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PRELIMINARY ANALYSIS OF OBSERVATIONS FROM THE JACK RABBIT II–2015 FIELD EXPERIMENT ON DENSE GAS DISPERSION IN A BUILT ENVIRONMENT

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Abstract: The Jack Rabbit II field experiment, carried out in August and September 2015 at Dugway Proving Ground, Utah, USA, involved five releases of 4.5 to 8.3 tons of pressurized liquefied chlorine within a "mock urban" environment of about 80 CONEX shipping containers set up on a staggered grid in a packed gravel area 122 m square. In addition, trailers and a two-wide by three-high CONEX stack were placed about 70 m downwind of the source, to study the transport and dispersion of dense gas around and inside urban structures. Chlorine was released at the center of a 25 m diameter concrete pad as a downward-directed two-phase momentum jet in about one minute from a horizontal tank with a 15 cm opening at about 1.0 m agl. The concrete pad's center was positioned 31 m from the upwind edge of the mock urban area. Wind speeds at a height of 2 m ranged from 2 to 5 m/s during the five trials. 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. The initial jet formed a broad and shallow dense wall jet that rapidly spread in all directions to a distance of about 50 to 75 m, before moving with the wind across the urban array and over the desert surface downwind. When encountering obstacles, the wall jet mixed up and around them. Limited liquid pooling was observed on the concrete pad. Quantitative observations, photos, and videos have passed QA/QC, and this paper describes some results of preliminary analysis. For example, the decrease of concentration is seen to follow basic dense gas similarity relations.

Key words: *dense gas dispersion, chlorine releases, dispersion in urban built environment*

INTRODUCTION

As has been known for many years, chlorine gas is very toxic (Marshall 1989). There has been much recent 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 compare predictions of six widely used dense gas models. It appears that, at these sites, there were fewer observed casualties than would be expected from the model predictions. Consequently, the U.S. Department of Homeland Security (DHS) initiated a research program to study the source emissions characteristics, transport and dispersion, and deposition of large releases of pressurized liquefied chlorine. Several other sponsors and collaborators also contributed resources. The research program is centered on the Jack Rabbit (JR) field experiments. JR I, which took place at Dugway Proving Ground (DPG) in the U.S. in 2010, used one and two ton releases from a tank mounted about 1 m above ground, with the initial jet pointed downward. The tank was in the center of a depression of depth 2 m and diameter 50 m dug into the flat desert surface. There were five releases of chlorine and five of anhydrous ammonia, with about one to two tons released in each trial. Videos during the 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; Bauer, 2013). The characteristics of the releases conform to general models of mass flux, flashing, and velocities of jets from pressurized liquefied tanks (see Britter et al., 2011). Concentrations were measured from the edge of the depression to a distance of about 500 m, although samplers were sparse at that distance. It was found that the gas was "held-up" for several minutes in the depression at lighter wind speeds (< about 2 m/s), but was transported downwind for a wind speed of 6 m/s. The variation of arc-maximum 1-min-avg concentration with distance during JR I was found to follow basic dimensional relations suggested by Britter and McQuaid (1988) and Hanna et al. (1996) as shown in Figure 1 from Hanna et al. (2016).

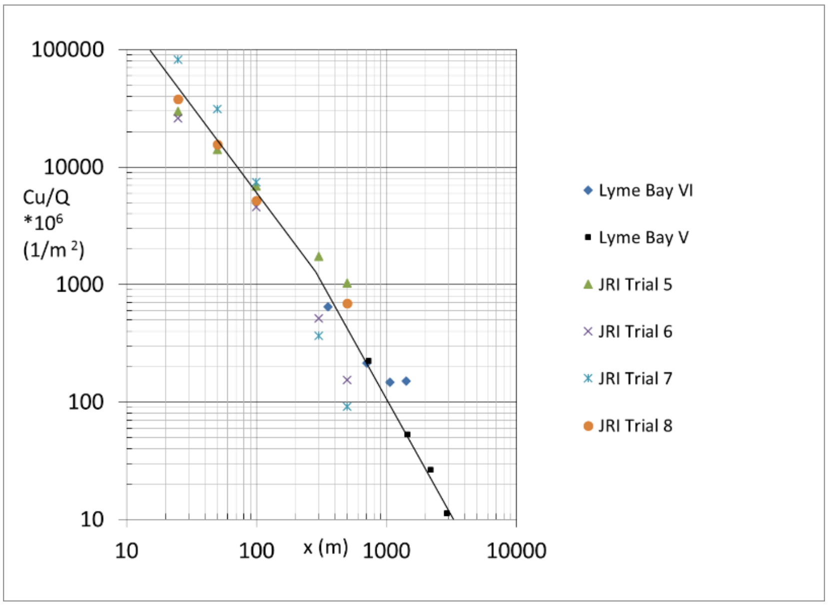

Figure 1. Lyme Bay and JR I observed ln Cu/Q_c versus ln x (from Hanna et al., 2016). C is one-min avg arc max, u is wind speed, and Q_c is mass emission rate.

However, several of the stakeholders in the Jack Rabbit study pointed out that the one and two ton releases during JR I in 2010 were significantly less than the 20 to 60 tons that can be released from a railcar. Therefore, the JR II experiments were planned for 2015 and 2016, where 10 to 20 tons of chlorine would be released from larger tanks. In addition, JR II includes indoor measurements. The 2015 JR II experiments took place at DPG with the source location 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. In addition, trailers and a two wide by three high CONEX stack were placed about 70 m downwind of the source, to study the transport and dispersion of dense gas around and inside urban structures. Chlorine was released at the center of a 25 m diameter concrete pad as a downward-directed two-phase momentum jet in about 30 to 60 seconds from a horizontal tank with a 15 cm opening at about 1.0 m agl (Spicer et al., 2016). The concrete pad's center was positioned 31 m from the upwind edge of the mock urban area. Figure 2 provides a view of the experiment setup. 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. Figure 3 shows the sensor placements on the 2, 5, and 11 km arcs. The 11 km experimental domain is within a relatively flat salt playa at DPG, although there were 1000 m mountain ranges about 40 km to either side of the playa. The JR II domain is about 10 km west of the JR I domain. The JR II site was chosen because winds are known to be steady from the south at dawn most of the time during the summer.

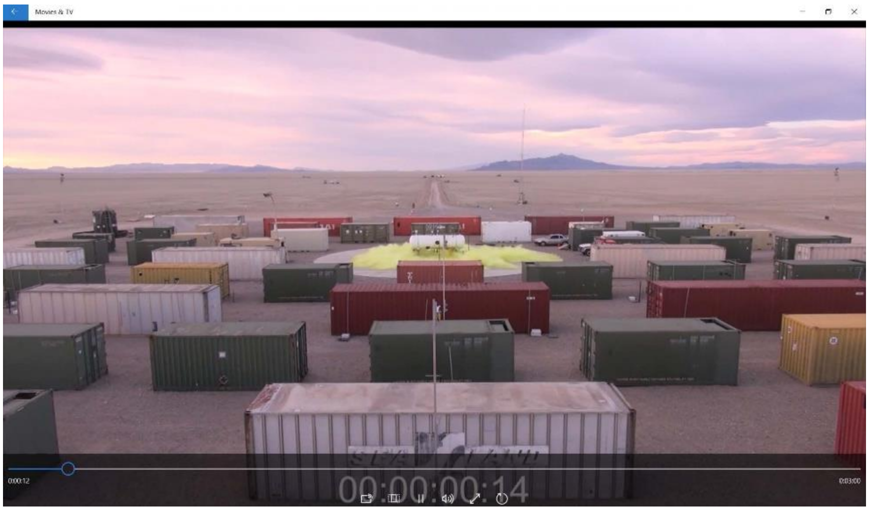

Figure 2. JR II 2015 Trial 5, looking towards south (upwind), 0.5 sec after release. Note tank and yellow chlorine cloud.

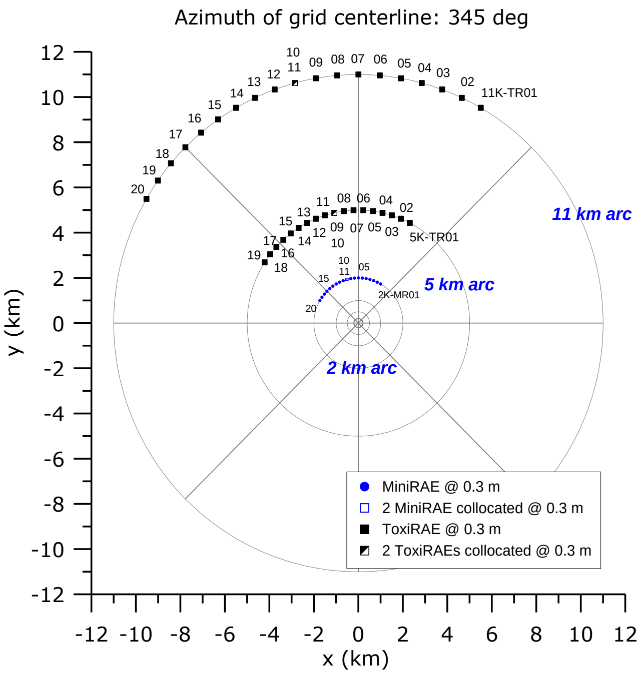

Figure 3. JR II 2015 sampler grid for 2, 5, and 11 km arcs.

For large releases of pressurized liquefied chlorine, the resulting initial cloud is characterized by a strong momentum jet consisting of about 20 % gas, and 80% liquid (by mass) in the form of aerosol (drops) with a broad size range but a mass median diameter of about 20 to 100 μm (Britter et al., 2011). Several attempts were made to measure the chlorine aerosol in 2015 but with limited success. It is uncertain whether an observed drop consists of chlorine, ambient water, natural particles, or a combination.

All JR II experiments have extensive observations of winds, as well as surface energy budget and turbulence. The releases took place only if the average on-site wind speeds were roughly in the range from 2 to 6 m/s, and wind directions were within the 90° sampling arcs.

The JR II experiment planned for 2016 will be at the same location as the 2015 experiment but most of the mock urban obstacles will be removed. One obstacle will be retained for an indoor experiment. Ten to twenty tons of chlorine are planned to be released in seven trials, with different jet orientations: upwards, horizontal downwind, 45 degrees downwards and downwind, and directly downwards. There will be deposition measurements taken.

The current paper describes some general characteristics of the JR II 2015 field experiment. The data have recently passed QA/QC and are being distributed to JR II participants. However, these data are all "raw" in the sense that they have not been corrected for known biases. For example, a correction curve is available for each MiniRae concentration sampler, based on laboratory calibrations carried out after the field experiment, but has not been applied to the raw data in the data archive.

OVERVIEW OF JR II 2015

Table 1 lists the characteristics of the five JR II chlorine release trials during 2015, where the mass released ranged from 4518 to 8321 kg. The details of the tank and the pressurized releases from the 6" (15.2 cm) hole are described by Spicer et al. (2016). The duration of the two-phase release was about 30 to 60 sec. All experiments were conducted in early morning. Videos showed that rain-out (liquid pooling) was relatively small (less than 10 % of the total mass), and most of the small pool evaporated within a few minutes. The strong downward pointing dense momentum jet spread out in all directions for about 50 to 75 m, and the videos showed the material "splashing" upwards to the above the tops of the obstacles when it encountered the CONEX obstacles in the near field. This broad spread was able to be simulated by several models that were run prior to the experiments. After the initial jet and outwards cloud motion ceased, the cloud settled down and began being transported downwind as a "normal" shallow dense cloud. As concentrations dropped below about 1000 ppm at the 200 to 500 m arcs, the cloud density effects gradually became insignificant and the cloud behaves as a neutral passive cloud. Many samplers recorded significant chlorine concentrations with resolution of about 1 sec and the duration of time for cloud passage across a sampler at the larger ranges was on the order of five to ten minutes.

Table 1. Summary of JR II 2015. Note that MDT = GMT-6. PWIDS are aerovanes on short towers at heights of about 2 m. There were 34 PWIDS placed over the JR II domain.

Trial		1	2	3	4	5
Release (MDT, = UTC-6)	Date	8/24/2015	8/28/2015	8/29/2015	9/1/2015	9/3/2015
	Start Time	7:35:45	9:24:21	7:56:55	8:38:50	7:28:19
	Duration (sec)	30	60	30	45	60
Release Amount (kg)		4,518	8,168	4,521	6,985	8,321
AVG PWIDS Wind Direction (deg)		147	158	170	184	183
AVG PWIDS Wind Speed (m/s)		1.9	4.3	4.0	2.3	2.8
AVG PWIDS Temperature (C)		17.7	22.7	22.6	22.6	22.2

Although the data have just recently passed QA/QC, preliminary analysis shows good consistency among the five trials and agreement with results of previous analyses with JR I and other dense gas data (such as shown above in Figure 1 for JR I and Lyme Bay). Figure 4 contains the observed JR II 2015 Cu/Q values versus x, for the five trials and for downwind distances, x, from 50 m to 11 km. C(g/m^3) is the arc max 1 sec average concentration, u(m/s) is the average wind speed, and Q(g/s) is the source mass emission rate. The data from the five trials all follow an approximate -5/3 power law, as found at other locations and in approximate agreement with suggested relations by Britter and McQuaid (1988). At any given distance, the range of the five data points is about a factor of plus and minus three about a best-fit line.

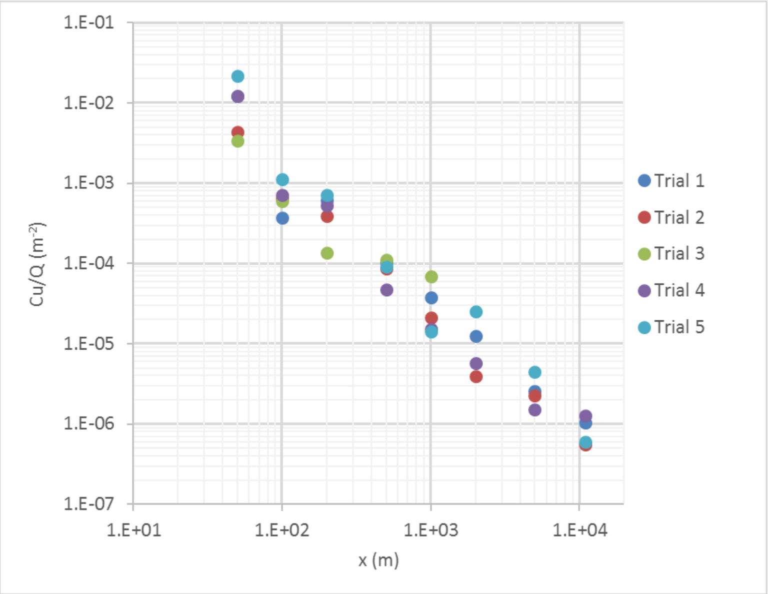

Figure 4. Observed JR II 2015 arc max 1 sec avg Cu/Q (m^{-2}) vs x (m).

Figures 1 and 4 both have Cu/Q plotted versus x, although 1-min concentration averages are used in Figure 1 and 1 sec averages in Figure 4. The units of the y-axis are different by 10^6. If the same y-axis units were used, the JR II points are slightly below (about a factor of two on average) the JR I and Lyme Bay points. We note that a major difference is that the JR II release duration is much smaller than the JR I and Lyme Bay release durations, causing the JR II cloud to be effectively a puff (not a continuous plume) over nearly all of its range (all x >50 m). However, the overall agreement is fairly good.

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 CASAC (JackRabbit@st.dhs.gov) pending successful approval of access to the HSIN web site.

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