TESTING OF AN ANALYTICAL FORMULA FOR ESTIMATING MAXIMUM PLUME RISE AND TOUCHDOWN FOR A DENSE PLUME, USING THE JACK RABBIT II TRIAL 8 OBSERVATIONS

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Jack Rabbit II Trial 8

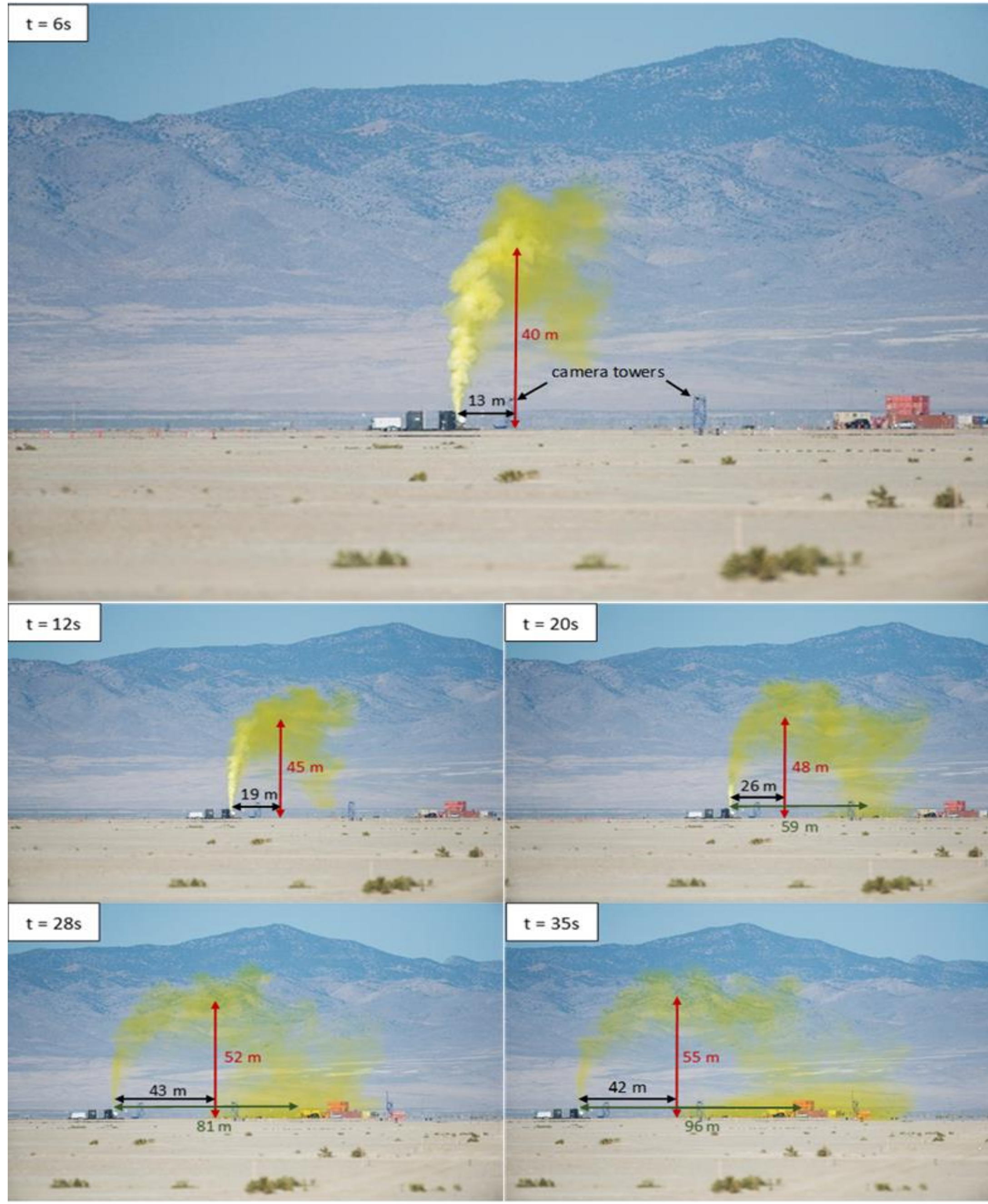
- Jack Rabbit II Trial 8 involved a vertical release of 2400 kg of pressurized liquefied chlorine
- Never has there been a field experiment with such large emissions of chlorine in an upwards direction
- Videos and near ground concentration samplers allowed plume trajectory and maximum ground level concentration to be observed.
- The plume first rose up, then sunk to the ground
- We test analytical formulas for maximum plume rise, distance to touchdown, and maximum concentration at touchdown suggested by Hoot Meroney and Peterka (HMP), derived using basic plume rise theory and wind tunnel observations. We also test the Briggs model.

Release Tank. Orange Arrow indicates upward jet location for Trial 8

Trial 8 dense plume from Utah Valley University drone

Time series of photos of Trial 8 visible plume

Camera towers (height 6.4 m) provide scaling



Initial conditions (after the jet reached ambient pressure at a distance of 2 or 3 m) input to models.

Release time ending	td obs Duration of release	Mass flux Qc	T obs cloud	Mass fract vapor	rhoc Model 1 cloud density	rhoc Model 2 cloud density	Qc/rhoc Model 1 Volume flux Vc	Qc/rhoc Model 2 Volume flux Vc	wo Model 1 Initial vert vel	wo Model 2 Initial vert vel	Ro Model 1 Initial Radius	Ro Model 2 Initial Radius
sec	(s)	kg/s	K		kg/m3	kg/m3	m3/s	m3/s	m/s	m/s	m	m
5	5	139.4	286.2	0.19	16.71	16.35	8.34	8.53	84.6	51.0	0.185	0.235
10	5	66.8	283.7	0.31	10.11	9.71	6.61	6.88	148.2	87.1	0.120	0.160
15	5	48.8	281	0.42	7.57	7.23	6.45	6.75	182.3	108.1	0.110	0.140
20	5	37.8	277.9	0.53	5.96	5.66	6.34	6.68	210.0	126.4	0.100	0.130
25	5	30.1	274.9	0.66	4.80	4.56	6.27	6.60	234.2	143.7	0.095	0.120
30	5	24.3	271.8	0.81	3.93	3.73	6.18	6.51	255.8	160.7	0.090	0.115
40	10	18.1	267.4	0.98	3.21	2.88	5.64	6.28	263.3	176.0	0.085	0.105
50	10	12.4	262	1	3.16	2.84	3.92	4.37	221.1	175.3	0.080	0.090
60	10	8.64	257.4	1	3.16	2.89	2.73	2.99	164.3	161.0	0.075	0.075
80	20	5.24	252.3	1	3.08	2.95	1.70	1.78	97.9	97.9	0.075	0.075
100	20	2.71	247.2	1	3.05	3.01	0.89	0.90	49.7	49.7	0.075	0.075

Analytical Models Tested Here

Hoot-Meroney-Peterka (HMP)

Briggs

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 Δh above source:

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

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.

More Hoot, Meroney, and Peterka

Distance to max rise $x/2R_o = w_o u/(2R_o g')$

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.

Max C at touchdown

$$C/C_o = 2.43\ (w_o/u)\ [(h_s + 2\Delta h)/(2R_o)]^{-1.95}$$

Briggs

$$\Delta h = [(19(\rho_o/\rho_a)(M_o/u^2)x - 4.2\ (B_c/u^3)x^2]^{1/3}$$

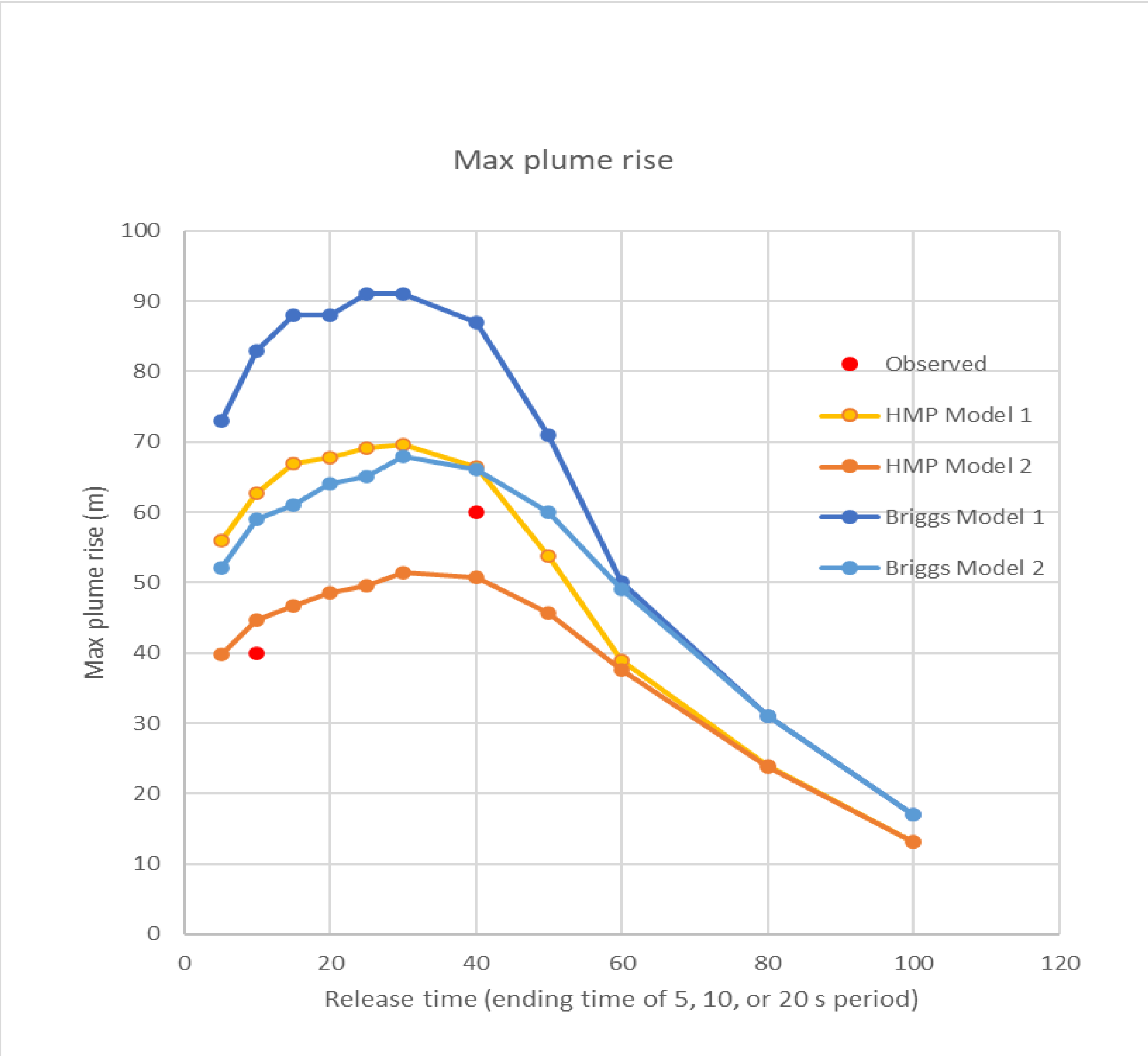
where $M_o = w_o^2 R_o^2$ is proportional to the initial momentum flux and $B_c = g[(\rho_o - \rho_a)/\rho_a] w_o R_o^2$ is proportional to the initial buoyancy flux (here assumed positive for a dense cloud).

The mass emission rate and other characteristics of the initial jet were determined by Spicer et al (2018, 2020). Two alternate expansion models were used to determine the flow characteristics at the point where the jet pressure decreases to ambient:

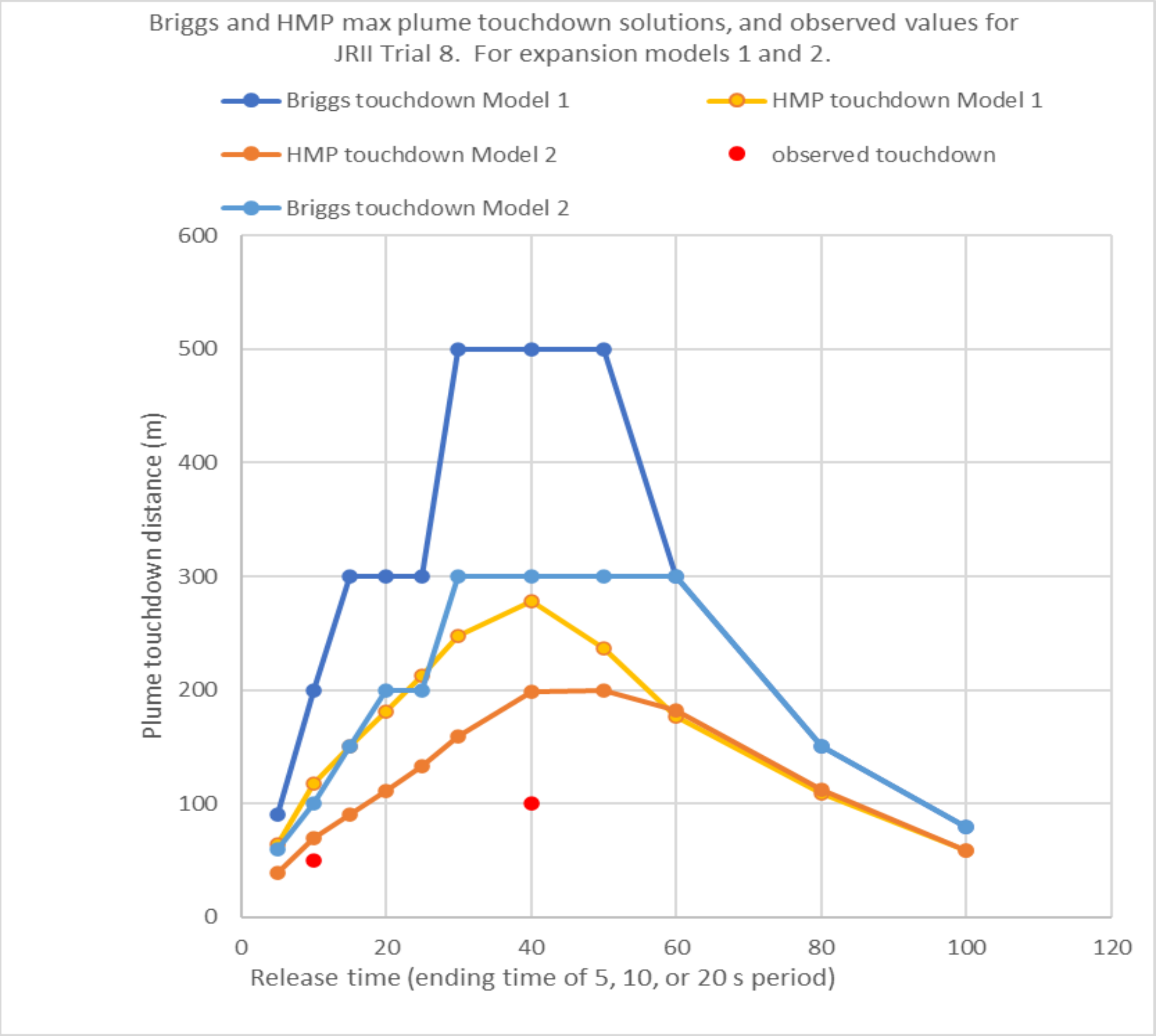
Expansion Model 1. Velocity increases above the exit value due to acceleration by excess pressure at the exit. This is also referred to as a momentum conservation model.

Expansion Model 2. Velocity unchanged from exit velocity.

Max plume rise observed and predicted by models



Observed and predicted touchdown distance



Observed and predicted max C

	Observed at 85 m	HMP Model 1	HMP Model 2
Max C (ppm)	12080	9570	17660

Conclusions

- The HMP dense gas plume rise model (with either momentum or velocity conservation expansion models) is able to match the observations of maximum plume rise, touchdown distance, and maximum ground level concentration at JR II Trial 8 within a factor of about two.
- The Briggs plume rise model tends to predict larger maximum plume rise than the HMP model by about 30 to 40 %.