# 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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HARMO 18, Bologna, Italy, 9-12 October 2017

# 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

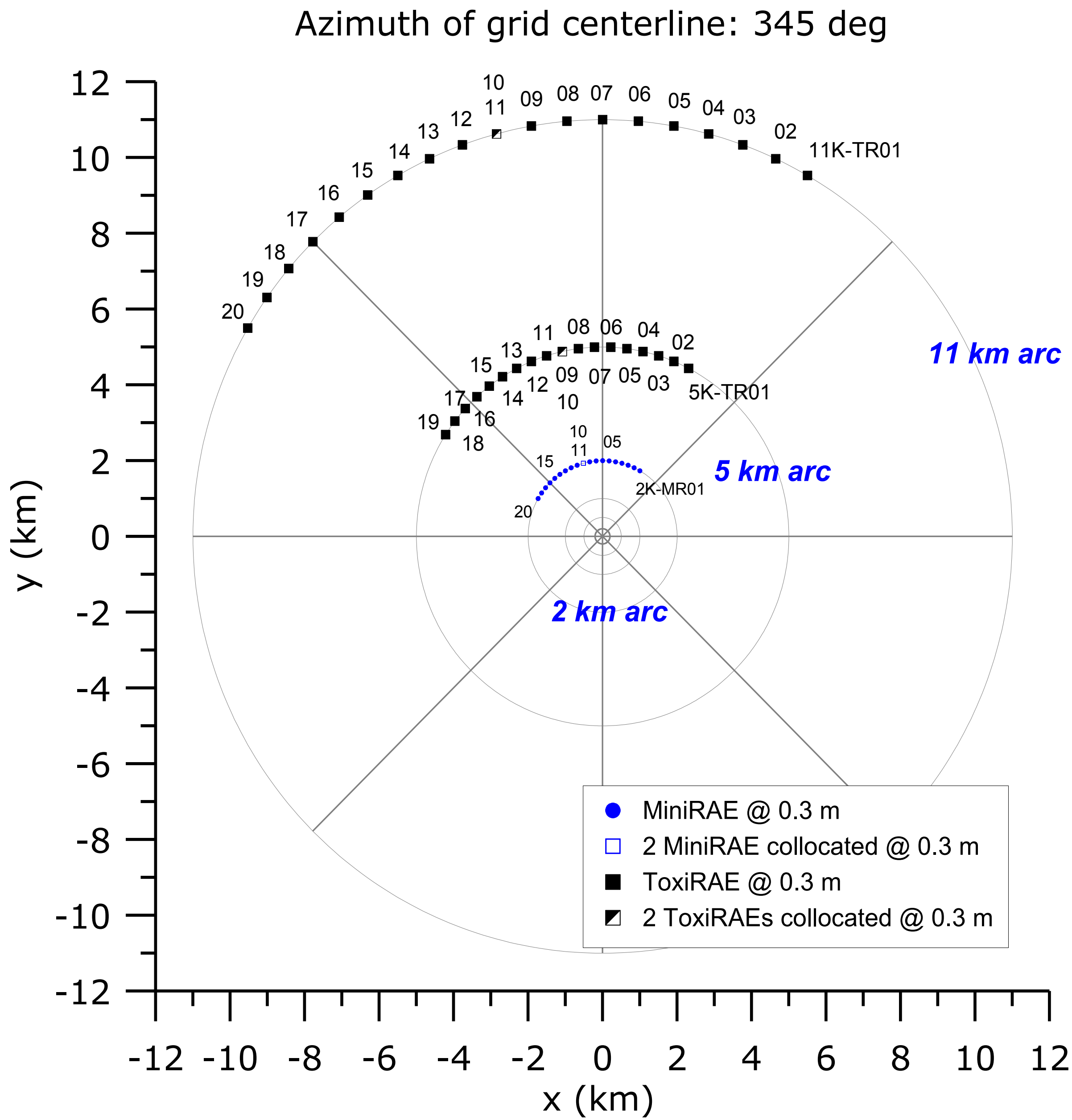
- Follows JR I (10 trials in 2010), releasing 1 or 2 tons of pressurized liquefied chlorine or anhydrous ammonia.  Mostly light winds, downward release into artificial 2 m deep by 25 m radius depression. C observations to 500 m.
- JR II 2015 – 5 trials, releasing 5 to 9 tons. Moderate winds, downward 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

| 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 |

# JR II C Samplers on 2, 5, and 11 km arcs

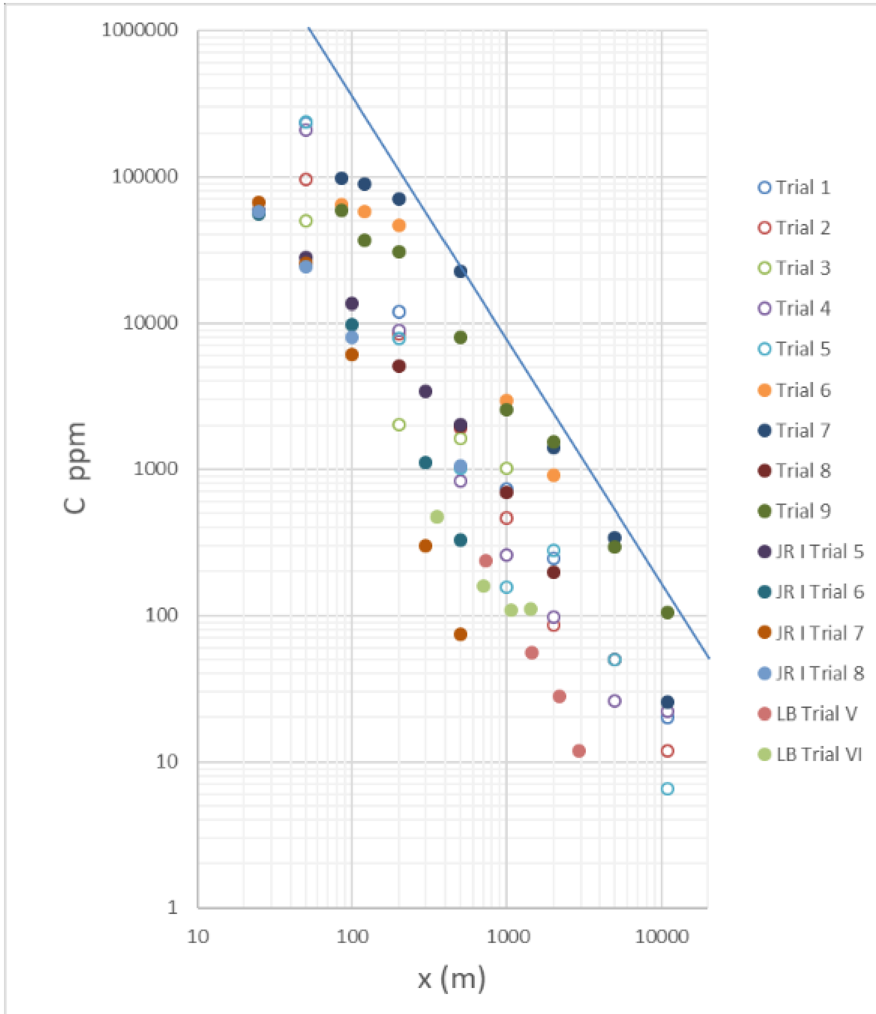


# JR II Trial 2, 4.3 sec after the release starts

# Part 1 of paper – Plots of C and Cu/Q versus distance x

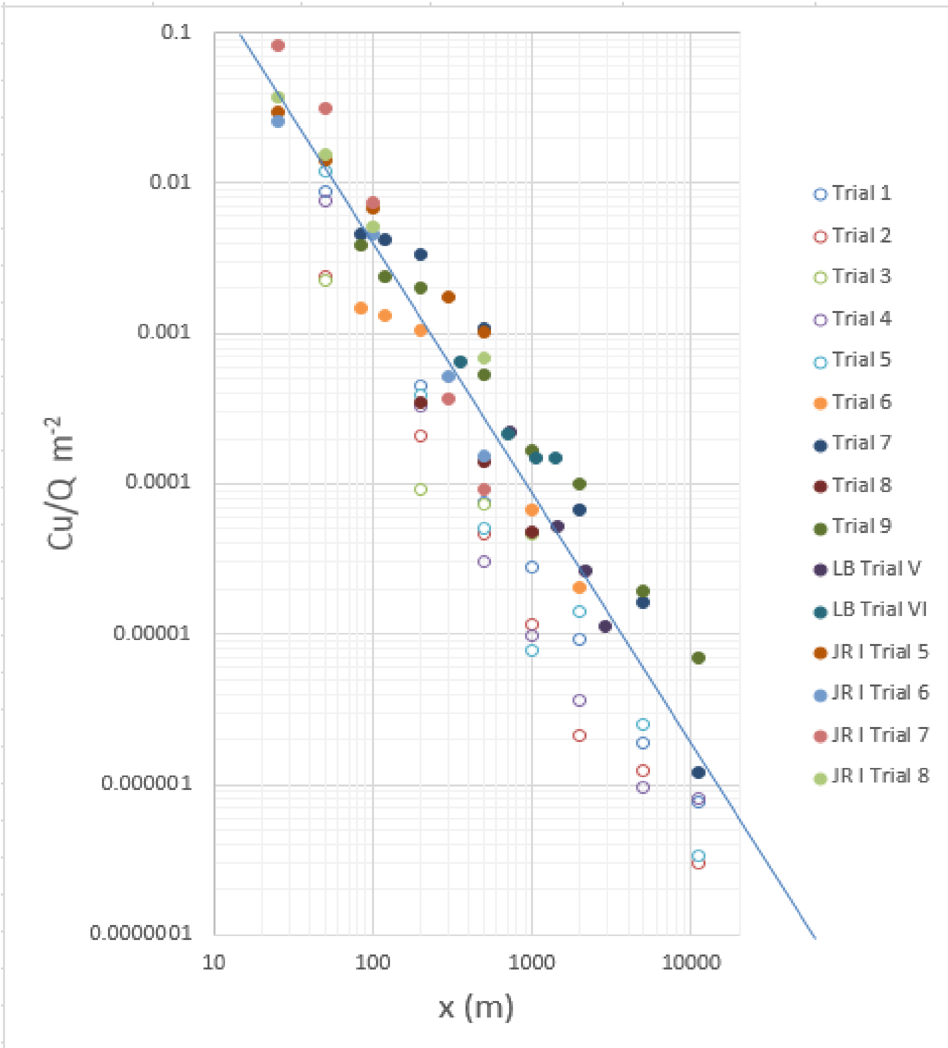
- C is arc max 1-3 s average concentration; u is 2 m wind speed, Q is mass emission rate
- For emergency response guidance, a plot of C vs x combined for all release trials shows what to expect from release of 1 to 20 tons of chlorine
- Dimensional analysis should allow scatter to be reduced. Thus Cu/Q 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 $Cu/Q = 8.5x^{-5/3}$, 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:

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

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.

# Hoot, Meroney, and Peterka (1973) slide 2

Plume touchdown distance $x_g$ downwind:

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

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

# Inputs to Hoot et al. formula

- $Q = 79$ kg/s
- $T = -34$ 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.