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ANALYSIS OF VARIATIONS OF CONCENTRATIONS WITH DOWNWIND DISTANCE AND CHARACTERISTICS OF DENSE GAS PLUME RISE FOR JACK RABBIT II–2015 AND 2016 CHLORINE FIELD EXPERIMENTS

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Abstract: The multi-year series of Jack Rabbit (JR) chlorine field experiments concluded in 2016 with four experiments involving 10 to 20 ton releases of pressurized liquefied chlorine. Unlike the 2015 portion of Jack Rabbit II (JR II), there was not an array of CONEX obstacles in the near field. Also, one of the 2016 field experiments involved a hole oriented 45° downwards, and another involved a hole at the top of the tank. All other hole locations in JR were at the bottom of the tank. This paper describes two aspects of the analysis – the variation of arc-maximum chlorine concentrations with downwind distance for all JR trials and the Lyme Bay (LB) trials, and the characteristics of the dense jet vertical trajectory for the JR II upward release Trial 8. It is found that the observed normalized arc-maximum concentrations, Cu/Q, follow the same $x^{-5/3}$ power law for the JR II 2015 and 2016, the JR I 2010, and the LB chlorine experiments. Note that u is the representative wind speed and Q is the mass emission rate per unit time. Downwind distance, x, ranges from about 25 m to 11 km for these data. For JR II Trial 8 (with the hole at the top of the tank), the dense jet trajectory approximately agrees with the analytical formulas suggested 44 years ago by Ooms et al. and by Hoot et al. During the first 10 or 20 seconds of the release, the videos show that the dense jet rises up to about 40 m, then sinks towards the ground, touching down at about x = 60 m. The portion of the plume that sinks to the ground then spreads out in all directions due to gravity slumping. Due to the decrease with time of the momentum jet release rate, the jet gradually becomes less dense and less powerful and the touchdown distance is seen to increase. After about 30 or 40 s, the chlorine gas jet rises up to 40 m but is no longer sufficiently dense to sink.

Key words: *dense gas dispersion, chlorine releases, plume rise of dense jet*

INTRODUCTION

Plans and results of the JR series of chlorine releases (JR I in 2010 and JR II 2015) have been described by the current authors at several HARMO conferences over the past ten years (e.g., Hanna et al., 2016b). The JR field experiments were initiated because there had been much concern about the possible effects of pressurized liquid chlorine released from storage tanks and transportation vessels. Hanna et al. (2008) reviewed three railcar accidents involving chlorine, and compared predictions of six widely used dense gas models. JR I, which took place at Dugway Proving Ground (DPG) in the U.S. in 2010, involved one and two ton releases of pressurized liquefied chlorine or ammonia from a tank mounted about 1 m above ground, with the initial jet pointed downward (Fox and Storwold, 2010). The tank was in the center of a depression of depth 2 m and diameter 50 m dug into the flat desert surface. Videos during the five JR I chlorine experiments clearly show the two phase chlorine momentum jet striking the ground and deflecting into a donut-shaped dense wall jet (Hanna et al., 2012) that filled the depression. Concentrations were measured from the edge of the depression (about 25 m) to a distance of about 500 m.

While the above JR I analysis was underway, we rediscovered the 90-year-old LB (England) field experiment involving releases of 5 to 10 tons of chlorine in 15 minutes from a ship over water (CDE, 1927; Wheatley et al., 1988). Concentrations were observed by several ships taking cross-plume samples. Hanna, Chang and Huq (2016a) analyzed the JR I and LB observations and showed that, when plotted versus downwind distance, x, the observed Cu/Q values from the two field experiments roughly overlapped and conformed to a Cu/Q proportional to x^{-p} relation with $3/2<p<2$. Here, C was the one-minute averaged arc-maximum concentration.

The current paper adds the JR II Cu/Q observations to the above analysis. Nine JR II trials are available from 2015 and 2016, and involve releases of 5 to 20 tons of pressurized liquefied chlorine. In addition, the current paper analyzes the dense gas plume rise observed during JR II trial 8, the only trial with an upward directed release. We compare the predictions of the Hoot, Meroney, and Peterka (1973) analytical formula for plume rise and for subsequent touchdown (to the ground) of the dense gas plume.

OVERVIEW OF JR II

The 2015 and 2016 JR II experiments (nine trials) took place over an extensive dry lake bed (salt playa) at DPG. The release was initiated between about 7 to 9 AM (depending on when the wind speed and direction were within prescribed bounds) in late August and early September. The chlorine release was at the center of a 25 m diameter concrete pad and was a two-phase momentum jet with duration about 30 to 60 seconds. There was a 15.2 cm hole on a horizontal ten-ton tank (Nicholson et al. 2017 and Spicer and Miller 2017). The bottom of the tank was about 1 m agl. The hole was at the bottom of the tank for trials 1-6, at the top of the tank for trial 8, and pointing 45°downwards and downwind for trial 7. In the final 2016 trial 9, the 20 ton "mule tank" was used and the jet direction was downwards. During 2015, the source location was within a mock urban environment of about 80 CONEX shipping containers (2.3 by 2.6 by 6.1 or 12.2 m) set up on a staggered grid in a packed gravel area 122 m square. The concrete pad's center was positioned 31 m from the upwind edge of the mock urban area. Concentrations and winds were measured within the obstacle array and on 90° arcs at distances of 0.2, 0.5, 1, 2, 5, and 11 km.

For JR II 2016, the CONEX obstacle array was removed. Otherwise, the release tank, sampler arrays, meteorological instruments, and other instruments were very similar in 2015 and 2016. In 2016, a drone was used to take videos from above the chlorine cloud. For trials 7 and 8, when the hole was not at the bottom of the tank, significant chlorine liquid remained in the tank after the momentum jet stopped. This remaining liquid was dumped onto the concrete pad about 10 minutes later and subsequently evaporated over 10 to 20 minutes. Chlorine samplers continued to collect data during this period, thus effectively creating two additional "trials". The current paper deals only with the jet release trials.

All JR II experiments have extensive observations of winds, as well as surface energy budget and turbulence, and vertical profiles using rawinsondes and remote sounders. The releases took place only if the average on-site 2 m wind speeds were in the range from 2 to 6 m/s, and wind directions were within the 90° sampling arcs. Table 1 lists the characteristics of the nine JR II chlorine release trials. The details of the tank and the pressurized releases from the 6" (15.2 cm) hole are described by Nicholson et al. (2017) and Spicer and Miller (2017). The primary concentration averaging time that we analyze is the minimum reported for the various field experiments (about 1 s for JR I and II and 1 min for LB).

Table 1. Summary of JR II. Note that MDT = GMT-6. Winds measured by aerovanes at heights of about 2 m.

Trial	day	time MDT	release duration s	total jet mass kg	Q (kg/s)	wind speed at z = 2 m m/s	wind direction	Avg T C
1	8/24/2015	7:35:46 AM	22.2	4545	204.7	3.1	147	17.7
2	8/28/2015	9:24:21 AM	32.4	8192	252.8	2.5	158	22.7
3	8/29/2015	7:56:55 AM	20.3	4568	225.0	4.1	170	22.6
4	9/1/2015	8:39:33 AM	28.8	7017	243.6	3.6	184	22.6
5	9/3/2015	7:29:09 AM	33.6	8346	248.4	5.0	183	22.2
6	8/31/2016	8:23:35 AM	33.2	8392	252.8	2.3	160	22.0
7	9/2/2016	7:56:00 AM	36.4	8620	236.8	4.5	160	18.9
8	9/11/2016	9:01:45 AM	30.0	2368	78.9	2.2	175	14.8
9	9/17/2016	8:05:00 AM	133	17700	133.5	3.5	165	10.5

PLOTS OF ARC MAX C AND Cu/Q vs x FOR FIELD EXPERIMENTS

For emergency response purposes, there is interest in knowing the maximum concentration expected at various distances downwind of an accident involving a tank of pressurized liquefied chlorine. The 15 trials from the LB, JR I, and JR II field experiments cover a range of release masses, from about 1 to 20 tons, over a duration ranging from about 30 s (JR II) to 15 min (LB). These release masses represent the amount typically carried by a truck. Figure 1 contains the observations of arc-max C (in ppmv) versus distance for the 15 experiment trials. It is seen that the maximum observed concentration in Figure 1 at x = 0.5 km is about 20,000 ppm, and at x = 11 km is about 100 ppm. Note that the maximum concentration is approximately following a -5/3 power law. The solid line is the -5/3 line that barely touches the maximum C points.

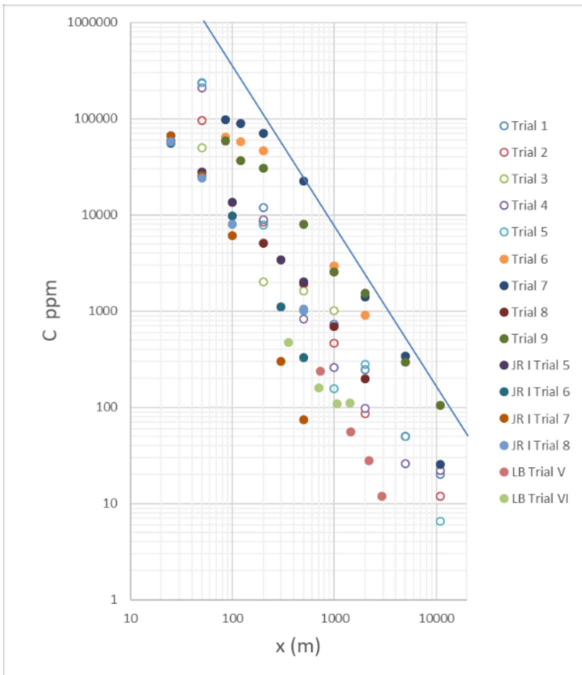

Figure 1. Plot of arc maximum C (in ppm) versus x for Lyme Bay (LB), Jack Rabbit I (JR I), and Jack Rabbit II (Trials 1 – 9). The straight line represents the -5/3 power law that best fits the max C point at the various x.

As pointed out by Britter and McQuaid (1988), knowledge of the basic physics processes can be used to normalize the concentrations and hopefully reduce the scatter. Following the method used by Hanna et al. (2016a), in Figure 2 we plot the observed Cu/Q values versus x, for the 15 field trials (2 LB, 4 JR I and 9 JR II). Recall that C is the arc-max concentration. The points again follow a -5/3 power law (shown in blue), agreeing with Britter and McQuaid (1988). The scatter is slightly reduced. At any given distance, the range of the 15 data points is about a factor of plus and minus three or four about the best-fit line $Cu/Q = 8.5x^{-5/3}$. It is seen that the JR II 2015 points (for trials 1-5) generally show the smallest Cu/Q at any x. This may be due to the enhanced mechanical mixing in the near field due to the presence of the CONEX obstacles.

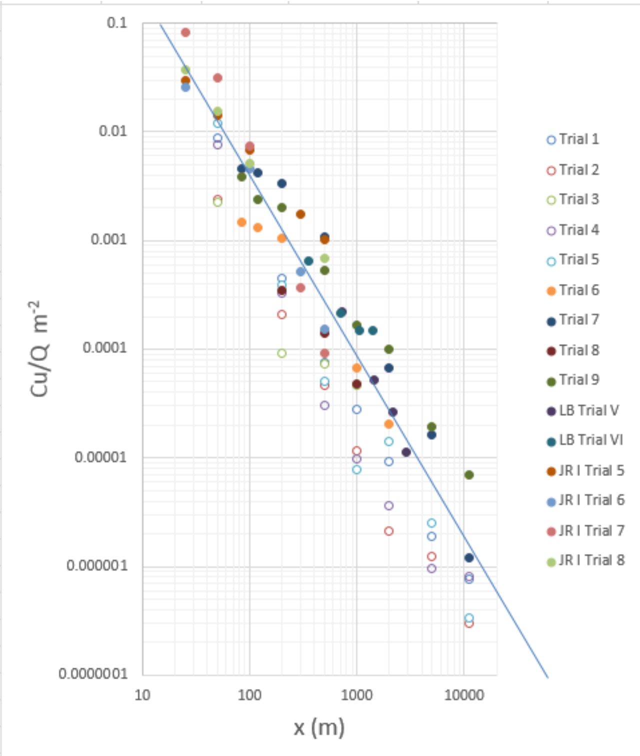

Figure 2. Scatter plot of Cu/Q versus x for Lyme Bay (LB), Jack Rabbit I (JR I), and Jack Rabbit II (Trials 1 – 9). The line represents the relation $Cu/Q = 8.5x^{-5/3}$, where Cu/Q has units m^{-2} and x has units m.

DENSE JET RISE IN TRIAL 8

JR II trial 8 involved a vertically upwards release. Although the total mass in the tank was 9122 kg, only 2368 kg was released in the pressurized two-phase jet. As seen in videos and described by Spicer and Miller (2017), the two phase jet lasted only about 30 sec, and was followed by a steadily diminishing chlorine gas jet for another 60 sec. The videos from the side showed a white two-phase cloud in the rise phase. After the plume centerline rose to a height of about 40 m at a distance of about 30 m downwind, the plume's density caused it to slump to the ground, reaching the ground at a downwind distance of about 60 m. Figure 3 is a photo of the plume at 30 s. The green cloud appeared to be 100 % gas phase as it was slumping to the ground. The videos indicated that, over a period of a minute, the plume "touchdown" distance increased from about 60 m initially to about 100 m after 30 sec, to about 200 m by 40-60 sec after touchdown. After that, the visible green plume remained aloft. During the duration of the Trial 8 jet, the 32 m meteorological tower just upwind of the source indicated a 2 C inversion from 2 to 32 m, and wind speeds of about 2 m/s at 2 m and 3.5 m/s at 32 m (i.e., slightly stable ambient conditions).

Figure 3. Photo of JR II Trial 8 dense jet plume about 30 s after the release initiated. The distance from the source tank to the tall red obstacle is about 85 m.

As an initial assessment, we tested the Hoot et al. (1973) analytical one-line formula (also see p 57 of Hanna et al. 1996) for dense gas plume rise and downwind touchdown. In the 1970s there was much concern about dense gases released from vents. Hoot et al. (1973) and Ooms et al. (1974) analyzed field and laboratory data and developed simple models for dense plumes. The Hoot et al. model equations are given below.

Plume rise Δh above source: $\Delta h/2R_o = 1.32\ (w_o/u)^{1/3}(\rho_o/\rho_a)(w_o^2/(2R_o g'))^{1/3}$ (1)

where $g' = g(\rho_o-\rho_a)/\rho_o$; g is acceleration of gravity (9.8 m/s^2), ρ_a is ambient air density, u is wind speed, and ρ_o, R_o, and w_o are initial plume density, radius and vertical velocity after depressurization.

Plume touchdown distance x_g downwind:

$$x_g/2R_o = w_o u/(2R_o g') + 0.56\{(\Delta h/2R_o)^3\ ((2 + h_s/\Delta h)^3 -1)u^3/(2R_o w_o g_a')\}^{1/2} \qquad (2)$$

where $g_a' = g(\rho_o-\rho_a)/\rho_a$ and h_s is elevation of the stack or vent opening above the ground.

Spicer and Miller (2017) and Babarsky (2017) point out that after depressurization the velocity w_o is likely to be near sonic (206 m/s). About 20 % of the chlorine mass exiting the hole will have flashed to gas. The remaining 80% of the mass will consist of very small aerosol drops with a mass mean diameter of about 50 to 100 µm. The jet temperature will be close to the chlorine boiling point of –34 C. Although the above variables are observed and modeled to vary with time, for the purpose of solving equations (1) and (2), we assume they are constant, with the values of mass release rate Q listed in Table 1.

Thus, Q = 79 kg/s, with 20 % gas and 80 % liquid aerosol drops. We assume that the gas phase accounts for all of the volume flux (6.3 m^3/s). The resulting "effective density" of the two phase plume is about 12.5 kg/m^3. After depressurization, the plume would have an initial vertical velocity w_o close to sonic (206 m/s); however, as a sensitivity study, we also consider w_o = 50 m/s. For w_o = 206 m/s and 50 m/s, the corresponding initial radius R_o would be 0.1 m and 0.2 m, respectively. Solving equation (1), we find that maximum plume rise Δh is 92 m for w_o = 206 m/s and 36 m for w_o = 50 m/s. From equation (2), the touchdown distance x_g is 100 m for w_o = 206 m/s and 39 m for w_o = 50 m/s. These two solutions roughly bracket the observed JR II Trial 8 plume as seen on the videos and the still photos.

Much more analysis will be carried out and the data archive and video footage are being made accessible to stakeholders upon request to DHS S&T CSAC (JackRabbit@st.dhs.gov) pending successful approval of access to the Homeland Security Information Network web site.

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