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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JR II Cloud, Trial 5, looking toward south (upwind) 0.5 sec after release starts

Side to side dimension of obstacle array = 100 m
Jack Rabbit II

• Follows JR I (10 trials in 2010), releasing 1 or 2 tons of pressurized liquefied chlorine or anhydrous ammonia. Mostly light winds, downward release into artificial 2 m deep by 25 m radius depression. C observations to 500 m.

• JR II 2015 – 5 trials, releasing 5 to 9 tons. Moderate winds, downward release in middle of mock urban array. Downwind C observations to 11 km, and inside some buildings.

• JR II 2016 – 4 trials, releasing 10 to 20 tons over flat desert surface (same set-up as 2015 but with mock urban array removed). Trials 6 and 9 downwards, trial 7 45° downwards, trial 8 up.
10 ton Tank used for JR II Chlorine Releases
Designed by Tom Spicer (in photo)
# Summary of JR II – 2015 and 2016

<table>
<thead>
<tr>
<th>Trial</th>
<th>day</th>
<th>time</th>
<th>release duration</th>
<th>total jet mass kg</th>
<th>Q (kg/s)</th>
<th>wind speed at z = 2 m</th>
<th>wind direction</th>
<th>Avg T C</th>
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<td>22.2 s</td>
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JR II C Samplers on 2, 5, and 11 km arcs

Azimuth of grid centerline: 345 deg
JR II Trial 2, 4.3 sec after the release starts
Part 1 of paper – Plots of C and Cu/Q versus distance x

- C is arc max 1-3 s average concentration; u is 2 m wind speed, Q is mass emission rate

- For emergency response guidance, a plot of C vs x combined for all release trials shows what to expect from release of 1 to 20 tons of chlorine

- Dimensional analysis should allow scatter to be reduced. Thus Cu/Q vs x.

- Fit line to observed Cu/Q vs x plot. It is found that Cu/Q is proportional to $x^{-5/3}$
Arc max 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
Arc max Cu/Q versus x for Lyme Bay (LB), Jack Rabbit I (JR I), and Jack Rabbit II (Trials 1 – 9)

The straight line represents the relation \( \frac{Cu}{Q} = 8.5x^{-5/3} \), where Cu/Q has units \( m^{-2} \) and x has units m
Comments on Plot of Cu/Q vs x

• Normalization with Q/u brought the Lyme Bay, JR I and JR II 2016 points closer together (reduced the scatter seen in the C vs x plot)

• However, the JR II 2015 points (where there was a mock urban obstacle array at x < 100 m) were not moved much closer to the others and now are the “low values” on the plots

• The mock urban obstacles were seen to visibly enhance mixing and thus there may be an “initial mixing” effect that reduces concentrations over the whole sampling array
Part 2 of paper - Vertical dense jet in Trial 8 (hole at top of tank)

• The dense jet rises up about 40 m (plume centroid height), then touches down to the ground at a distance of about 60 m

• Compare maximum rise and touchdown distance with Hoot et al (1973) analytical formulas
Trial 8 dense plume about 30 s after release. Distance from the source to the red obstacle is about 85 m
Hoot, Meroney, and Peterka (1973)

Analyzed dense plume observations from many experiments in their wind tunnel. Came up with simple analytical formulas based on fundamental science

Plume rise $\Delta h$ above source:

$$\frac{\Delta h}{2R_o} = 1.32 \left( \frac{w_o}{u} \right)^{1/3} \left( \frac{\rho_o}{\rho_a} \right) \left( \frac{w_o^2}{2R_o g'} \right)^{1/3}$$

where $g' = g(\rho_o - \rho_a)/\rho_o$; $g$ is acceleration of gravity, $\rho_a$ is ambient air density, $u$ is wind speed, and $\rho_o$, $R_o$, and $w_o$ are initial plume density, radius and vertical velocity after depressurization.
Plume touchdown distance $x_g$ downwind:

$$\frac{x_g}{2R_o} = \frac{w_0 u}{(2R_o g')} + 0.56\left\{\left(\frac{\Delta h}{2R_o}\right)^3 \times \left((2 + \frac{h_s}{\Delta h})^3 - 1\right) \frac{u^3}{(2R_0 w_0 g'_a)}\right\}^{1/2}$$

where $g'_a = g(\rho_0 - \rho_a)/\rho_a$ and $h_s$ is elevation of the stack or vent opening above the ground.
Inputs to Hoot et al. formula

• $Q = 79 \text{ kg/s}$

• $T = -34 \degree C$ (chlorine boiling point)

• 20% of mass released flashes (to gas). The rest is small aerosol drops. Assume effective initial density $\rho_o$ is 12.5 kg/m$^3$.

• Sensitivity study with initial vertical velocity $w_o$ of 206 m/s (sonic) and 50 m/s. These imply initial radius $R_o$ of 0.1 and 0.2 m.
Results of Hoot et al. formula

• For initial vertical velocity $w_o$ of 206 m/s (sonic) and initial radius $R_o$ of 0.1 m, plume rise $\Delta h$ is 92 m and touchdown distance $x_g$ is 100 m

• For initial vertical velocity $w_o$ of 50 m/s (sonic) and initial radius $R_o$ of 0.2 m, plume rise $\Delta h$ is 36 m and touchdown distance $x_g$ is 39 m

• These two predictions roughly bracket the observed values
Conclusions

• The two types of initial analysis described above demonstrate that the JR II data follow expected scientific relations regarding variations of concentrations with downwind distance, and rise of dense plumes.

• As with all analysis of environmental data, there is much scatter.