Jack Rabbit II Source Description for Atmospheric Dispersion Modeling

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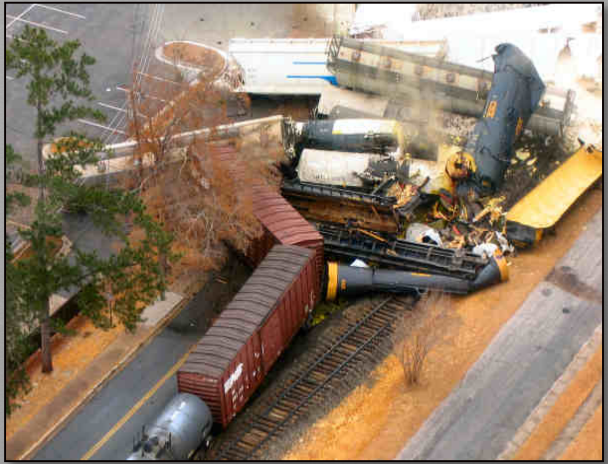
Overview

- Brief background of Jack Rabbit II test program
- Measurement of mass release rate
- Rainout estimation
- Simplified airborne source description for atmospheric dispersion model
- Conclusions

Jack Rabbit II - Overview

Problem: DHS, partners, and stakeholders must better understand behavior and consequences of large-scale chlorine releases.

- Millions of tons of chlorine, a potent toxic inhalation hazard (TIH), are shipped annually through highly-populated areas
- Transported in bulk as a pressurized, liquefied gas
- Hazard prediction models have been shown to be inconsistent with the evidence, data, and observations from previous fatal chlorine disasters
- Rapid chlorine releases have never been tested at operationally-relevant scales
- Critical knowledge and data gaps exist for source terms and other relevant phenomena
- Improved understanding of large-scale chlorine releases to properly inform, train, and prepare emergency responders
- 2010 Jack Rabbit 1-2 ton chlorine trials identified phenomena and scaling factors that required additional testing.



Jack Rabbit II - Objectives

- **Objectives:**
  - Execute multiple 5 to 20-ton chlorine release trials.
  - Track and quantify downwind plume movement and concentration to at least 7 mi.
  - Measure key source term parameters for each trial, including mass rate, tank pressure and temperature dynamics, and phase distribution.

  - Examine effect of chlorine exposure on emergency response equipment and vehicles.
  - Measure near-source chlorine concentrations up to 100,000 ppm.
  - Determine effects of obstacles and structures on cloud movement and behavior (2015 test season).
  - Examine chlorine reactivity with soil, vegetation, and common urban materials.

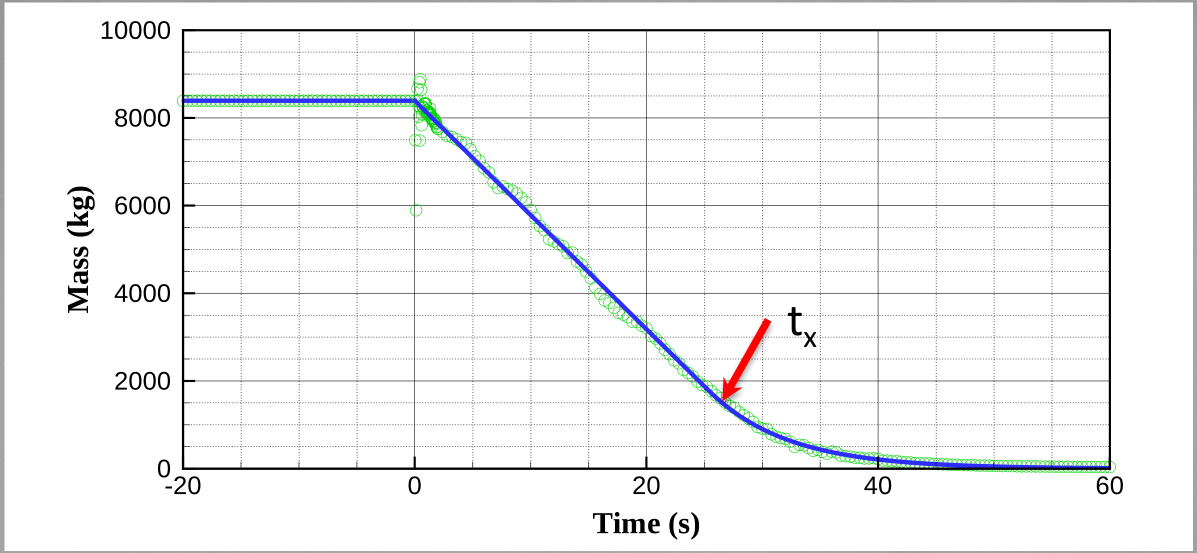
Disseminator

- **Load cells assemblies** -- flexures mounted on both sides of a load cell for chlorine mass and thrust.
- **Bare-Wire Thermocouples** -- Type K 24 AWG Teflon for internal vertical temperature profile. One set of vertical thermocouples was replaced with Type K 36 AWG thermocouples.
- **Absolute Pressure** -- four locations each aligned with the top of one of the 6 in port openings (90 degrees upward, horizontal, 45 degrees downward, and 90 degrees downward).
- **Differential Pressure** -- between top of the tank and elevations that correspond to the top of each of the 6 in port openings.
- **Guided-Wave Radar (GWR)** – to measure the liquid chlorine depth.

Release Orientations:

- Vertically down (Trials 1-6)
- 45° below horizontal (Trial 7)
- Vertically up (Trial 8)

Mass from Load Cells – Trial 6

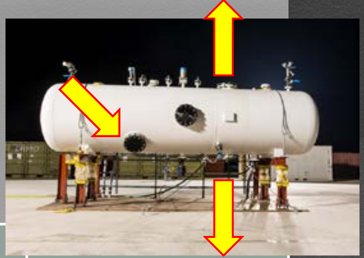


Initial constant release rate up to t_x

Transition to exponential decay (slope matches initial rate at M_x)

$$(M - M_h) = (M_x - M_h)\, exp\left(-\left(\frac{t - t_x}{\tau_x}\right)^p\right)$$

JR II Test Release Rates



Trial	Initial Mass (kg)	Initial Rate (kg/s)	Inventory after Initial Rate at Time (kg @ s)	Time Constant τ_x (s)	Heel (kg)	Data Rate (Hz)
1	4,545	224	1,524 @ 13.5	6.80	0	1
2	8,192	273	1,968 @ 22.8	7.20	0	10
3	4,568	275	1,988 @ 9.39	7.24	0	10
4	7,017	271	1,784 @ 19.3	6.59	0	10
5	8,346	not available			0	10
6	8,391	260	1,779 @ 25.4	6.83	0	25
7	9,072	259	3,149 @ 22.7	10.5	446	25
8	9,120	170	8,591 @ 3.12	23.9	6,698	25
9	17,700	not available				

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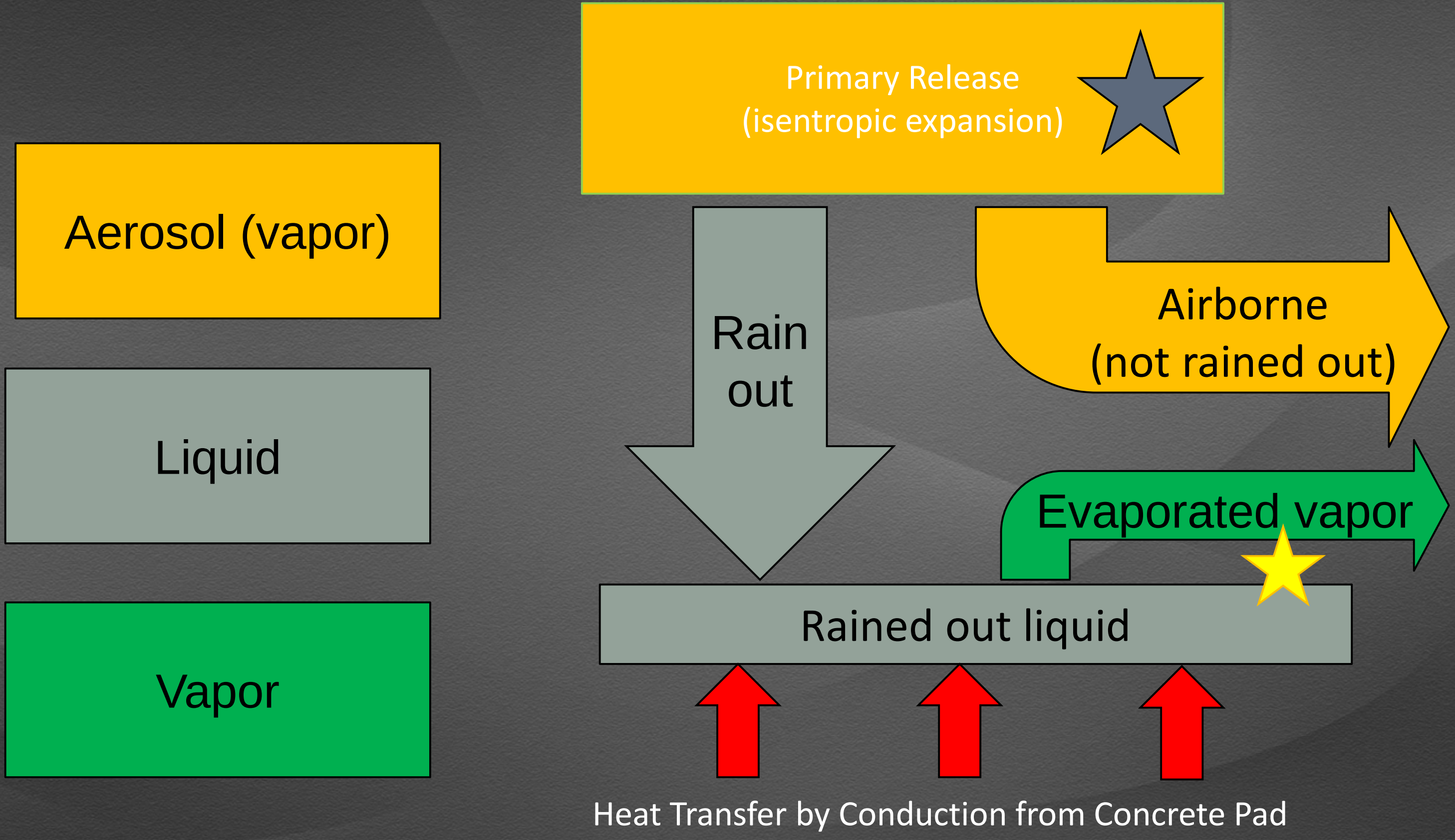
Mass remaining after primary release

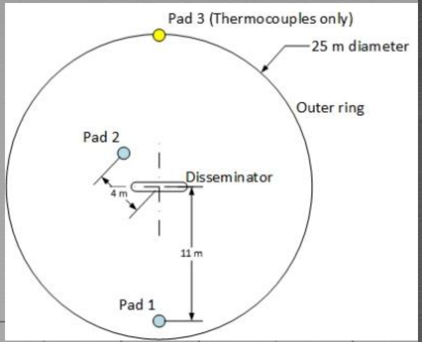
- Trial 7: 45° below horizontal release
  - Initial charge: 9,072 kg
  - Maximum liquid which could remain: 686 kg
  - Actual liquid that did remain in disseminator: 446 kg
  - Actual/maximum remaining: 66%
- Trial 8: Vertical upward release
  - Initial charge: 9,120 lbm
  - Maximum liquid which could remain: 9,120 lbm
  - Actual liquid that did remain in the disseminator: 6,698 kg
  - Actual/maximum remaining: 71%
- **29 to 34% of the maximum liquid which would be contained below a breach was flashed during the initial release. These two tests represent the extreme conditions of any practical release.**

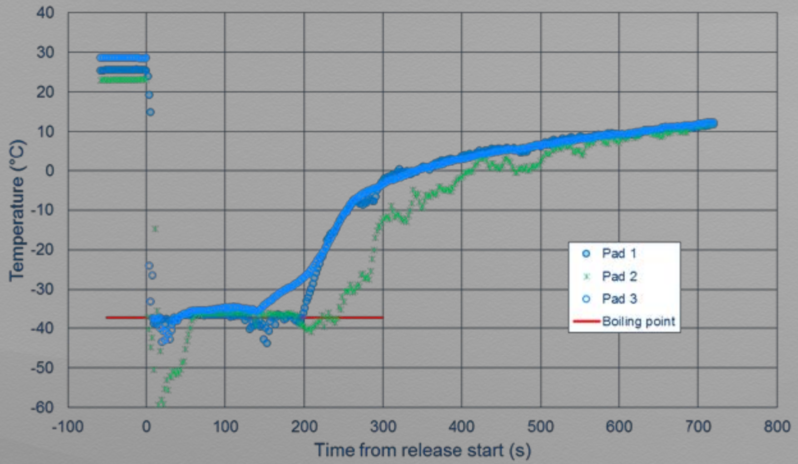
Airborne process

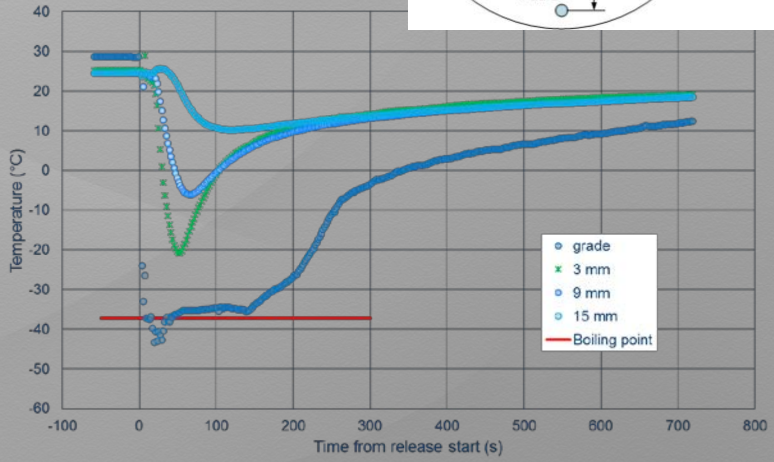


Concrete Pad Instrumentation

- Temperature profile within the concrete pad (0, 3, 6, 9, 15, and 22 mm) and above grade.
- Thin film or puddle of chlorine?
- Surface temperature at liquid boiling point until abrupt change (evaporation complete).
- Pad 3 temperature profile measurements are consistent with thermal diffusion in concrete pad.

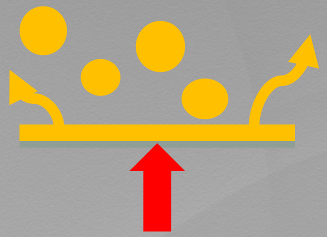




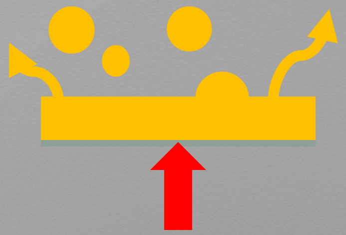


Surface Heat Transfer Process

- Rained out liquid forms a thin film as aerosol is deposited on the concrete surface; heat transfer from concrete (conduction) immediately starts the evaporation process evolving gas. Entire concrete pad covered immediately.



- Liquid film deepens as aerosol continues to be deposited during the release; heat transfer continues evaporation process.



- Liquid film becomes thinner due to evaporation after aerosol rainout no longer present. Areas covered by liquid shrink, but all area with liquid film covered by liquid from the spill beginning.

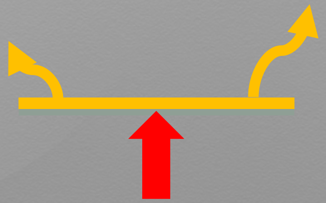
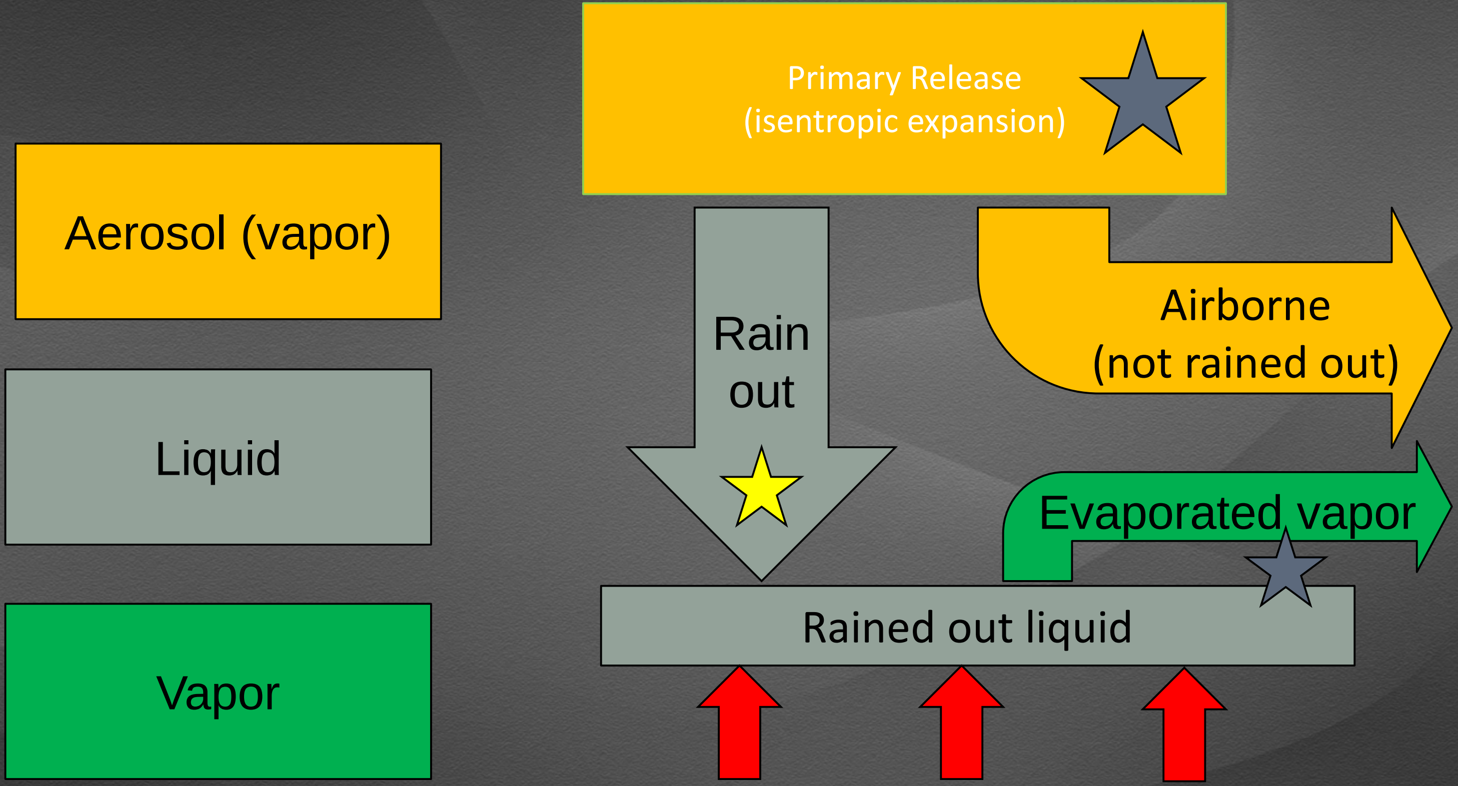


Image Processing from Trial 6

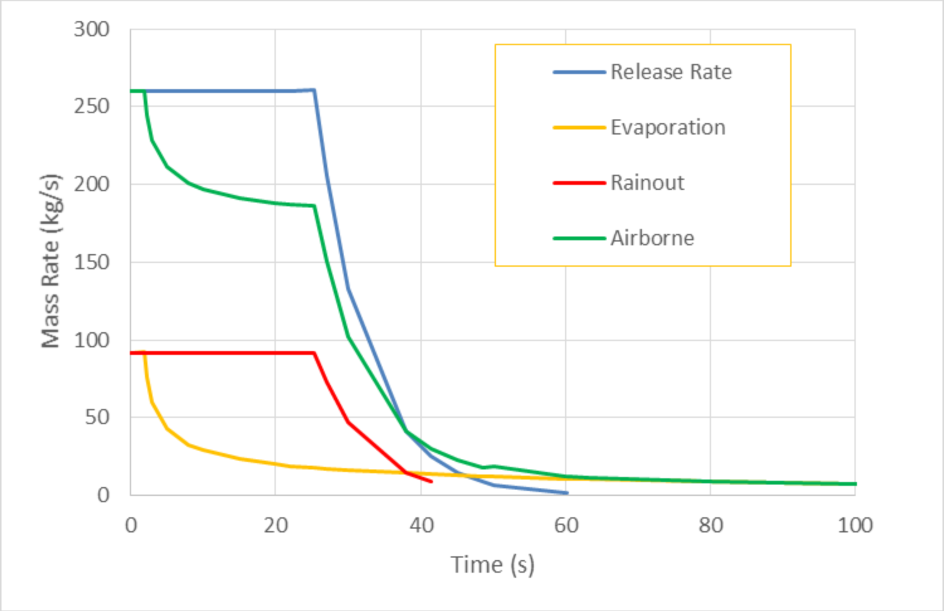
- Mask (black region) created to exclude parts of the image where concrete is not visible.
- Key locations identified on the pad where liquid present at all times during the release.
- For each frame analyzed, the gray scale at the key locations were used to determine what was covered by liquid and what was not.

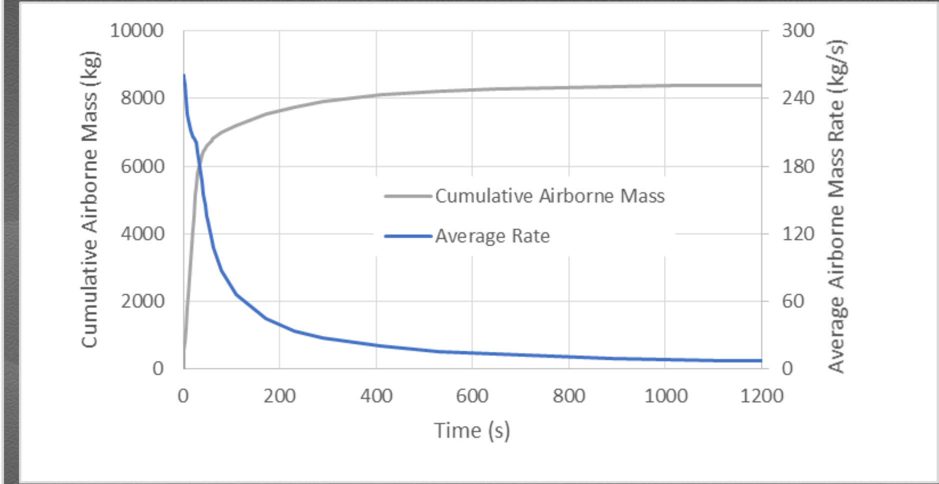
Airborne process



Heat Transfer by Conduction from Concrete Pad

Summary of Estimates for Trial 6





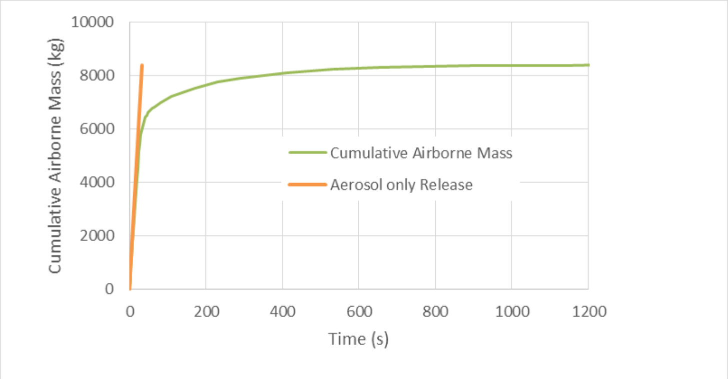
- Total airborne rate (from primary source and evaporation) is less than primary release rate.
- Evaporation from rained out liquid lasts for a long time (near source issue), but downwind concentrations are driven by airborne rate.
- Simplification needed for ATD model comparison

Simplifications for ATD comparison: Downward releases

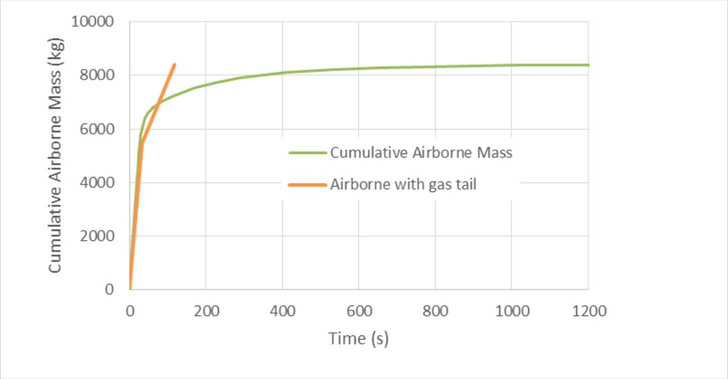
- Rates and release duration were specified so that the total inventory of chlorine was included.
- Two choices considered for mass release rates.
- Single mass rate at the primary release rate (as an aerosol)
- Two mass rates divided between mass rate airborne from primary release (as an aerosol) and evaporation rate (as a gas or vapor).
  - Mass rate airborne from primary release based on difference between primary release rate and initial (constant) deposition rate.
  - (Average) Evaporation rate based on total mass evaporated over duration t_x. This rate then applied to account for all mass rained out/evaporated.

Simplified Mass Release Schedule

- Single mass rate at the primary release rate (as an aerosol)



- Two mass rates divided between mass rate airborne from (a) primary release (as an aerosol) plus evaporation and (b) evaporation rate (as a gas or vapor).



Depressurized Velocity and Area Estimates

- Two methods were used to estimate the velocity and density after depressurization. (With the velocity, density, and mass rate determined, the depressurized area was fixed.)
- Frozen Flow
  - The actual mass rate and area of the opening were used to calculate a mass flux at the exit.
  - The (vapor) flash fraction was chosen so that the calculated two-phase density in the Meta-stable Liquid Model (with pressure difference between storage conditions and ambient pressure and a discharge coefficient of 0.61) matched the mass flux at the exit. The temperature corresponding to the flash fraction was found by isenthalpic expansion ignoring kinetic energy effects.
  - This approach gave flash fractions at the exit of around 2% and velocities around 40 to 50 m/s.
- Isentropic expansion of vessel contents (using process simulator Aspen 8.8)
  - Isentropic expansion of chlorine to critical flow conditions determines the exit temperature, pressure, flash fraction, and two-phase density.
  - This density was used in the Meta-stable Liquid Model (with a discharge coefficient of 0.61) to obtain the exit velocity using the actual mass rate.
  - This approach gave comparable results to the Frozen Flow approach.

Conclusions

- Data from the Jack Rabbit II test program has been made available (email Jack.Rabbit@st.dhs.gov).
- Load cell data were used to determine dynamic mass measurements from which the mass release rate as a function of time was obtained.
- Based on vertically upward and 45° downward releases, 29 to 34% of the maximum liquid which would be contained below a breach was flashed during the initial release. These two tests represent the extreme conditions of any practical release.

Conclusions (2)

- Pad surface temperature data and simulations are consistent with a thin liquid film which creates a constant temperature boundary condition on the pad where liquid chlorine is present. This allows an estimate of the mass rained out on concrete surface where liquid is present.
- In Trial 6, video images were analyzed to estimate the area coverage of the thin liquid pool. The total rainout in Trial 6 was estimated to be 35% of the mass that was released. An approach was developed to extend a similar analysis to the other trials.
- Simplified release scenarios were developed for downward directed releases to facilitate comparison of atmospheric dispersion models in conjunction with available concentration data.

Conclusions (3)

- Episodic Modeling Session
- "Jack Rabbit II Inter-model Comparison Exercise," Joe Chang, RAND
- "Experimental Program to Model Chlorine Reactivity with Environmental Materials in Atmospheric Dispersion Models," Tom Spicer, University of Arkansas

References

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