

2.3 COMPARING RESULTS OF TWO CHLORINE RELEASE FIELD EXPERIMENTS – WILD STALLIONS AND JACK RABBIT

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ABSTRACT

Two important field experiments involving releases of pressurized liquefied chlorine have taken place in the last three years – The Wild Stallions (WS) and the Jack Rabbit (JR) experiments. The one and two ton chlorine releases took place near the ground at Dugway Proving Ground, with. However, because of the differing source release configurations and meteorological conditions, the resulting chlorine clouds looked quite different. This paper compares and contrasts the two field experiments and suggests scientific reasons for the differences that were seen. The source orientations were different primarily because of differing goals of the experiments. WS was addressing releases caused by explosive devices over the open flat desert during the daytime. Thus the chlorine cylinders were ruptured in specific ways and the momentum jet, of duration 30 s for the smaller hole and one second for the larger hole, was oriented horizontally or at an upward angle. Also the wind speeds were moderate (not light) at WS. As a result, the WS chlorine jet “looked like” a vigorous jet at all times, extending outward 50 m or more, and forming a large (50-100 m diameter) hemispherical cloud of chlorine gas and aerosol, part of which subsequently slumped towards the ground, and then moved downwind. However, JR was addressing the specific issue of chlorine released towards the ground from a short 3 inch pipe with a controlling valve, and forced confinement (initially) in a depression of 2 m depth and 50 m diameter during light winds in the early morning. Indeed, with wind speeds less than about 1 or 2 m/s, the gas and aerosol cloud was largely confined in the depression for many minutes, after which it was scoured out of the depression and moved downwind. There was an obvious axisymmetric dense “wall (or ground) jet” seen while the release occurred over about 30 s. At wind speeds exceeding 1 or 2 m/s during JR, the initial cloud was not well-confined in the depression and moved downwind. Some scientific explanations for the observed differences between WS and JR are provided in this paper, based on basic fluid dynamic principles and similarity arguments. For example,

it is shown that formulas suggested by Briggs in 1990 can satisfactorily predict the dependence on wind speed of the times observed at the JR site for the dense gas cloud to be removed from the depression.

1. BACKGROUND AND OBJECTIVES

Large amounts of chlorine are transported around the U.S. 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. When released through a break in a short pipe or a rupture in the tank wall, the liquid chlorine depressurizes and flashes to a mixture of gas and liquid aerosol, with about 20% of the chlorine in the gas phase and about 80% in the liquid phase. For typical current storage pressures and ambient temperatures, the resulting liquid aerosol drops have a relatively small diameter on the order of 10 microns and therefore do not significantly rain out (i.e., fall to the ground due to gravity). Experiences with railcar accidents and calculations with thermodynamic models suggest that as much as 60 tons of chlorine can be released as a two-phase aerosol in a time period of a few minutes or less.

Due to the three effects – the high molecular weight of chlorine, the cold temperature of the release, and the presence of high concentrations of liquid aerosol – the chlorine aerosol cloud can have an effective initial density as much as 20 times that of ambient air. Thus the initial chlorine 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 the large chlorine release from a railcar is expected to have a potentially large effect on the nearby population. Six widely-used dense gas models were applied by Hanna et al. (2008) to three recent accidents involving large releases of chlorine from railcars (Festus, MO; Macdona, TX; and Graniteville, SC). Most of these 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 (Hanna et al., 1993). The six models also agreed fairly well with each other on their predictions of chlorine concentrations variation with downwind distance for the three railcar accidents.

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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. But 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 to much larger distances.

Several possible reasons for the difference between observed and expected casualties have been advanced and are the subject of current research (Hanna, 2008). The relation between exposure and health effects is under investigation with a thorough review of the existing literature (e.g., Sommerville et al., 2007). The possibility of removal of chlorine gas and aerosol by chemical reactions (e.g., Tanaka et al. 2003 and Burns et al. 2007), by dry and wet deposition (e.g., Dillon 2009 and Hanna, Hansen et al. 2009), and by collection on vegetation is being studied. The uncertainties regarding the very large source term and the aerosol properties are being assessed (e.g., Britter et al., 2011), as well as possible removal due to the impaction of the aerosol jet on the ground, gravel, or other substrate under the railcar. Another concern, and the subject of the Jack Rabbit field experiment, is the possible “hold-up” of the large dense aerosol cloud formed around the source, especially during light wind stale conditions and with a natural depression in the area (see Briggs et al., 1990 for a discussion of removal of dense gases from a depression by a crosswind).

No one has carried out a research-grade field experiment with a full scale chlorine release from an actual railcar. That experiment would be difficult and dangerous. However, as described in this paper, there have been two recent sets of field experiments where one or two tons of chlorine are released. Even though the two field experiments had different goals, they provide fundamental data that can be used to develop a universal understanding. It is hoped that the results can be scaled to a full size release of about 60 tons.

The first of the two field experiments discussed here is the U.S. Army’s 2007 Wild Stallions (WS) field experiment, where there were six release trials involving a standard one-ton chlorine cylinder (Babarsky, 2007 and 2009; McEntire et al., 2009). Those all resulted in a strong momentum jet, large initial hemispheric cloud, and subsequent gravity slumping, followed by a transition to passive dispersion at larger distances. The second field experiment is the Department of Homeland Security’s (DHS’s) 2010 Jack Rabbit field experiment, where there was one trial involving a one-ton release of chlorine, and three additional experiments involving two-ton releases (Fox 2010, Storwold 2010, and Storwold and Fox 2011a and b). There were also four releases of anhydrous ammonia of the same magnitude. The releases

were all from downward pointing apertures and the tank was set up in a 50 m wide and 2 m deep man-made bowl-shaped depression. Releases were in the early morning, aiming for light wind stable conditions. Indeed the cloud was initially “held-up” in the depression for the light wind trials (wind speed less than about 2 m/s).

The objective of the paper is to describe the two field experiments and compare and contrast the findings. The Wild Stallion (WS) analysis is much farther along, since the experiment took place over three years ago. Thus we have some specific WS results to show. However, the Jack Rabbit (JR) data, collected about 8 months ago, are still going through QA/QC and have not been released for analysis. We are fortunate, though, to have excellent videos and still photographs to study.

We are attempting to find fundamental results that can be explained using basic fluid and thermodynamic principles and can be expressed in similarity (normalized) form. The similarity relations should be valid even for scaled up release rates, approaching the magnitude of a full railcar release.

2. OVERVIEW OF WILD STALLIONS FIELD EXPERIMENT

The Wild Stallions (WS) field experiment took place at Dugway Proving Ground in October, 2007. Babarsky (2007 and 2009) provides an overview of the field experiment and Henn and Sykes (2007) and Sykes (2009) describe an analysis of the jet. The terrain at WS was flat desert with a few small bushes. Several release trials took place, but the current paper focuses on Trials 3 through 8, which involved one-ton chlorine cylinders. The chlorine was stored as a pressurized liquefied gas. When the liquid chlorine is released and its pressure decreases to atmospheric, it “flashes” to a mixture of about 20 % gas and 80 % liquid (by mass). For large superheats (i.e., for ambient air temperature more than about 40 C above the chlorine boiling point of -34 C), the liquid is present in small aerosols of diameter 10 microns or less. These aerosols do not settle out appreciably. Thus for all of the WS trials, the chlorine release appears visually to generate a large volume of two-phase cloud.

The layout of samplers in the near-field (50 and 100 m) and the far-field (500 and 1000 m) are shown in **Figures 1** and **2**, respectively.

In Trials 3 and 4, the covers of two 10 inch holes were instantaneously removed, and all of the chlorine was released in about one second. In Trials 5 and 6, the cylinder was instantaneously split in half, and therefore the chlorine was released in a fraction of a second. Thus for trials 3 through 6, the release takes place in less than about 1 second, and “looks” in the videos like a violent instantaneous formation of a spherical mist cloud with diameter about 50 m. **Table 1** summarizes the WS trials. The color of the WS cloud is green-

yellow, which is the color of chlorine gas. There are aerosols seen in the cloud, but they may be a mixture of chlorine aerosol and natural aerosol raised from the surrounding desert surface as a result of the initial explosion/jet and condensed water in the entrained air. Because of the fact that the cloud is dense (due to a combination of the high molecular weight, the cold cloud temperature, and the imbedded aerosols), most of the cloud is seen to slump to the ground over a period of about 10 or 20 seconds. Subsequently, as it is diluted, the cloud moves downwind and gradually becomes neutrally buoyant.

Trials 7 and 8 were designed so that a cover on a two inch hole was removed instantaneously. This results in a two phase jet that lasts on the video for about 30 seconds and extends about 50 m from the tank. In Trial 7, the tank hold-down failed and the tank is seen to rotate, causing the jet to be aimed in several directions. **Figure 3** shows the cloud shortly after the release was initiated. The swirling momentum jet can be seen. In Trial 8, the hold-down did not fail and thus the observations from that trial are more consistent. Trial 8 was used as a test case for the source emissions models recommended by Britter et al. (2011). The test case was run by Dr. Joseph Leung (see Hanna Consultants, 2009, and Section 4 of the current paper) who was able to satisfactorily simulate the observed release rate and duration. Like the clouds for Trials 3 through 6, the clouds for Trials 7 and 8 initially form a large gas-aerosol volume extending to heights of about 50 m or more, but then slumps to the ground due to density effects.

McEntire et al. (2009) provide an overview of the concentration sampling systems. The initial cloud and subsequent slumping show up in the observed MiniRAE chlorine concentration time series in the near-field (50 and 100 m sampling arcs, see **Figure 1**) as a series of two or three concentration peaks extending over a time period of as much as 200 sec, and sometimes with clear air in between. The initial peak might be due to the initial large gas-aerosol cloud, the second peak might be due to the slumping dense cloud, and the third (and more) peaks may be due to the passage of a part of the cloud that had slumped upwind and took a while to be advected to the sampler. In the far-field (500 and 1000m sampling arcs, see **Figure 2**), the chlorine concentration time series were more regular, with a single peak.

The arc maximum concentrations measured by the MiniRAEs are listed for Trials 3-8 in **Table 2**. The analysis is somewhat hampered by the fact that the MiniRAEs had a 10,000 ppm maximum cut off concentration. Nevertheless, the data in **Table 2** indicate a decrease in concentration with distance roughly in agreement with dense gas observations at other field experiments. Also, we calculated the travel time and effective travel speeds based on the time that the peak concentration occurred at the four distance arcs, and these agreed fairly well with

the observed ambient wind speeds. This latter result suggests that there was not a significant “hold-up” of the dense aerosol cloud near the source during WS, even for relatively low wind speeds of 1.8 m/s.

3. OVERVIEW OF JACK RABBIT FIELD EXPERIMENT

The Jack Rabbit (JR) field experiment took place at Dugway Proving Ground in April and May of 2010 (Fox 2010, Storwold 2010, Storwold and Fox 2011a and b). The terrain was flat desert modified by construction of a 50 m diameter by 2 m deep bowl shaped depression, with the release occurring at the center. The edge of the depression had a lip that extended somewhat above the surrounding terrain. 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, and these were called Trials 1 and 2 and noted in the summary tables as the “pilot tests”. These 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 **Figure 4**, where the source location and several sampling rings are indicated. **Figure 5** is a field sketch of the chlorine concentration samplers set out by a contractor, CTEH, for Trial 8. There were extensive video and still cameras placed around the site to capture the visible clouds from multiple angles and distances. 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. Besides the primary experiment, there were several other specific measurements being made by different groups who were using the opportunity to test, for example, the effects of chlorine on different metals and the absorption of chlorine by different types of surfaces.

As with WS, the chlorine is stored as a pressurized liquefied gas at ambient temperature which “flashes” to a mixture of about 20 % gas and 80 % liquid (by mass). The liquid is present in small aerosols which do not settle out (i.e., rain out) appreciably. Thus the chlorine release appears visually to generate a large volume of two-phase cloud. For the JR trials, the chlorine was released as a downward pointing jet from a tank elevated 2 m above ground. The details of the pipe and the valve were designed by the JR planning team to assure that no flashing occurred in the pipe prior to release from the aperture. The jet impacted a steel plate on the ground, removing some of the chlorine aerosol through impaction and creating a small pool of liquid chlorine on the ground. Some of the chlorine was also absorbed into the ground (packed desert sand) adjacent to the steel plate. It was believed that the magnitude of this removal was

relatively small compared to the total mass released. However, 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.

Figure 6 is a photo from JR Trial 2, a one ton pilot release, showing the chlorine disseminator, the flashing chlorine jet, and the radial-moving chlorine cloud at about 2 seconds into the test. **Figure 7** shows the cloud at later times for the same trial. In this trial, with very light winds (0.6 m/s at a height of 2 m) the dense chlorine cloud was held-up in the basin due to the very light winds.

Table 3 provides summary information for all ten of the JR anhydrous ammonia and chlorine tests and **Table 4** provides a summary of the meteorological conditions for the five JR chlorine tests. The target JR test conditions were low speed, steady winds. Consequently, the tests were conducted in the early morning, as soon after sunrise as possible, based on the first occurrence of steady winds. In four of five chlorine tests, low wind conditions were achieved, with wind speeds of 0.6 to 1.4 m/s. The low speed winds did not generally persist for long, often increasing rapidly as morning progressed, and were not always steady, making analysis of the data more difficult. The low speed winds did allow the dense chlorine cloud to persist in the basin for several minutes after the release stopped. In **Figure 8**, showing JR Trial 6 with a 6.2 m/s wind speed, there is no significant chlorine cloud persistence beyond the release duration period, because of the higher wind speed.

Anhydrous ammonia and chlorine concentrations were measured by several types of samplers, including those that output dosages or averages over times such as 30 minutes, and those that output rapid-response concentrations every second. For example, many fast response MiniRAEs were used (see **Figure 5**), similar to what was used at WS. Remote sampling of the cloud also took place. Extensive meteorological measurements were made. Winds were observed by a network of standard anemometers as well as by several sonic anemometers. The latter, which provide high-resolution measurements, operate satisfactorily in very light mean winds and can output turbulence measures such as variances of wind components and temperatures, and fluxes of momentum and sensible heat.

As discussed in other papers in this special session of the conference, the measurement team is currently analyzing the data from the point of view of QA/QC needs. Thus none of the data have been officially released. This is why the current paper mainly focuses on discussion of phenomena evident in the photographs and videos.

4. SOURCE RELEASE RATE

Calculations of hazard effects are obviously dependent on good inputs of the source release rate and the chemical and physical properties of the release. These are impossible to accurately measure (in situ) in these experiments because of the very strong jet at the release point and the flashing that is taking place. Some formulations for estimating source emissions are available (see Britter et al. 2011 for a review) and these have been used in the WS and JR planning. For example, at JR, the science team did not want the chlorine to flash prior to reaching the release aperture, since that would have decreased the mass flow rate. Therefore, as described in Fox (2010) Storwold (2010) and Storwold and Fox (2011a), the pipe length, valve size and mechanical components were specially designed to meet this goal, which appears to have been mostly achieved.

Most transport and dispersion models cannot handle the source inputs directly at the release aperture, due to the depressurization and expansion, and thermodynamic effects in the strong momentum jet. These models prefer to receive their inputs at some point after the significant momentum effects are no longer evident. Recently, models such as SCIPUFF (Henn and Sykes, 2007, Sykes et al. 2008, Sykes 2009) have been modified to better treat the flashing momentum jet.

As an example of the application of the basic source emissions formulas to the WS and JR chlorine release scenarios, Hanna Consultants (2009) present a worked example of the calculation of the source emission rate for a WS trial. The source emission formulas suggested by Britter et al. (2011) are used, and Dr. Joseph Leung (a coauthor of the 2009 report and the 2011 paper) made the calculations. It is assumed that the following initial conditions apply:

- D = 0.74 m (tank diameter)
- L = 1.84 m (approx. tank length)
- V = 0.8 m³ (cylinder internal volume)
- m_o = 909 kg (chlorine mass)
- T_o = 35°C (308K) (initial temperature)
- P_o = 10 bar (chlorine vapor pressure, abs)
- P_g = 0 bar (no pad air)

Thermophysical properties are obtained from: Properties of Chlorine in SI Units, Pamphlet 72, 2nd ed., The Chlorine Institute Inc., 1986). Below are saturation properties at 308K and 10 bar:

- v_{l0} = 0.000735 m³/kg (liquid specific volume)
- v_{g0} = 0.032 m³/kg (vapor specific volume)
- h_{fg0} = 243000 J/kg (latent heat vaporization)
- C_{pl} = 977 J/kgK (liquid specific heat)
- σ = 0.016 N/m (surface tension)

The following properties can be calculated:

- ρ_{l0} = 1/v_{l0} = 1360 kg/m³ (liquid density)
- ρ_{g0} = 1/v_{g0} = 31.3 kg/m³ (vapor density)
- v_{fg0} = v_{g0} - v_{l0} = 0.0313 m³/kg (specific volume increase upon vaporization)

$$\omega_s = \rho_{i0} C_{pf} T_0 P_s \left(\frac{V_{i0}}{h_{i0}} \right)^2 \quad \text{from Eq. 3.23}$$

$$= \left(1360 \frac{\text{kg}}{\text{m}^3} \right) \left(977 \frac{\text{J}}{\text{kgK}} \right) (308\text{K}) \left(10^6 \frac{\text{N}}{\text{m}^2} \right) \left(\frac{0.0313 \frac{\text{m}^3}{\text{kg}}}{243000 \frac{\text{J}}{\text{kg}}} \right) = 6.8$$

In the above equation, ω is the so-called omega parameter for saturated liquid and will be useful for calculating similar parameters for other two-phase inlet conditions.

Two WS hole orientations are considered by Dr. Leung. Case 1 is a 2-inch hole near the bottom, at a location 45° below the midplane of the horizontal tank. The discharge rate is estimated based on the two-phase HEM omega method (see Britter et al., 2011). Initially the inlet condition would be saturated liquid (with zero void fraction), and yields $\omega_s = 6.8$ as seen above. The reference goes through the details. The final result is a mass emission rate of 23.1 kg/s. From geometry considerations, the liquid mass inventory below the 2-inch hole is about 125 kg. A total of (909–125) kg or 784 kg chlorine would be discharged via two-phase flow. Hence the two-phase blowdown time can be estimated to be 34 sec, which is fairly close to what was observed.

The second WS scenario, Case 2, is a 2-inch hole near the top, at a location 45° above the midplane. In this case two-phase discharge will end when the level swell falls below the hole elevation. The condition at this transition to vapor discharge can be calculated by accounting for the bubbling (or level swell). The mass emission rate here is 20.6 kg/s. At the transition from two-phase to vapor venting, the remaining mass is estimated to be 560 kg. Thus the blowdown time (or duration of two-phase release) is 15 seconds in this case

As he did for the WS trials, Dr. Joseph Leung used the equations suggested by Britter et al. (2011) to calculate the source emission rates and durations for the Jack Rabbit (JR) trials. These source emissions estimates are being used as inputs to the HPAC/SCIPUFF runs described by Sykes et al. in another paper at this special session. We do not have the detailed report, and the source data are not yet released, but the calculated emission rates and durations agree approximately with what was observed at JR. For example, in all JR trials, the chlorine two-phase release appeared to last for about 30 seconds.

As mentioned earlier, the JR tank and valve set up was designed so as to assure that flashing would not occur prior to the fluid reaching the end of the release pipe. Using similar source emissions methods to those described in the previous paragraphs, Dr. Thomas Spicer made the source calculations during the JR planning and it appears that there was success in delaying the flashing until the chlorine exited the pipe. **Figure 6** is a close-up photograph of the one-ton pilot test chlorine release at JR, and the downward-pointing flashing chlorine

jet can be clearly seen. However, Dr. Spicer's model simulations have not yet been checked with the actual quantitative observations.

5. MOMENTUM JET BEHAVIOR

The momentum and mass fluxes from the source can be estimated, as discussed in Section 4. The various chemical and physical properties can also be estimated. For example, the buoyancy flux can be determined from the momentum flux and the plume and air densities. Initially the momentum flux is the dominant parameter in determining the flow. The momentum flux dominates the flow near the source and the buoyancy flux (negative in the case of a chlorine release) will dominate the flow well away from the source. Away from the nozzle the momentum flux of the jet is conserved except for any drag force from the ground and any mixing with moving air, and at first order these can be neglected. During WS, the momentum jet was usually pointed away from the ground. However, during JR, the flow was directed downwards, impacted the hard surface, and turned (without energy loss) to travel radially with the same velocity as prior to turning from vertical to horizontal. The flow is now a radial wall jet with radial momentum equal to the previous vertical momentum.

At WS and JR, phase changes would have occurred due to flashing and to evaporation of liquid particles in the air that has been entrained into the jet. Note that because the ambient air is comparatively calm initially, the momentum arguments above still hold.

At JR, ignoring the drag force on the underlying surface and any mixing with moving air, the radial momentum will be conserved as the jet flows out. **Figures 6 and 7** show the radial jet during Trial 1. The radial velocity, v_R of the jet must vary inversely with the radial position: $v_R \sim R^{-1}$, and this implies that $R \sim t^{1/2}$. The proportionality constant should be $((\text{momentum flux}/2)\pi\alpha\rho_a)^{1/2}$ where α is the entrainment rate and will be of order 0.05 to 0.1. This leads to cloud height $h = \alpha R$ so at 30 m radius, cloud height h would be 1.5 to 3 m.

If a fraction of the mass flux from the source is removed to the underlying surface (due to gravitational deposition or absorption) then this can be accommodated by reducing the momentum flux by the same proportion. Also, the leading edge of the developing flow will actually travel at half the velocity calculated above. The leading edge is driven up and remains above the advancing flow and behind the leading edge. Consequently the depth of flow near the leading edge may be double the height indicated above. It is important to note that the mass and momentum flux at the source are likely to be declining with time and this will complicate interpretation of the result. There may be a need to consider heat transfer from the underlying surface. And finally, the flow will "look"

highly turbulent. This was indeed seen at the JR experiments (Figures 6 through 8).

6. TRANSITION FROM MOMENTUM JET TO DENSE CLOUD

The WS and JR videos and still photographs show that the momentum jet described in the preceding section is very much in evidence all during the two phase release period. At WS, where the jet was not pointed towards the ground, it extended about 50 m from the source. At JR, where the downward jet was deflected by the steel plate at the ground level to form a radial jet, it extended to the edge of the depression (about 20 to 25 m). For higher winds (6.2 m/s) in Trial 6 (see Figure 8), the radial jet was distorted in the direction of the ambient wind flow. At both locations, after the two-phase jet ceased, there was a period of chlorine gas release lasting a few more seconds but with much less mass flux and less of a momentum jet. 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.

During the time when the momentum jet was in evidence, there would have been dilution of the released chlorine by entrained ambient air. The amount of dilution would be much larger at WS where the jet was pointing tangentially upwards, and the videos suggested that the cloud had hemispheric shape with radius of about 50 m. Subsequently, the WS cloud could be seen to slowly "collapse" towards the ground due to the density effects.

The amount of dilution at the end of the momentum jet phase was much less (by design) at JR. For wind speeds less than about 2 m/s, the quiescent chlorine cloud approximately filled up the depression (again by design). For higher wind speeds, the effect of the depression was not as obvious (see Figure 8, for Trial 6, when the wind speed was 6.2 m/s).

The dilution at the transition from momentum jet to dense cloud has yet to be calculated from the detailed WS and JR observations. However, the dilution could be estimated from the outputs of the SCIPUFF model runs that appear to approximately match both field experiments (e.g., Sykes, 2009).

7. DENSE CLOUD BEHAVIOR, INCLUDING DETRAINMENT AND ENTRAINMENT

After the momentum jet effects become small, the chlorine cloud transitions to a phase dominated by the conditions in the ambient atmosphere, by the buoyancy (negative) of the cloud, and by the underlying topography. The dense cloud movement and dilution are strongly affected by the entrainment of ambient air into the chlorine cloud (the standard view applicable to WS) or by the detrainment of chlorine from the dense cloud into

the overlying ambient atmosphere (the view of most relevance to the JR cloud confined in the depression).

Briggs et al. (2001) review the literature on "standard" entrainment into unconfined dense plumes being transported over flat terrain, and analyze the results of their three wind tunnel experiments in order to justify their recommended entrainment formula. As part of the same large research program, Britter et al. (2003) review the literature on vertical entrainment into passive plumes.

The above papers are distinguished from JR and from papers by Briggs et al. (1990) and Castro et al. (1993) by the fact that the latter are for a dense cloud initially confined in a 2D valley/depression, where the dense gas can escape the valley only by detrainment out of the valley top. The Briggs et al. (1990) study was funded by the EPA because the Bhopal accident occurred in a valley and there had been instances of CO₂ clouds resulting from water overturning in lakes in African confined valleys.

In the four papers referenced above, the entrainment applies to a plume after the initial momentum or dense gas slumping effects become insignificant. Thus it is important to get the "initial dilution" right, as discussed in the previous section.

In Britter et al. (2003), the vertical entrainment velocity, w_e , is found to be best fit by $0.65u^*$ for numerous field and laboratory observations for a passive plume. In Briggs et al. (2001) the $w_e = 0.65u^*$ value is used as the asymptotic limit as the plume excess density approaches zero (i.e., a neutral or passive plume). It is recommended that $w_e = 0.65u^*/(1+0.2Ri^*)$ where the in-cloud local Richardson number, Ri^* , equals $g_s'h/u^{*2}$ and $g_s' = g(\rho_p - \rho_a)/\rho_a C_s/C_o$. g is the acceleration of gravity, ρ_p is local plume density and ρ_a is ambient air density. Subscript "o" refers to initial conditions (at hand-off from the momentum jet). C_o is initial source concentration (at hand-off) and C_s is local near-surface concentration. At $Ri^* > 20$ it is found that molecular diffusion (at $\kappa = 0.15 \text{ cm}^2/\text{s}$) takes over (i.e., the cloud is so dense that there is no turbulence at its upper edge). The general dense gas entrainment formula above is found in slightly different form in all widely-used dense gas models (e.g., DEGADIS by Spicer and Havens (1987); SCIPUFF by Sykes et al. (2008); TRACE by SAFER (1996); HEGADAS by Witlox and McFarlane (1994) and Hanna and Chang (2001); SLAB by Ermak (1990); and ALOHA by NOAA (1992)).

For the valley, a different approach is needed because the dense cloud is confined. In this case there are two different approaches recommended in the literature depending on whether the dense cloud is very dense or just slightly dense. Briggs et al. (1990) used theoretical analysis and wind tunnel results to study the very dense case, where detrainment occurs only on the upwind top edge of

the dense cloud in the valley. Their work built on previous related studies by Seeto (1987) and Britter and Snyder (1988). The detrainment process is related to Kelvin-Helmholtz instabilities. **Figure 8** shows the valley cross-section and the variables assumed by Briggs et al. (1990). They calculate that v_o , the chlorine momentum flux per unit cross wind distance, is proportional to U^3/g_i' , where U is the speed "above the cloud in the valley" and g_i' is $g(\rho_o - \rho_a)/\rho_a$ 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 implies a strong (cubic) dependence on wind speed, U . Also, in this relation there is no dependence on the along-wind width of the dense gas cloud, because nearly all of the detrainment occurs close to the upwind edge. For low Re , Briggs et al. (1990) find that v_o approaches $(Uw\kappa)$ where w is along-wind width of the top of the dense cloud and κ is molecular diffusivity. They suggest an interpolation formula that provides a solution for the two extremes.

The above solution applies to a steady state dense gas inflow that approximately balances the outflow. Briggs et al. (1990) also studied the variation of time of v_o for cases where an instantaneous dense gas cloud is initialized in the valley and then is "scoured out" or "evacuated" by the detrainment over time. A time scale, t_r , for evacuation is defined as the cross-sectional area of the cloud in the valley, $(Wh/2)$, times g_i'/U^3 . A normalized volume flux, $V' = v_o g_i'/U_o^3$ is plotted versus normalized time, $T = t/t_r$. For several sets of experiment conditions, the plots of V' versus T in the paper can be approximated by

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

The wind tunnel experiments conducted by Briggs et al. (1990) were idealized. For example, no cross-wind effects were considered because the valley and the cloud are uniform across the width of the wind tunnel. There were several alternate ways tested for prescribing the wind speed to be used in the scaling relations and for defining Re and Fr . Nevertheless, the recommended formulas provide a framework for analyzing and interpreting the JR data.

Castro et al. (1993) extended the Briggs et al. (1990) work to dense gas pools in valleys with only slight density effects (low Ri_o and g_o'). In this case the detrainment occurs over the entire surface instead of just at the upwind edge. It is uncertain whether, as the valley becomes very shallow, this solution approaches the solution for the dense gas on a flat surface as derived by Briggs et al. (2001).

Both Briggs et al. (1990) and Castro et al. (1993) point out that, for a flat valley floor, as the depth of the dense cloud decreases and becomes very shallow, their solution will need modification.

Coincidentally, Briggs et al. (1990) and Castro et al. (1993) include worked examples of the application of their formulas to chlorine releases. Briggs et al. (1990) use a scenario with a mass release close to the JR scenario, applying their formulas to a 1000 kg gas (not aerosol) nearly-instantaneous release into a holding pond 30 m square. Castro et al. (1993) use a scenario where 60 tons are released (similar to the mass released at the Macdona and Graniteville chlorine railcar accidents) nearly instantaneously over a 400 m cross-wind span at the bottom of a valley of width 250 m and depth 50 m. For Briggs et al.'s example, it is calculated that fully turbulent entrainment occurs at $U_s > 1.23$ m/s. For $U_s = 1$ m/s, it is calculated that the wind will evacuate the pond in 40 minutes. They state that "For diffusion beyond the pond, this practically could be treated as a continuous source of chlorine gas". For the same example, a 5 m/s wind gives full evacuation in a time of about 25 seconds. These times are similar to what was found at JR for Trials 1 and 6 (seen in **Figures 6 and 7** and **Figure 8**, respectively).

8. DOWNWIND TRANSPORT AND DISPERSION

This section concerns the dense gas dispersion model that is applied after the initial source, momentum jet, valley effects, and dense gas slumping have occurred. For WS, this begins after the hemispheric cloud has slumped to the ground and begins moving downwind. For JR, this begins after the chlorine cloud exits the depression and begins moving downwind. The existing widely-used models such as DEGADIS and SCIPUFF can be applied, and they account for the transition from dense gas to passive gas. The latter occurs at larger distances for larger source emission rates and smaller wind speeds. Most of these models, however, do not adequately account for removal by chemical reactions or deposition, and do not account for complex terrain.

In the videos, the WS chlorine cloud "looks" like a dense cloud only in the near field. At downwind distances of 100 m to 200 m or larger, the cloud starts to "look" more neutral or passive. This is reflected in the observed time series of concentrations (Hanna, 2010), which show a typical Gaussian-shaped cloud at the distances of 500 and 1000 m. But at 50 and 100 m, the rapid response concentration measurements often exhibit multiple peaks, with the first associated with the initial jet, the second associated with the slumping of the dense chlorine cloud after the momentum jet ceases, and even a third associated with the movement over the receptor of the edge of the donut shaped dense cloud that had initially moved upwind and was now being advected downwind. Nevertheless, as seen in Table 2, the variation of maximum concentration with distance follows an approximate $x^{-1.5}$ to x^{-2} power law, in agreement with many other field experiments.

For the JR trials, the transport and dispersion model must have the source emission rate input. This is not necessarily the mass emission rate out of the orifice under the storage tank. As seen in the literature (e.g., Briggs et al., 1990) described in the previous section, for light winds and dense clouds in a confining valley, the “source term” due to detrainment from the surface of the dense cloud is actually spread out over time. Thus the initial jet release of about 30 to 60 kg/s over 30 s is converted to an extended release rate of about 0.25 to 0.5 kg/s over an hour. This leads to smaller 10-second averaged maximum concentrations at far distances although the time of exposure is much longer. However, there is likely to be 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 greater health effects for small durations than large durations.

The AIChE Guidelines for Vapor Cloud Dispersion Modeling by Hanna et al. (1996) points out that the transition from dense cloud behavior to passive cloud behavior occurs when the cloud Richardson (Ri) number (proportional to relative density times cloud volume flux divided by the square of the cloud diameter scale times the wind speed scale) drops below a critical value. The critical Ri value that is suggested depends on whether the source is a jet or a ground-level area source and whether the cloud is a continuous plume or an instantaneous puff. In any case, the critical Ri values are highly arbitrary and need to be better “calibrated” with observations. As shown by Briggs et al. (2001) and Hanna and Chang (2001), and discussed in the previous section, the vertical entrainment rate into a dense plume is proportional to $1/(1 + 0.2Ri)$, where Ri is the local cloud Ri. Thus there is not an abrupt transition from dense gas to passive gas behavior; instead, there is an asymptotic variation with x. Clearly we do not have sufficient observations to calculate the local cloud Ri during WS or JR. However, the outputs of a model such as SCIPUFF applied to the WS trials can be used to calculate the variation of cloud Ri with x and try to estimate where the critical Ri might be.

9. CAVEATS

The analyses in this paper of the WS and JR field experiment data are based on the limited data that we have been provided. Our main goal has been to provide a start to developing a scientific framework for further analysis and for planning of possible new field experiments.

It has been shown that methodologies currently available in scientific journals can be used to estimate chlorine cloud behavior in fairly close agreement with the available observations. For example, the persistence of the chlorine cloud in the JR depression can be satisfactorily estimated

using a formulation by Briggs et al. (1990). But clearly a much more thorough evaluation is needed, using a full set of QA/QC'd data.

As we mention in the first section, there are other knowledge gaps in the total chlorine modeling system that also need to be investigated, such as deposition and chemical reactions, dense gas flow down drainage patterns in the terrain, collection of chlorine aerosol by vegetation, and health effects.

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REFERENCES

- Babarsky, R.J., 2007: Preliminary Results from Wild Stallions. PPT File presented at WS Information Conference, November, Charlottesville, VA.
- Babarsky, R.J., 2009: Wild Stallions Source Characterization and Modeling Update. PPT File presented at CB Warfare Delivery System and Consequence Assessment Modeling Conference, 27 April – 1 May 2009, Charlottesville, VA.
- Briggs, G.A., R.E. Britter, S.R. Hanna, J.A. Havens, A.G. Robins and W.H. Snyder, 2001: Dense gas vertical diffusion over rough surfaces: results of wind-tunnel studies. *Atmos. Environ.* **35**, 2265-2284.
- Briggs, G.A., R.S. Thompson and W.H. Snyder, 1990: Dense gas removal from a valley by crosswinds. *J. Haz. Mat.* **24**, 1-38.
- Britter, R.E., S.R. Hanna, G.A. Briggs and A.G. Robins, 2003: Short range vertical dispersion from a ground level source in a turbulent boundary layer. *Atmos. Environ.* **37**, 3885-3894.
- Britter, R.E. and W.H. Snyder, 1988: Fluid modeling of dense gas dispersion over a ramp. *J. Haz. Mat.* **18**, 37-67.
- Britter R.E., J. Weil, J. Leung and S.R. Hanna, 2011: Toxic Industrial Chemical (TIC) source emissions model improvements for pressurized liquefied gases. *Atmos. Environ.* **45**, 1-26.
- Burns, D.S., V. Chynwat, W. Moore, S. Rottmann, A. Plitz and M.V. Henley, 2007: Improvement and Sensitivity Analysis of the Atmospheric Chemistry Module for Modeling TICs in SCIPUFF, Poster Paper at DOD BACIMO Conference, Boston, MA., Nov 10, 2007.

- Castro, I.P., A. Kumar, W.H. Snyder and A.P.S. Arya, 1993: Removal of slightly heavy gases from a valley by crosswinds. *J. Haz. Mat.*, **34**, 271-293.
- Dillon, M.B., 2009: The role of deposition in limiting the hazard extent of dense gas plumes. *J. Hazardous Materials*, **164**, 1293-1303
- Ermak, D.L., 1990: Users Manual for SLAB: An Atmospheric Dispersion Model for Denser-than-Air Releases. UCRL-MA-105607, Lawrence Livermore Nat Lab, Livermore, CA.
- Fox, S.B., 2010: Project Jack Rabbit: Master Experimental Plan. Prepared by Chemical Security Analysis Center, U.S.. Department of Homeland Security for Freight Rail Security, Transportation Security Administration. 89 pp.
- Hanna, S.R., 2008: Gaps in toxic industrial chemical (TIC) model systems. Proceedings, 12th Harmonization Conference on Air Quality Models for Regulatory Purposes, Cavtat, Croatia.
- Hanna, S.R., 2010: Analysis of Chlorine Concentrations Observed by MiniRAE Samplers during Wild Stallions Field Experiment, Report Number P118-01. Prepared by Hanna Consultants, 7 Crescent Ave., Kennebunkport, ME 04046, 21 pp.
- Hanna Consultants, 2009: Worked Examples Using Improved Source Emission Models. Report number P098-05, prepared for DTRA by HC, 7 Crescent Ave., Kennebunkport, ME 04046, 40 pages. Worked Example 3 deals with the WS chlorine release (see pp 19-24).
- Hanna, S.R. and J.C. Chang, 2001: Kit Fox dense gas dispersion field experiments and HEGADAS model testing. *Atmos. Environ.* **35**, 2231-2242.
- Hanna, S.R., J.C. Chang and D.G. Strimaitis, 1993: Hazardous gas model evaluation with field observations. *Atmos. Environ.* **27A**, 2265-2285.
- Hanna, S.R., S. Dharmavaram, J. Zhang, R.I. Sykes, H. Witlox, S. Khajehnajafi and K. Koslan, 2008: Comparison of six widely-used dense gas dispersion models for three recent chlorine railcar accidents, *Process Safety Progress*, **27**, 248-259.
- Hanna, S.R., P.J. Drivas and J.C. Chang, 1996: Guidelines for Use of Vapor Cloud Dispersion Models. AIChE/CCPS, 345 East 47th St., New York, 285 pages.
- Henn, D.S. and R.I. Sykes, 2008: SCIPUFF Model Comparison with Chlorine Tank Rupture Data. Draft report by Sage Mgmt, Princeton, NJ dated Sept 2008, 30 pp.
- McEntire, L., C. Hobson, J. Berry and A. Thompson, 2009: Wild Stallions Test Design and Execution. PPT File presented at CB Warfare Delivery System and Consequence Assessment Modeling Conference, 27 April – 1 May 2009, Charlottesville, VA.
- NOAA/HMRAD and EPA/CEPPO, 1992: 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.
- SAFER Systems, 1996: Description of Modeling Algorithms, TRACE Version 8.0. Looseleaf notebook available from SAFER Systems, 4165 E. Thousand Oaks Blvd., Suite 350, Westlake Village, CA 91362.
- Seeto, C.M., 1987: An experimental study of entrainment at a density interface by mean velocity shear. Ph.D. Thesis, Dept. Mech. Eng. Univ Canterbury, NZ, 230 pp. (summarized in Appendix A of Briggs et al, 1990).
- Sommerville, D., J. Bray, S. Reutter-Christy and E. Shelly, 2007: 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, 126 pp. Limited Distribution FOUO.
- Spicer, T.O. and J.A. Havens, 1987: Field test validation of the DEGADIS model. *J. Haz. Mat.*, **29**, 1572-1579.
- Storwold, D., 2010: Jack Rabbit Dissemination Summary. Prepared by Meteorology Division, West Desert Test Center, Dugway Proving Ground, for Chemical Security Analysis Center, U.S.. Department of Homeland Security. 14 pp.
- Storwold, D. and S. Fox, 2011a: Project Jack Rabbit: Field Tests Final Report – Final. IA HSTS02-09-X-MLS36. Department of Homeland Security Chemical Security Analysis Center, 96 pp.
- Storwold, D. and S. Fox, 2011b: Project Jack Rabbit: Downwind Effects Assessment Report. IA HSTS02-09-X-MLS36. Department of Homeland Security Chemical Security Analysis Center, 10 pp.
- Sykes, R.I., S. Parker, D. Henn and B. Chowdhury, 2008: SCIPUFF Version 2.3 Technical Documentation. L-3 Titan Corp, POB 2229, Princeton, NJ 08543, 336 pp.
- Sykes, R.I., 2009: 3D Jet generalization. PPT File presented at CB Warfare Delivery System and Consequence Assessment Modeling Conference, 27 April – 1 May 2009, Charlottesville, VA.
- Tanaka, P.L., D.A. Allen, E.C. McDonald-Buller, S. Chang, Y. Kimura, C.B. Mullins, G. Yarwood and J.D. Neece, 2003: Development of a chlorine mechanism for use in the carbon bond IV chemistry model. *J. Geophys. Res.* **108**, doi: 10.1029/2002JD002432, 13 pages.
- Witlox, H.W.M. and K. McFarlane, 1994: Interfacing dispersion models in the HGSYSTEM hazard-assessment package, *Atmos. Environ.*, **28**, 2947-2962.

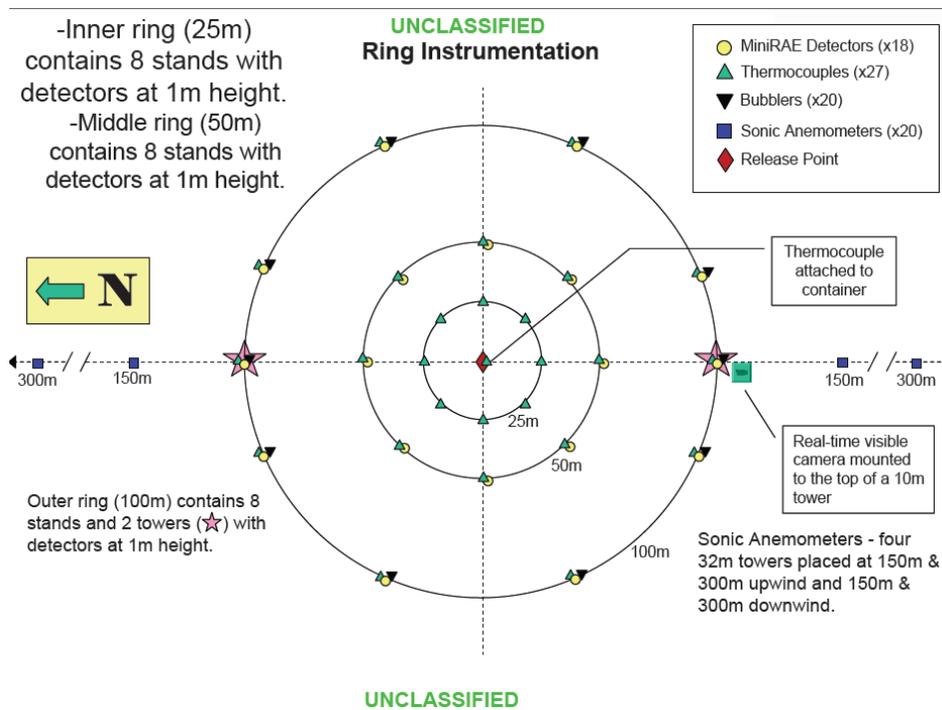


Figure 1. Wild Stallions near-field release and sensor array locations. Figure courtesy of Dugway Proving Ground.

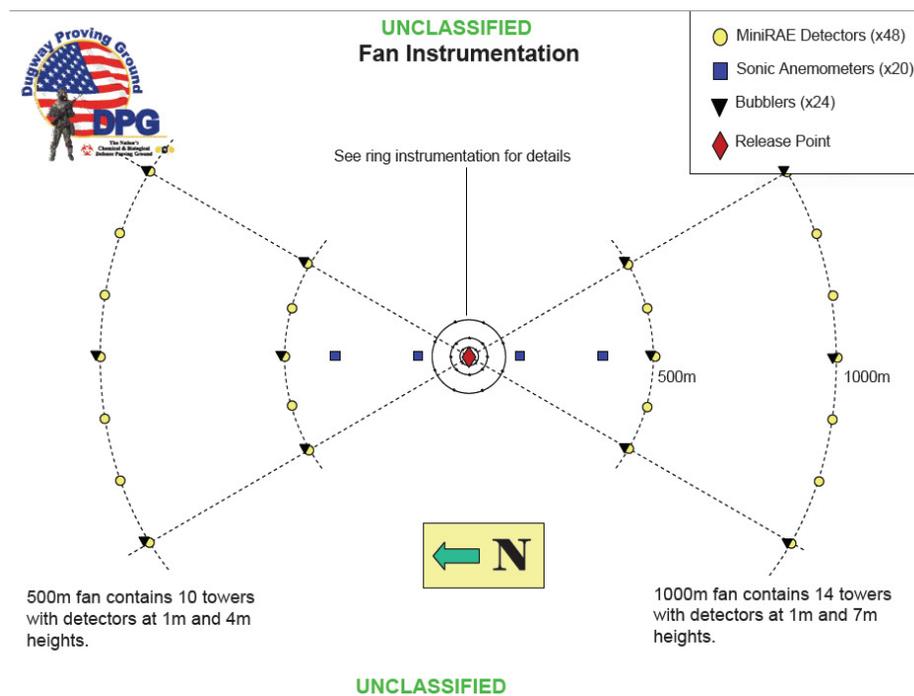


Figure 2. Wild Stallions far-field sensor array locations. Figure courtesy of Dugway Proving Ground.



Figure 3. Photo of Wild Stallions chlorine cloud during the release phase with a two-phase jet, from Trial 7 with a rotating tank.

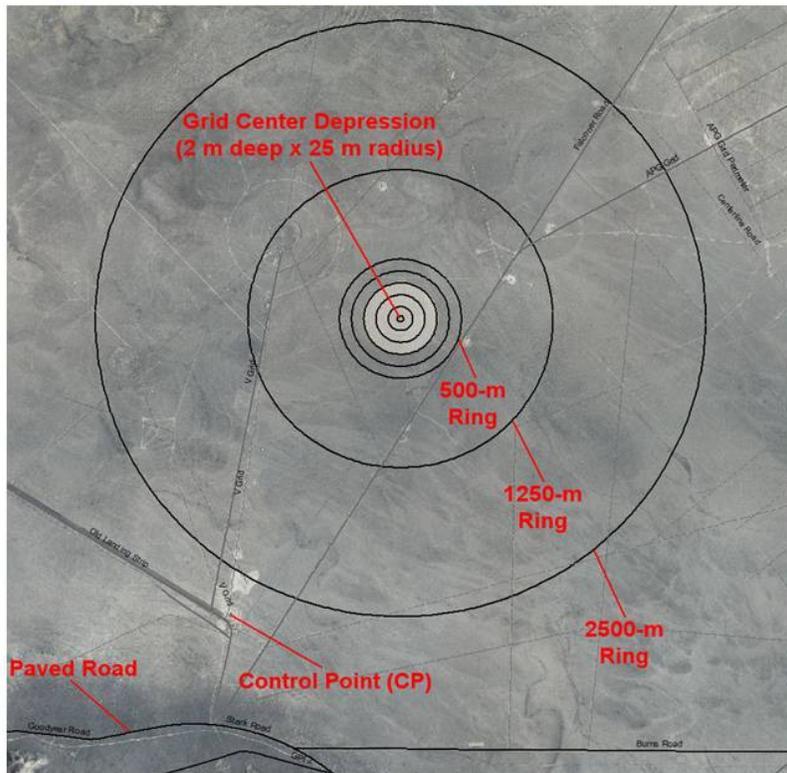


Figure 4. Jack Rabbit field site, showing source location (grid center depression) and rings of samplers. Figure courtesy of Dugway Proving Ground.

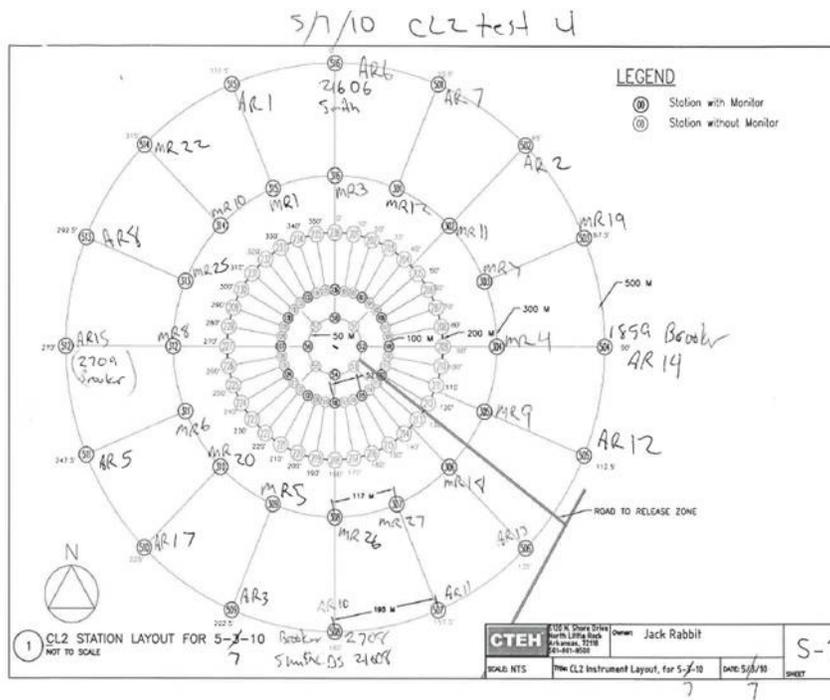


Figure 5. Field sketch from CTEH, showing their layout of concentration samplers for JR chlorine trial 8.



Figure 6. 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 Tables 3 and 4). The photo was taken about 2 seconds after the chlorine release began. The downward pointing two-phase momentum jet is seen, and the horizontal “wall-jet”, extending radially, is just becoming evident. Photo courtesy of Dugway Proving Ground.

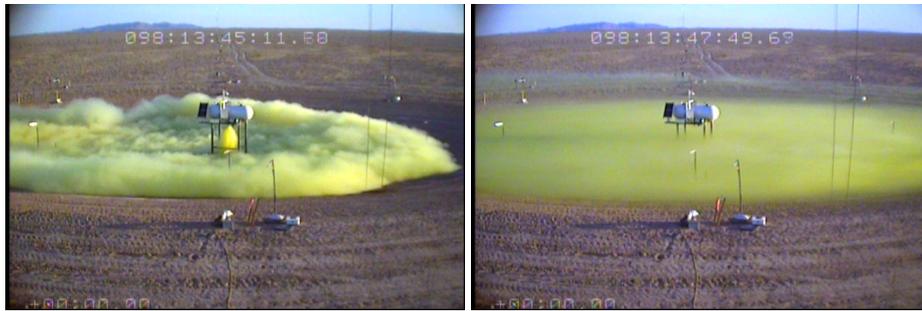


Figure 7. Jack Rabbit Trial 2 (see Tables 3 and 4) chlorine cloud, at 22 seconds (left) and 180 seconds (right) after the release began. This is the same one-ton pilot release (Trial 2, see Table 3) shown at 2 seconds after release in Figure 4. The downward pointing two-phase momentum jet is still seen at 22 seconds and the horizontal donut-shaped dense “wall-jet”, has reached the edge of the depression. At 180 seconds, the release has been ended for about 150 seconds and the cloud is held-up in the depression, mainly due to the very light winds. Photos courtesy of Dugway Proving Ground.



Figure 8. Jack Rabbit Trial 6 (see Tables 3 and 4) chlorine cloud, at 3 seconds (left), 34 seconds (center) and 180 seconds (right) after the release began. This trial had larger wind speeds (6.2 m/s vs 0.6 m/s) than Trial 2, and the cloud here is observed to not be held-up in the depression. Photos courtesy of Dugway Proving Ground.

Table 1. Summary information for Wild Stallions (WS) Field Experiment.

Trial	Date Oct 07	Release time MDT	Release duration sec	Wind Speed at 2 m	Mass released pounds	Release hole	Comment
3	19	092500	<1	6.0 m/s	2000	2 10" holes	two large holes
4	22	145700	<1	1.8 m/s	2000	2 10" holes	two large holes
5	23	123500	2	1.8 m/s	2000	split	split in half
6	26	114200	2	3.9 m/s	2000	split	split in half
7	29	143200	30	2.3 m/s	2000	2" hole	tank rotated
8	30	104700	30	2.9 m/s	2000	2" hole	tank stationary

Table 2. Wild Stallions observed MiniRae maximum concentrations at arc distances of 50, 100, 500, and 1000 m. Note that the sampler cannot observe a concentration exceeding 10,000 ppm.

Trial	C _{max} ppm 50 m	C _{max} ppm 100 m	C _{max} ppm Maximum at 50 m or 100 m	C _{max} ppm 500 m	C _{max} ppm 1000 m
3	9995	-	9995	486	140
4	3017	3400	3400	-	-
5	8658	7613	8658	44.3	-
6	9995	6332	9995	119	19.3
7	4631	3250	4631	-	-
8	5808	9995	9995	169	63
Median	7230	6332	9330	144	63
Average	7020	6120	7780	204	74

Table 3. Summary Information for Jack Rabbit field experiment.

Trial	Date	Dissemination Time (UTC)	Chemical	Amount	Valve Body Inside Diameter	Valve Outlet Diameter
01-PA	04/07/10	1400	Ammonia	1 ton	4"	2"
02-PC	04/08/10	1345	Chlorine	1 ton	3"	1.5"
03-RA	04/27/10	1315	Ammonia	2 tons	4"	2"
04-RA	05/01/10	1420	Ammonia	2 tons	4"	2"
05-RC	05/03/10	1320	Chlorine	2 tons	3"	3"
06-RC	05/04/10	1340	Chlorine	2 tons	3"	3"
07-RC	05/05/10	1405	Chlorine	2 tons	3"	3"
08-RC	05/07/10	1250	Chlorine	2 tons	3"	3"
09-RA	05/20/10	1245	Ammonia	2 tons	4"	4"
10-RA	05/21/10	1250	Ammonia	2 tons	4"	4"

Table 4. Meteorological conditions observed at a height of 2 m for the five Jack Rabbit chlorine release trials

Trial	Date	Time (UTC)	Wind speed m/s	Wind direction degrees	Temperature (C)
02-PC	04/08/10	1345	0.6	84	-0.3
05-RC	05/03/10	1320	1.6	346	3.5
06-RC	05/04/10	1340	6.2	20	6.1
07-RC	05/05/10	1405	1.4	235	6.3
08-RC	05/07/10	1250	1.2	160	-2.9