ambient wind flow, but still extended about 2–4 m upwind. As expected from theory, the turbulent momentum jet seen in the videos quickly quieted down within a few seconds of the cessation of the flashing release at the source aperture.

4. Dense gas cloud behavior, including entrainment and detrainment

After the momentum jet effects become small, the JR chlorine cloud transitioned so that it was dominated by the conditions in

Fig. 4. Jack Rabbit Trial 6 (see Table 1) chlorine cloud, at 3 s (left), 34 s (center) and 180 s (right) after the release began. This is the high wind (6.2 m s^{-1}) trial. Photos courtesy of Dugway Proving Ground.

the ambient atmosphere, by the buoyancy (negative) of the cloud, and by the underlying topography. The dense cloud movement and dilution were strongly affected by (1) the entrainment of ambient air into the chlorine cloud (the standard view for a pollutant plume), and/or by (2) the detrainment of chlorine from the dense cloud into the overlying ambient atmosphere (the view of most relevance to the JR cloud).

Briggs et al. [14] review the literature on "standard" entrainment into unconfined dense plumes being transported in the lower part of the atmospheric boundary layer. Britter et al. [15] focus on vertical entrainment into passive or neutral (non-buoyant) plumes, over flat surfaces with no hills or depressions. Briggs et al. [11] and Castro et al. [16] address the special case of a dense cloud initially confined in a two-dimensional (2D) valley or depression, where the dense gas can escape the valley only by detrainment out of the top of the confined cloud. Thus these papers are very relevant for the JR scenario. The difference between entrainment and detrainment is that in entrainment, the ambient air is being mixed into the plume, while in detrainment, the plume material is being (slowly) mixed into the ambient air. Entrainment is a much faster process, while detrainment is more appropriate for scenarios such as a dense cloud confined in a depression.

The vertical entrainment velocity, w_e, for ambient air being entrained into a passive plume is best expressed by $0.65u^*$, where u^* is the friction velocity [15]. For dense clouds over flat rural terrain, $w_e = 0.65u^*/(1 + 0.2Ri^*)$ where the in-cloud local Richardson number, Ri^*, equals $g'_s h/u*2$ and $g'_s = g((\rho_p - \rho_a)/\rho_a)$ [14]. In this equation, g is the acceleration of gravity, ρ_p is local plume density, ρ_a is ambient air density, and h is the cloud depth. The term g'_s is g weighted by the ratio of the relative density difference between the plume and the ambient air. The term Ri^* is the ratio of the static energy (due to density excess and expressed as $g'_s h$) of the plume divided by u^{*2}, which is proportional to the square of the wind speed or the kinetic energy of the ambient flow. Thus for very small excess densities and/or very large wind speeds, w_e approaches the value for a passive plume. The term w_e decreases as Ri^* increases, until at $Ri^* > 20$, molecular diffusion (at $\kappa = 0.15$ cm^2 s^{-1}) takes over (i.e., the cloud is so dense that there is no turbulence at its upper edge) [14]. The general dense gas entrainment formula above is found in a similar but slightly different form in all widely used dense gas models [13,17–21].

For the valley or depression, a different approach is needed because the dense cloud is confined. Briggs et al. [11] study the very dense case, where detrainment occurs mainly on the upwind top edge of the dense cloud in the valley. Their work built on previous related studies by Seeto [22] and Britter and Snyder [23]. Briggs et al. [11] calculate that v, the chlorine volume flux per unit cross wind distance (units of m^2 s^{-1}) on the downwind edge of the valley, is proportional to U^3/g'_i, where U is the wind speed "above the cloud in the valley" and g'_i is $g(\rho_p - \rho_a)/\rho_a$ in the initial cloud in the valley. The proportionality constant is found to be 0.05. This solution is valid for high Reynolds number, Re, and low Froude number, Fr. Note that this relation indicates a strong (cubic) dependence on wind speed, U. The cubic relation is also found for other "lift-off" phenomena, such as the mass flux of small dust particles raised up by the wind blowing across the surface. Also there is no dependence on the along-wind dimension, W, of the dense gas cloud, because most of the detrainment occurs close to the upwind edge for very dense clouds [11].

The above solution applies to a steady state dense gas inflow that approximately balances the outflow (i.e., a continuous release). Briggs et al. [11] also studied cases where an instantaneous dense gas cloud is initialized in the valley and then is "scoured out" or "evacuated" by the detrainment over time. This scenario is more consistent with the JR scenario. A time scale, t_f, for evacuation is defined as equal to the cross-sectional area of the dense cloud in the valley, $(Wh/2)$, times g'_i/U^3, where h is the dense gas cloud depth. A normalized volume flux, $V' = vg'_i/U^3$ is plotted versus normalized time, $T = t/t_f$. The following relation is derived:

$$V' = 0.06\exp(-0.05T) \quad (1)$$

The wind tunnel experiments conducted by Briggs et al. [11] were idealized. Nevertheless, the recommended formulas provide a framework for analyzing and interpreting the JR data.

Castro et al. [16] extended the Briggs et al. [11] work to dense gas clouds in valleys with only slight density effects (i.e., low Ri^* and g'_i). In this case the detrainment occurs over the entire surface instead of just at the upwind edge. It is not certain whether, in the limit as the valley becomes very shallow, this solution approaches the solution for the vertical entrainment velocity, w_e, of ambient air into a dense gas on a flat underlying surface (i.e., no valleys or hills or other topography variations) as derived by Briggs et al. [14].

Worked examples of the application of the formulas to chlorine releases are provided [11,16]. Briggs et al. [11] use a scenario with a mass release close to the JR Trial 2 scenario, applying their formulas to a 1000 kg chlorine gas (not aerosol) nearly instantaneous release into a holding pond (depression) that is 30 m square. Castro et al. [16] use a scenario where 60 tons of chlorine are released (similar to the mass released at the Macdona and Graniteville chlorine railcar accidents [1]) nearly instantaneously over a 400 m cross-wind span at the bottom of a valley of along-wind dimension 250 m and depth 50 m. For Briggs et al.'s [11] example, it is calculated that fully

turbulent entrainment occurs at $U > 1.23\ m\ s^{-1}$. For $U = 1\ m\ s^{-1}$, the model estimates that the wind will evacuate the pond in 40 min, and "For diffusion beyond the pond, this practically could be treated as a continuous source of chlorine gas" [11]. For the same example, a $5\ m\ s^{-1}$ wind speed gives full evacuation in a time of about 25 s. These predicted times are close to what was found at JR for Trials 2 and 6 (seen in Figs. 2–4).

5. Downwind transport and dispersion modeling and comparisons with JR observations

A dense gas dispersion model can be applied after the initial source, momentum jet, valley effects, and dense gas slumping have occurred. For JR, this begins approximately at the edge of the depression (25 m radius). Many of the models, however, ignore processes that are sometimes important, such as removal by chemical reactions or deposition [7–9], or the influence of complex terrain and/or barriers such as vegetation and buildings.

As discussed in previous sections, the mass emission rate needed for input to the dispersion model is not necessarily the mass emission rate out of the orifice under the storage tank. For light winds and dense clouds in a confining valley or basin, the "source term" due to detrainment from the surface of the dense cloud may be spread out over time. Thus for the JR trials with light winds, the initial jet release from the pipe aperture of about 30–60 kg s^{-1} over 30 s might be converted to an extended-duration release rate from the cloud trapped in the basin of about 30 kg s^{-1} (30 s/3600 s) = 0.25 kg s^{-1} to 60 kg s^{-1} (30 s/3600 s) = 0.5 kg s^{-1} over an hour. The videos of the light-wind JR trials indicate that the release from the surface of the dense cloud in the basin to the ambient atmosphere did extend over a 30–60 min duration. This increase in the effective duration of the release leads to smaller 10 or 20 s – averaged maximum concentrations at short distances. But since the total mass that is released does not vary, there will not much difference in the time and space-integrated dosages. The health effects will depend on the toxic load, which, for a given time-integrated dosage of chlorine, tends to have worse health effects for small durations than large durations.

For a given mass release of dense gas, the worst case may not be a scenario with a short duration release with light winds and extreme stability [24,25]. This is partially because the cloud is "like a puff" for travel times larger than the release duration, t_d, and is "like a continuous plume" for travel times less than t_d. The puff has dispersion occurring in the along-wind directions, and thus its concentration decreases more rapidly with time or distance than that for a continuous plume.

5.1. SLAB model runs for different release durations

The SLAB dense gas model [20] has been used in the current study to investigate the variations of maximum 20 s average chlorine concentrations for JR Trials 2 and 6. SLAB can handle certain special jet orientations but has been primarily applied to pool evaporation (surface area source) scenarios. Thus SLAB is not intended to handle the near-source details related to the JR jet and basin. The chlorine cloud was simulated as a "continuous evaporating pool" area source with a certain size, mass emission rate, duration, temperature, and initial density. Even though the area source is actually the upper surface of the dense gas cloud in the basin, the SLAB model category "continuous evaporating pool" is the closest to our scenario. The mass emission rate was assumed constant over t_d. The diameter of the area source was assumed to be the diameter of the depression, 50 m. The mass emission rate was assumed to equal 908 kg for Trial 2 and 1826 kg for Trial 6, divided by t_d. The release time duration, t_d, was estimated using a combination of the observed values from the JR videos and calculations by theory [11], and ranged from 30 s to 3680 s. The initial temperature was assumed to be the boiling point of chlorine, 239.1 K. Chlorine properties that were input to SLAB are: molecular weight = 70.91, vapor heat capacity at constant pressure $c_p = 498\ J\ kg^{-1}\ K^{-1}$, initial liquid mass fraction = 0.8105, heat of vaporization = 287,840 J kg^{-1}, liquid heat capacity = 926 J $kg^{-1}\ K^{-1}$, and liquid density = 1574 kg m^{-3}.

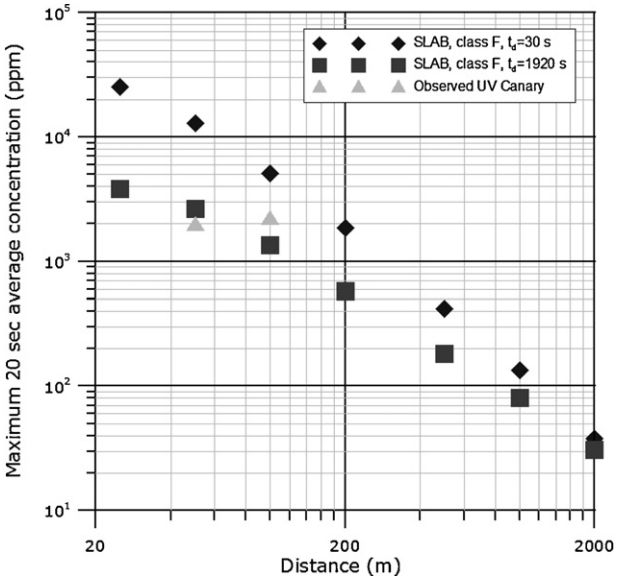

Fig. 5. Trial 2 comparisons of SLAB predictions of 20 s arc maximum chlorine concentrations (ppm) with observations by UV Canary samplers. SLAB predictions for 30 s and for 1920 s release durations are shown.

Ambient atmosphere inputs to SLAB were: surface roughness $z_o = 0.05$ m, wind measurement height = 2 m, wind speed $u = 0.6\ m\ s^{-1}$ for Trial 2 and $6.2\ m\ s^{-1}$ for Trial 6, relative humidity RH = 75% for Trial 2 and 40% for Trial 6, and temperature $T = 273$ K for Trial 2 and 279 K for Trial 6. Best estimates of stability class are F for Trial 2 and D for Trial 6. However, SLAB was run for all cases for stability classes D, E, and F for Trial 2.

The SLAB calculations extended to downwind distances of about 2000–3000 m, and included heights of 0.5, 1.0, 2.0, and 4.0 m. These correspond to distances and height of concentration samplers operating during JR. Some of the specific results are given in Figs. 5 and 6 and Table 2.

As seen in Fig. 5, the simulated cloud from the Trial 2 release with a release duration, t_d, of 30 s starts out, on the edge of the depression ($x = 25$ m), with about 6.5 times higher concentrations than the cloud from the Trial 2 release with a t_d of 1920s. However, the cloud from the t_d of 30 s switches over to effectively being a puff at $x >$ about $ut_d = 18$ m, or about at the edge of the depression. On the other hand, the simulated cloud for the t_d of 1920 s remains a "continuous plume" until $ut_d = 1152$ m. By $x > 1000$ m, the Trial 2 concentrations for the two different release durations are approaching each other and there is only a 20% difference at $x = 2000$ m. As mentioned earlier, the $t_d = 1920$ s assumption is more realistic (closer to observations and theory) than the $t_d = 30$ s assumption.

The simulated Trial 6 cloud for the release duration, t_d, of 30 s is acting as a continuous plume out to almost 200 m, and Fig. 6 shows that its concentrations decrease by about a factor of 5 between 25 and 200 m. The Trial 2 $t_d = 30$ s cloud concentrations, plotted in Fig. 5, decrease by a much larger factor, about 14, over the same distance, since that cloud is acting like an instantaneous puff. Beyond a distance of about 200 m, the clouds from both Trials 2 and 6 are dispersing "like a puff" and therefore their concentrations decrease

Table 2
Observed and SLAB-predicted maximum 20 s average chlorine concentrations (in ppm) for Trials 2 and 6, for several downwind distances, x. For Trial 2, two SLAB predictions are listed, for two assumptions regarding release duration t_d (30 s and 1920 s) from the depression.

Distance x (m) from center of depression	Trial 2 observed UV Canary	Trial 2 SLAB, class F $u = 0.6\ m\ s^{-1}$ $t_d = 30$ s	Trial 2 SLAB, class F $u = 0.6\ m\ s^{-1}$ $t_d = 1920$ s	Trial 6 observed JAZ	Trial 6 observed UV Canary	Trial 6 observed MiniRAE	Trial 6 SLAB, class D $u = 6.2\ m\ s^{-1}$, $t_d = 30$ s
25		25,200	3800	63,500			19,900
50	2030	12,900	2640		13,940	4950	13,900
100	2240	5100	1360		11,520	5020	8300
200		1850	580				4000
300						2870	2600
500		420	181			1050	1100
1000		134	80				344
2000		38	31				104

with distance by about the same relative amounts (see Figs. 5 and 6). At a distance of 2000 m, their maximum 20 s average concentrations differ by only about 30%.

The implication of the SLAB simulated results is that the delayed release (leading to larger t_d) due to detrainment or scouring from the JR depression is important mainly in the near-field for calculated 20 s averaged arc-maximum concentrations for what is thought to be worst case ambient conditions—light winds and stable. For the JR light wind release scenario, the larger t_d would make little difference on 20 s averaged arc maximum concentrations at distances beyond one or two km.

5.2. Comparisons of SLAB predictions for JR with observations of concentration

The many types of samplers taking concentration observations during Trials 2 and 6 were investigated in order to determine the best available observed 20 s averaged arc maximum concentrations for comparisons with the SLAB predictions reported in the previous section. The sampling instruments are described in Fox and Storwold [12] and Argenta et al. [26]. We emphasize that the observations used here are preliminary and the full data set is still being thoroughly quality-assured.

Trial 2, being a "pilot" test, had limited observations since the systems were being set up and tested at that time. The only short-term chlorine measurements during Trial 2 were from the so-called UV Canary sampler system, and those data were available only at downwind distances of 50 and 100 m.

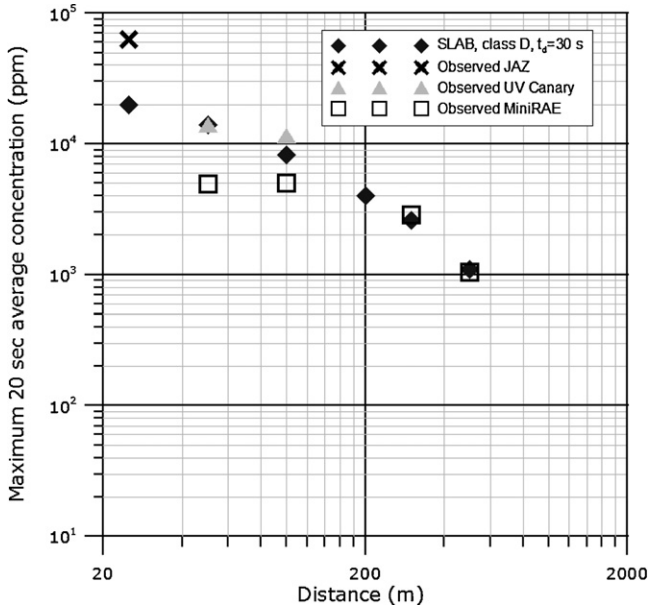

Fig. 6. Trial 6 comparisons of SLAB predictions (diamonds) of 20 s arc maximum chlorine concentrations (ppm) with observations by JAZ (cross), UV Canary (triangle) and MiniRAE (open square) samplers.

Trial 6, being a "record" test, had more complete short term observations, from the so-called JAZ, UV Canary and MiniRAE sampler systems [26]. Unfortunately, the farthest sampling distance was only 500 m. Table 2 contains the available observed and SLAB-simulated maximum 20 s average concentrations. It is believed that the 1920 s release duration is more consistent with observations and is supported by theory [11]. The SLAB predictions for t_d of 1920 s, at distances of 50 and 100 m, are seen to be within a factor of two of the UV Canary observations. Fig. 5 contains a plot of the predictions and observations of maximum 20-s averaged concentrations from Table 2 for Trial 2, confirming that the SLAB predictions for $t_d = 1920$ s pass closely through the two observed points.

The comparisons of maximum 20-s averaged concentrations in Table 2 and in Fig. 6 for Trial 6 also show fairly good agreement, especially with the UV Canary (at 50 and 100 m) and the MiniRAE observations (at 300 and 500 m). The SLAB model simulations are about a factor of 3 less than the JAZ observations at $x = 25$ m, but Argenta et al. [26] report that the JAZ samplers sometimes record readings that are high. At $x = 50$ and 100 m, the model predictions are about 10,000 ppm but the MiniRAE observations are only about 5,000 ppm. However, the maximum concentration limit of the 1-s concentration observations by the MiniRAEs is 9999 ppm. The 20-s averaging periods used for the MiniRAE observations at $x = 50$ and 100 m in Fig. 6 contain a few seconds at this maximum concentration of 9999 ppm, implying that the true concentration was likely to exceed 9999 ppm during those seconds. Therefore the reported MiniRAE observations of maximum 20-s averaged concentrations are likely to be low, although the magnitude of the bias is unknown.

6. Caveats

The analyses in this paper focus on the JR chlorine trials (2 and 6) with the smallest and largest winds. There are four additional chlorine trials with low winds, and six additional anhydrous ammonia trials with similar ranges of wind speeds which are currently being analyzed.

It has been shown that methodologies currently available in scientific journals [11,16] can be used to estimate the release duration, t_d, associated with detrainment from the dense cloud in the depression, and the estimates are in fairly close agreement with the available observations. Clearly a much more thorough evaluation is needed.

The sensitivity studies with SLAB indicate that the "worst case" condition is not always what might be expected, and depend on the initial Ri^* and on the ratio $t_d x/U$. The comparisons of SLAB predictions with JR observations show fair results, but more study is

needed of the observed data in order to better know mean biases, uncertainties, and thresholds.

The concentration samplers employed at JR have not previously been used together in a comprehensive field experiment of this type, and there was limited time during JR to do calibrations and co-located instrument comparisons. A major goal of JR was simply to demonstrate that a field experiment with this magnitude of chlorine gas release (one to two tons) could be satisfactorily carried out and various measurement systems deployed and used in an environment with very high concentrations of gas and aerosol. An analysis is currently underway by SciTech Services, Inc., of Havre de Grace, Maryland, entitled "Analysis of the Jack Rabbit Field Trials" and a final report is expected in mid-2012. This report will contain detailed results concerning uncertainties in concentration samplers, as well as all other instruments fielded at JR. This information is being used to plan the next field experiment in the series.

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References

[1] S.R. Hanna, S. Dharmavaram, J. Zhang, R.I. Sykes, H. Witlox, S. Khajehnajafi, K. Koslan, Comparison of six widely-used dense gas dispersion models for three recent chlorine railcar accidents, Process Saf. Prog. 27 (2008) 248–259.
[2] L. Zhang, L. Ding, G. Tao, Simulation of accident consequences of liquefied chlorine pipeline leakage, Huagong Xuebao/J. Chem. Industry Eng. (China) 59 (5) (2008) 1333–1337.
[3] R.K. Gangopadhyay, S.K. Das, M. Mukherjee, Chlorine leakage from bonnet of a valve in a bullet—a case study, J. Loss Prev. Process Ind. 18 (4–6) (2005) 526–530.
[4] R.K. Gangopadhyay, S.K. Das, Chlorine emission during the chlorination of water—case study, Environ. Monit. Assess. 125 (1–3) (2007) 197–200.
[5] S.R. Hanna, J.C. Chang, D.G. Strimaitis, Hazardous gas model evaluation with field observations, Atmos. Environ. 27A (1993) 2265–2285.
[6] D. Sommerville, J., Bray, S. Reutter-Christy, E., Shelly, Review and Assessment of Chlorine Mammalian Lethality Data and the Development of a Human Estimate, CBRNIAC Contract #STO-700-00-D-3180, Task 328, Delivery order 483, US Army Edgewood Chemical and Biological Center, Aberdeen Proving Ground, MD, 2007, pp. 126.
[7] P.L. Tanaka, D.A. Allen, E.C. McDonald-Buller, S. Chang, Y. Kimura, C.B. Mullins, G. Yarwood, J.D. Neece, Development of a chlorine mechanism for use in the carbon bond IV chemistry model, J. Geophy. Res. 108 (2003), doi:10.1029/2002JD002432, 13 pages.
[8] M.B. Dillon, The role of deposition in limiting the hazard extent of dense gas plumes, J. Hazard. Mater. 164 (2009) 1293–1303.
[9] S.R. Hanna, O.R. Hansen, M. Ichard, D.G. Strimaitis, CFD model simulations of dispersion from chlorine railcar releases in industrial and urban areas, Atmos. Environ. 43 (2009) 262–270.
[10] R.E. Britter, J. Weil, J. Leung, S.R. Hanna, Toxic industrial chemical (TIC) source emissions model improvements for pressurized liquefied gases, Atmos. Environ. 45 (2011) 1–26.
[11] G.A. Briggs, R.S. Thompson, W.H. Snyder, Dense gas removal from a valley by crosswinds, J. Hazard. Mater. 24 (1990) 1–38.
[12] S.B. Fox, D. Storwold, Project Jack Rabbit: Field Tests, Chemical Security Analysis Center, Science and Technology Directorate, U.S. Department of Homeland Security, CSAC 11-006, 2011, pp. 162.
[13] R.I. Sykes, S. Parker, D. Henn, B. Chowdhury, SCIPUFF Version 2.3 Technical Documentation, L-3 Titan Corp., POB 2229, Princeton, NJ 08543, 2008, 336 pp.
[14] G.A. Briggs, R.E. Britter, S.R. Hanna, J.A. Havens, A.G. Robins, W.H. Snyder, Dense gas vertical diffusion over rough surfaces: results of wind-tunnel studies, Atmos. Environ. 35 (2001) 2265–2284.
[15] R.E. Britter, S.R. Hanna, G.A. Briggs, A.G. Robins, Short range vertical dispersion from a ground level source in a turbulent boundary layer, Atmos. Environ. 37 (2003) 3885–3894.
[16] I.P. Castro, A. Kumar, W.H. Snyder, A.P.S. Arya, Removal of slightly heavy gases from a valley by crosswinds, J. Hazard. Mater. 34 (1993) 271–293.
[17] T.O. Spicer, J.A. Havens, Field test validation of the DEGADIS model, J. Hazard. Mater. 29 (1987) 1572–1579.
[18] H.W.M. Witlox, K. McFarlane, Interfacing dispersion models in the HGSYSTEM hazard-assessment package, Atmos. Environ. 28 (1994) 2947–2962.
[19] S.R. Hanna, J.C. Chang, Kit Fox dense gas dispersion field experiments and HEGADAS model testing, Atmos. Environ. 35 (2001) 2231–2242.
[20] D.L. Ermak, Users Manual for SLAB: An Atmospheric Dispersion Model for Denser-than-Air Releases, UCRL-MA-105607, Lawrence Livermore Nat Lab, Livermore, CA, 1990.
[21] NOAA/HMRAD and EPA/CEPPO, ALOHA Users Manual and Theoretical Description, Reports available from NOAA/HMRAD, 7600 Sand Point Way NE, Seattle, WA 98115 and on CAMEO/ALOHA web site, 1992.
[22] C.M. Seeto, An experimental study of entrainment at a density interface by mean velocity shear, Ph.D. Thesis, Dept. Mech. Eng. Univ. Canterbury, NZ, 1987, pp. 230 (summarized in Appendix A of Briggs et al., 1990).
[23] R.E. Britter, W.H. Snyder, Fluid modeling of dense gas dispersion over a ramp, J. Hazard. Mater. 18 (1988) 37–67.
[24] R.E. Britter, J. McQuaid, Workbook on the Dispersion of Dense Gases, HSE Contract Research report no. 17/1988, Health and Safety Executive, Sheffield, UK, 1988, pp. 129.
[25] S.R. Hanna, P.J. Drivas, J.C. Chang, Guidelines for Use of Vapor Cloud Dispersion Models, AIChE/CCPS, 345 East 47th St., New York, 1996, 285.
[26] E.P. Argenta, J.M. White, D.P. Storwold Jr., J.C. Pace, A preliminary analysis of HPAC modeling during the Jack Rabbit test program, Paper 2.1, available at www.ametsoc.org, in: Special Symp. on Appl. Air Poll. Meteorol., AMS Annual Meeting, Seattle, 2011.