Final Report

The Jack Rabbit II Project's Impacts on Emergency Responders

Catastrophic Releases of Liquefied Compressed Chlorine 2015 – 2016

At U.S. Army Dugway Proving Ground, Utah

Utah Valley University
Emergency Services Department
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Executive Summary

In both 2015 and 2016, Subject Matter Experts (SME) in hazardous materials emergency response designed and conducted experiments in the Utah desert during the Department of Homeland Security's (DHS) research on catastrophic releases of chlorine named the "Jack Rabbit Project". Emergency Response SME's (UVU Team) worked collaboratively with project scientists to assure meaningful outcomes. The overall objective for the SME's was to answer questions for the emergency planning and response community regarding planning for, tactical and operational considerations of, and public protection actions during a catastrophic chlorine release.

In August of 2017 key contributors to the Jack Rabbit project, environmental systems researchers, plume modelers, Hazmat SME's, and atmospheric scientists were invited to Utah Valley University (UVU) to formulate conclusions based on the JR data.

After extensive analysis of the data and a scientific consensus, the UVU Emergency Responder SME Team supports the following conclusions from the Jack Rabbit Project:

- The 2016 Emergency Response Guidebook's (ERG) Initial Isolation and Public Protective Action distances are consistent with the Jack Rabbit data in both the upwind and downwind environment.
- Sheltering in place is the most survivable option as a primary means of public protection during such an emergency if evacuation is not possible. It is better to be inside a structure or vehicle than outside until the outside chlorine concentration drops and the danger has passed. Gas concentrations will be affected by multiple factors, primarily wind and terrain.
- Vehicles continued to be operational even when exposed to ultra-high concentrations of chlorine. Escaping a chlorine plume lateral to the wind in a vehicle is the best course of action if the public or emergency responders find themselves in that position.
- Photo Ionization Detectors (PID) with 11.7eV bulbs detected chlorine with reasonable accuracy and repeatability over broad chlorine concentration ranges.
- The primary strength of predictive plume models is in their use as planning guidance and/or forecasting tools rather than as emergency response tools due to the real-time uncertainty of some essential source data. First responders need to understand the application, limitations, and capabilities of the plume model they use, including the widely used ALOHA® model.
- Common urban surfaces and materials were not greatly affected, even by direct liquid exposure to chlorine. Heavy hydrocarbons dissolved and metal surfaces were immediately corroded. Electronics continued to operate after exposure, however, long term operability was erratic. No residual chlorine contamination was noted.

Finally, the UVU Team found that the application and use of a risked based response process is critical to the incident considering the container, stress/breach release, wind, exposures and environmental conditions.

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Introduction

In early 2010 the Transportation Security Administration (TSA) along with other Federal agencies endeavored to assess the vulnerability of rail tank cars containing and transporting Toxic Inhalation Hazard (TIH) liquefied gasses. The primary purpose of the initial Jack Rabbit I (JRI) Project in 2010 was to design experiments that would better identify source data and plume behavior of the most commonly transported TIH materials –Anhydrous Ammonia and Chlorine. Worst-case catastrophic release scenarios (90 tons) were considered to pose the greatest risks to communities and emergency responders. The initial release volumes from JRI in 2010 were represented by 1 and 2 tons.

In 2013, Wayne Yoder, the Training Specialist for Hazmat Programs at the National Fire Academy, invited hazmat Subject Matter Experts (SME's) from around the nation to attend an introductory meeting with scientists from the Chemical Safety Analysis Center (CSAC) at the Department of Homeland Security (DHS). Gaps in the JRI 2010 data were identified specific to what emergency responders and planners wanted to learn regarding TIH releases. The JRI 2010 releases were primarily focused on atmospheric data and detection on a limited scale (ATEC Inc., April 2013). Jack Rabbit II (JRII) was planned with releases in 2015 (Phase I) and 2016 (Phase II) to focus on these gaps. Release volumes during JRII in 2015 and 2016 ranged from 5 to 20 tons.

Utah Valley University (UVU) approached authorities at the U.S. Army Dugway Proving Ground (DPG) in Utah and confirmed that participation in the 2015 and 2016 releases would involve emergency responder objectives. With the support of Dr. Shannon Fox at CSAC, collaboration was developed with the "UVU Team" of SME's (see title page) and the test team at DPG. Emergency response experiments were designed around three main questions: (1) what do we know? (2) what do we think we know that must be validated? (3) what don't we know that we need to determine?

The 2015 and 2016 JRII trials were conducted on the ground at Dugway with the UVU Team fully integrated into the DPG test team under the primary direction of CSAC. The results of the 2015 and 2016 trials were detailed in two reports published by the McKinley Group: *Jack Rabbit II Phase I Trials: Training Needs Assessment and Analysis* (McKinley Group, Aug. 2016) and *Jack Rabbit II Phase II 2016: Findings and Observations* (Byrnes & Matthew, Nov. 2016).

Based on the identification of the emergency response gaps in the 2015 and 2016 reports, direct observations of the releases, the inclusion of subsequent science-based data analysis from the experiments and the summary conclusions of experts, a meeting was held at UVU in August, 2017. The objective of the UVU meeting was to achieve consensus and formulate final findings and observations, based on the science, which could be disseminated to the emergency planning and response communities. Further, the meeting produced conclusions regarding the impact on future planning and response incidents involving large scale releases of TIH materials. This final report enumerates those conclusions.

Discussion and Results

Recommended Mitigation Strategies for Public Protection

The JAZ® instruments used Ultraviolet (UV) technology and were deployed where the anticipated concentrations would be over 100,000 ppm (10%). See Figure 1. The instruments were located at ground level with the inlet being at 0.3 meters (12 inches) on average above ground level. The linear range for accurate readings of chlorine concentrations extended 15% above the highest calibration standard used. Therefore, measurements up to 115,000 ppm are considered to be accurate. The Immediately Dangerous to Life and Health (IDLH) level for chlorine is 10 ppm.

Each release in JRII 2016 demonstrated its own behavior. Due to the varied angles of the different releases the maximum concentration graphs varied in duration and concentration of the high readings; however, in every case, the downwind concentrations were thousands of times over the IDLH. A typical demonstration of this can be observed during the 135° downward Release 7 in 2016. See Figure 2.

Helpful when reading the graphic on Figure 2 is an explanation of the JAZ® identification numbers. The first number denotes distance from the release point. The second number is the designator of the JAZ® instrument and the third number is the distance off ground level in meters. So the graph for JAZ® 120-02-0.3 means that JAZ® number 2 was located on the 120m arc and the inlet was 0.3 m off the ground. The x-axis denotes the time from release while the y-axis denotes the concentration expressed in parts per million (ppm).

Figure 1. *Typical JAZ® deployment configuration.*

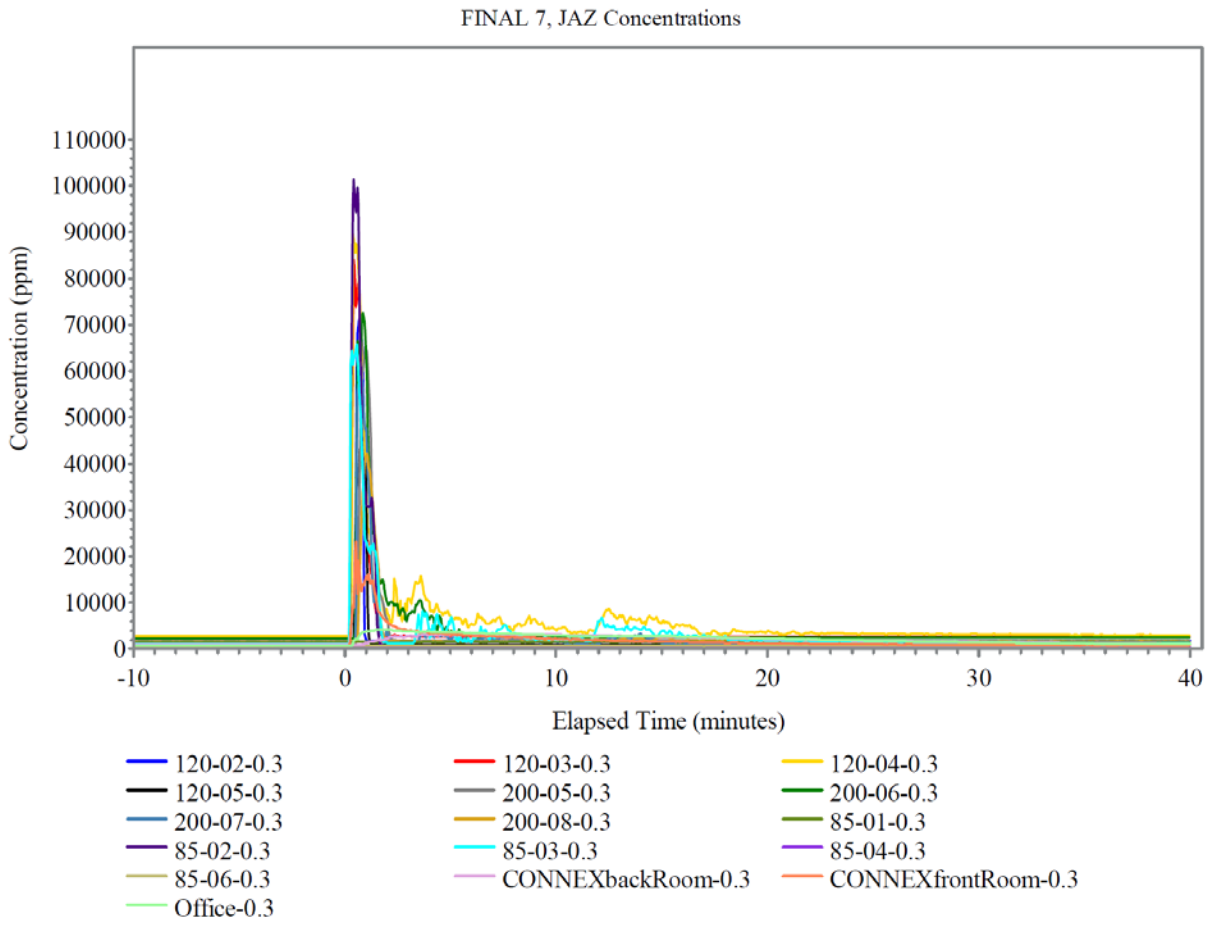

Figure 2. *Outside Concentrations at JR 2016, Release 7.*

Simply put, outside concentrations were "High" as confirmed by Lawrence Berkeley Labs (LBL) data from the exterior/interior ratios found in both the 2015 and 2016 JRII trials. According to Dr. Woody Delp of LBL, the 2016 peak data for all releases were key to this affirmation.

During the 2016 trails there were 188 'hits' on the arc deployed RAE's. A hit was defined as a detector reading levels above the background level but not saturating out. These profiles provided the basis for the simplified model predicting what the indoor profiles would have been using the outdoor profiles and a variety of ventilation rates. Figure 3 shows the ratio of the indoor to outdoor peak for any given ventilation rate. This assumes a worst case of no internal reactive losses. The heavy median line represents the median value (half above and half below) for a particular ventilation rate. The shaded area is the Interquartile Range (IQR) and is the 25th and 75th percentiles. The IQR is simply dividing a data set into quarters. Half of all the values fall between the two percentiles. The other numbers represent the listed percentile value. Being in a house like structure would have cut down the peaks by more than 95%, and would have to get up to the very high ventilation rates in a car with the AC set to fresh-air before the peaks were no longer cut in half.

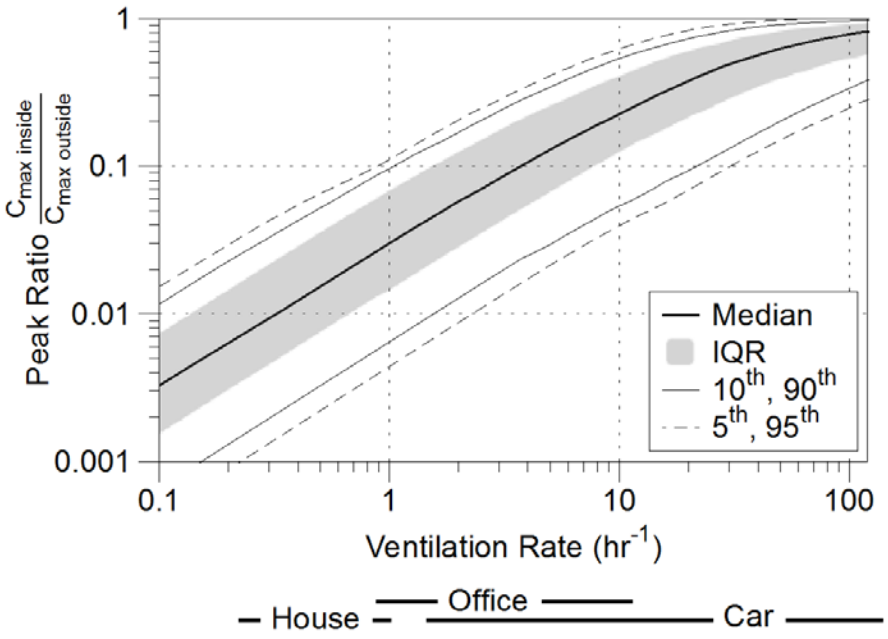

Figure 3. *Expected peak ratios as a function of ventilation rate using the data from JRII Releases 6-9.*

Figures 3 and 4 both depict common ventilation rates found in a house (0-1 ACH), an office space (1-10 ACH), and a vehicle (2->100 ACH) along the x-axis.

Another factor is the Toxic Load (TL) of the chemical. TL is a function of dose or concentration (c) over a period of time (t). TL = c t. Some chemicals are so toxic, including chlorine, that an additional multiplier, or exponent (c^n), is used which indicates extra toxicity. Chlorine has a TL exponent of n = 2.75. So you get TL = $c^{2.75}$ t. Cutting the concentration in half, you reduce the danger by 85%. Conversely, if you double the concentration, the danger is roughly 6.7 times greater.

Figure 4 uses the same data as Figure 3 but caries out the toxic load calculations, comparing the ratio of the toxic load outside to inside using a TL exponent of 2.75. Due to the high exponent the TL ratio is considerably lower than the peak ratios.

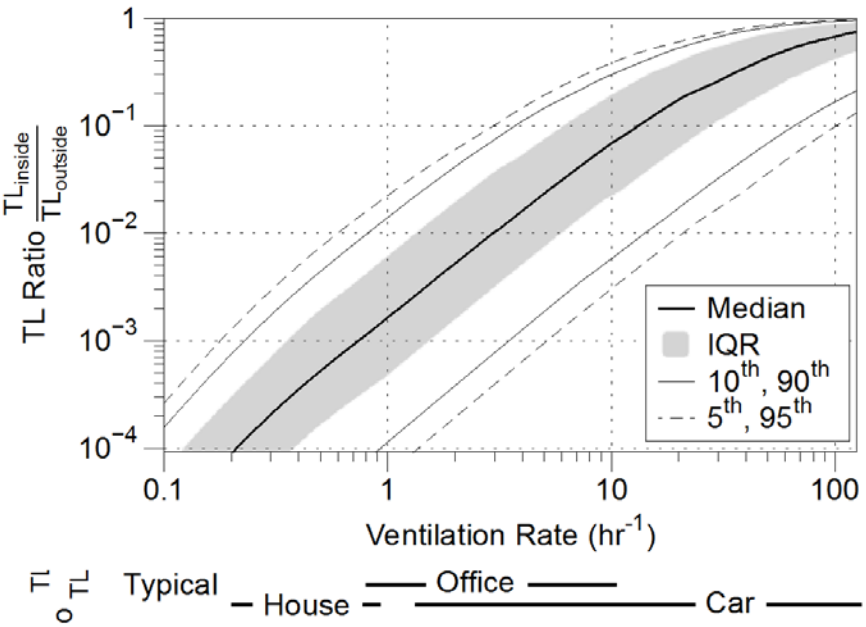

Figure 4. *Expected toxic load ratios as a function of ventilation rate using the data from JRII Releases 6-9 and a toxic load exponent of 2.75.*

The duration of the exterior plume is dependent on many factors: the product released, its chemical and physical properties, the size (volume) of the release, ambient temperature, relative humidity, wind direction and speed, terrain, natural or urban barriers, and environmental sorption factors such as dense vs. sparse foliage.

Interior and exterior sorption loss rates are unknown so the magnitude of influence is difficult to determine accurately. Interior sorption rates of various finishes, fabrics, and furnishings vary from structure to structure. In vehicles the surface area of seat upholstery, headliner and carpet all influence the sorption rate of the chlorine. Another major factor in both vehicles and structures is the air exchange rate or ventilation rate expressed in Air Changes per Hour (ACH). Any ACH over 1.0 is considered impactful. As a reference, most vehicles and structures have normal ACH rates of <1.0 ACH. Dr. Delp stated, “Inside can look like outside pretty quickly with high ventilation rates while lower ventilation rates can result in peaks being considerably lower than outside” (Personal Communication, August 7, 2017).

Dr Sohn from LBL stated, “A key take home point in this sort of analysis is the plume passed over an individual point relatively quickly” (Personal Communication, Aug. 7, 2017). For the JRII Trials, this happened on the order of 5-10 minutes with a few profiles persisting to 20-30 minutes. He went on to say, “The time constant of most buildings (1 over the ventilation rate) is much longer which is why we get such a benefit from being inside something. With longer duration plumes the results will differ.”

The interior concentrations were greatly influenced by the peak level of the plume which passed outside the structure. If the peak was high, there was a corresponding high concentration inside which must be exhausted from the structure over time. Dr. Sohn explained that during the

JR experiments the chlorine mixed evenly with the air inside the structures. This was typical of his experience with gas/vapor movement in other studies. He said, “Vapor density was less of a factor inside due to natural air mixing.”

Dr. Sohn then addressed mitigation strategies, supported by the UVU Team, and recommended the following public actions during a release:

1) It is almost always better to stay inside than go outside.

2) Close exterior openings and stop ventilation systems when feasible.

3) Retreating to an interior room, without windows and away from exterior walls, provides a magnitude of protection. A closet is ideal because all of the fabric hanging has a higher sorption rate than a bathroom with tile and glass surfaces.

4) Stay inside until the outdoor concentration is lower than the inside concentration.

There will come a time during the release when the concentration outside the structure or vehicle will be less than the concentration inside. Inside a structure or vehicle the lower concentration will have a longer duration. Outside, the higher concentration will have a shorter duration. This relationship between duration and concentration is depicted in Figure 5.

When will the time come that it’s safe to exit? It depends. “Wind is King” when considering when and if to move. High wind speeds outside, the absence of urban or natural barriers around the structure, and the amount of environmental sorption surfaces will affect the duration of the high concentration around the structure. Also see the discussion on the impact these variables have on plume duration. See Figure 6.

The group of scientists, subject matter experts, and emergency response professionals that evaluated the Jack Rabbit data for this report all concur that the mitigation strategy pronounced in the past which included ‘duct tape seals and plastic’ would not be advised. An imminent plume passing over a structure while time is being spent retrieving the materials and applying the correct procedures resulting in limited effectiveness of the ‘seal’. The group felt that the mitigation strategies recommended by Dr. Sohn and endorsed by the UVU Team are more realistic and possibly more effective than previous strategies in the compressed time frame of an emergency incident.

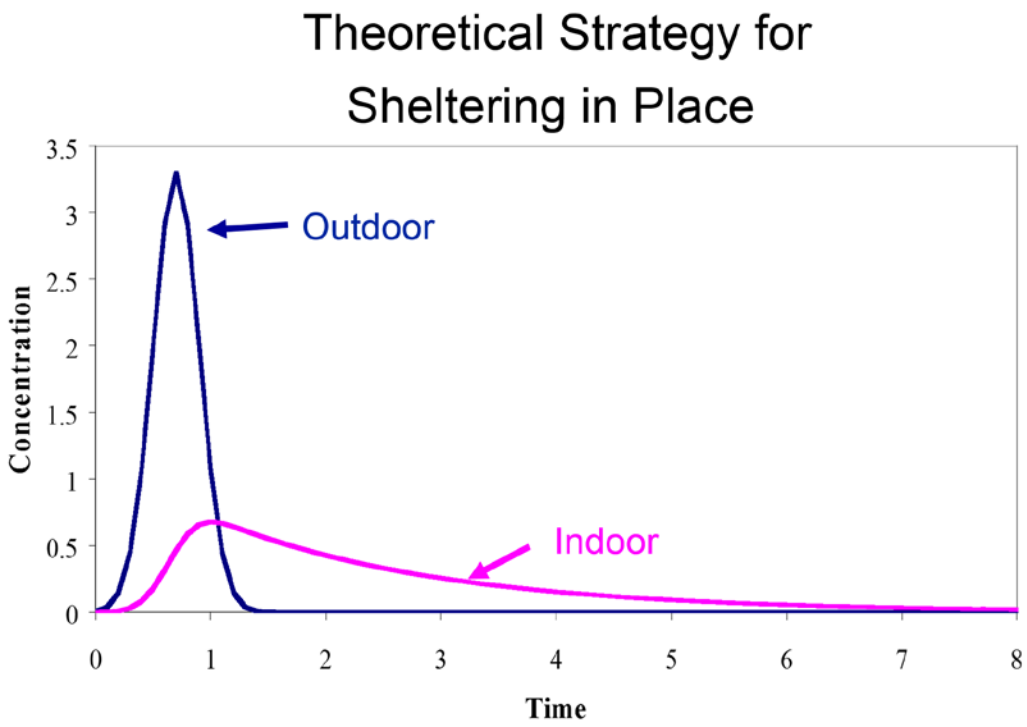

Figure 5. *The relationship between outdoor and indoor concentration over time. (LBL).*

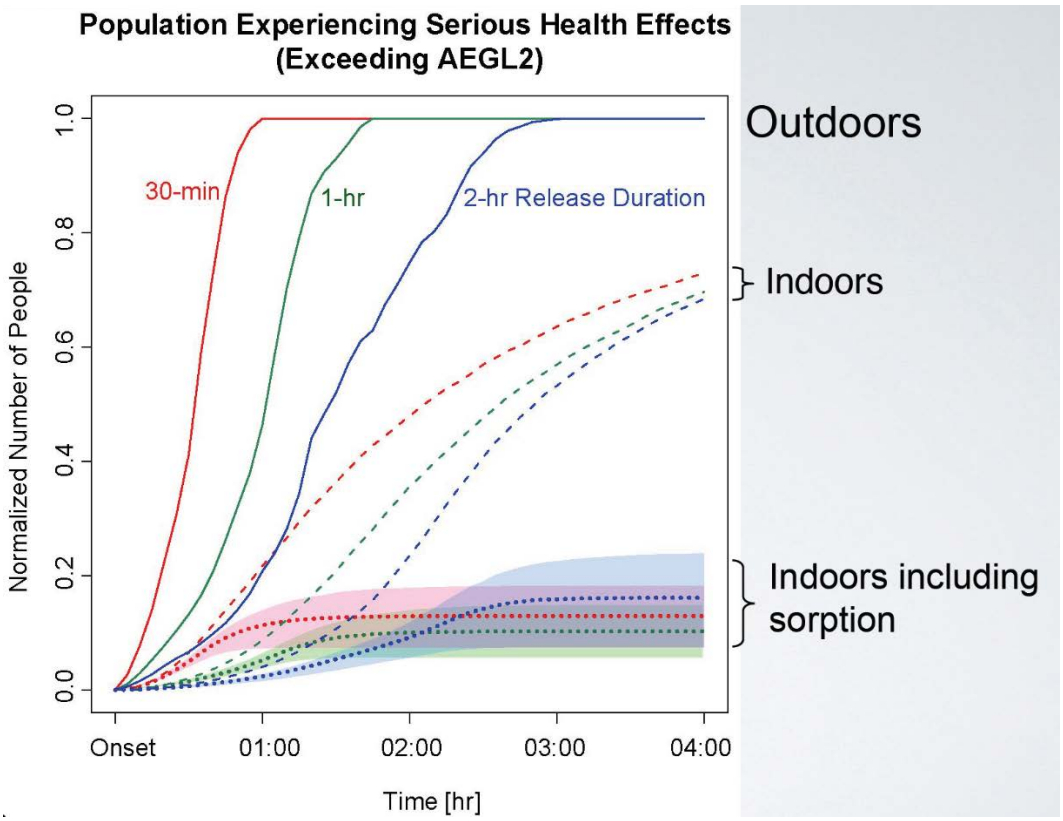

Figure 6. *Illustrative example of the differences in adverse effects for people inside vs. outside. Based on plume durations and AEGL2 levels, indoor concentrations are always less than outdoor concentrations and significantly less with more sorption.* ***Note:*** *this plot is representative and should not be used for emergency response.*

The infiltration data has led the UVU Team and scientists from Lawrence Berkeley Labs to conclude that recommended mitigation strategies coupled with an informed public would indeed be effective for public protection, specifically the shelter-in-place strategy.

Accuracy of the Current ERG Protective Zone Distances

Downwind guidance found in the Emergency Response Guidebook (ERG) was found to be reliable and accurate to 11 km. See Table 1. Variations in concentrations from detector to detector at 11 km is attributed to the naturally occurring turbulent boundaries of the plume and a characteristic non-uniform concentration of outdoor plumes due to air mixing and distance from the source.

Trial	Location	Type	Serial Number	Elevation (m)	Height (m)	Elapsed Time to Max Concentration (minutes)	Max Concentration (ppm)
6	11K-23	ToxiRAE	1956	1292.7	0.3	43.8	**1.1**
6	11K-24	ToxiRAE	1378	1292.7	0.3	46.2	**39.0**
6	11K-25	ToxiRAE	1358	1292.5	0.3	46.5	**49.9**
6	11K-26	ToxiRAE	1372	1292.3	0.3	49.4	**49.9**
6	11K-27	ToxiRAE	1384	1292.4	0.3	56.3	**49.9**
7	11K-25	MiniRAE	3326	1292.5	0.3	28.2	**1.0**
7	11K-25	ToxiRAE	1978	1292.5	0.3	28.1	**4.9**
7	11K-27	MiniRAE	4724	1292.4	0.3	35.0	**25.6**
7	11K-27	ToxiRAE	1448	1292.4	0.3	34.2	**49.9**
7	11K-28	ToxiRAE	1368	1292.3	0.3	40.5	**9.9**
8	11K	Nothing over background on ToxiRAE or MiniRAE @ 11K					
9	11K-18	MiniRAE	6071	1293.3	0.3	4.8	**2.3**
9	11K-18	ToxiRAE	1354	1293.3	0.3	0.0	**0.1**
9	11K-19	MiniRAE	8335	1293.1	0.3	38.5	**13.3**
9	11K-19A	ToxiRAE	1974	1293.1	0.3	39.5	**5.6**
9	11K-19B	ToxiRAE	1950	1293.1	0.3	39.6	**5.2**
9	11K-20	MiniRAE	4736	1293.0	0.3	44.9	**105.5**
9	11K-20A	ToxiRAE	1361	1293.0	0.3	41.3	**49.9**
9	11K-20B	ToxiRAE	1443	1293.0	0.3	41.3	**49.9**
9	11K-21	MiniRAE	4770	1292.7	0.3	62.5	**9.9**
9	11K-21	ToxiRAE	1426	1292.7	0.3	62.4	**15.2**
9	11K-22	MiniRAE	3378	1293.0	0.3	57.6	**0.6**
9	11K-22	ToxiRAE	1356	1293.0	0.3	57.4	**1.3**

Table 1. *Maximum concentrations for JR 2016 releases at 11 km downwind.*

Upwind guidance is a more complicated debate. Upwind but downhill conditions complicate all of the calculations and predictions. The ERG indicates a 3,000 foot initial isolation distance (upwind distance) and a 7 mile (11 km) downwind protective action distance for a railcar release of chlorine at night in low wind (PHMSA, 2016). Recommended protective actions for these releases are usually sheltering in place. See Figure 7. Dr. David Brown with the Argonne National Laboratory (ANL) stated that he "would not expect a fatality at 3,000 feet (1,000m) upwind," however, "environmental and incident variables would indicate caution when deciding to move closer to the release." Responders should use caution due to the many variables that affect a strict "upwind and uphill" policy. Response teams should further adjust the upwind distance based on an ongoing hazard/site assessment.

Dr. Brown considers "light wind" or "low wind" to be ~ 2 mph. In very low wind the plume will not travel as far. As a result, concentration durations are longer and the plume width wider as one gets closer to the release point. Moderate winds of 5-7 mph move the plume through vulnerable populations with greater energy, making emergency response operations difficult. High wind speeds (over 7 mph) will quickly move the plume out where concentration is still a concern; however, plume duration and width are minimized closer to the release.

Dr. Brown stated that the problem in determining Protective Action Distances (PAD) is how to balance the risk of insufficient protection with the risk of over-response. The solution, he explained, lies in a risk-based approach where a level of protection is specified using a statistical analysis. The level of protection is determined by the percentage of time that a PAD will be sufficient given a known concentration. The analysis (Historical, Meteorological, Chemical, and Dispersion Model data) simulates 1 million accidents for each chemical, in this case chlorine. The results are sorted into small or large spills, day or night, and the PAD is set using the 90th percentile of the Acute Exposure Guideline Level 2 (AEGL-2). See Table 2 and Figure 8.

Chlorine 7782-50-5 (Final)

	10 min	30 min	60 min	4 hr	8 hr
ppm					
AEGL 1	0.50	0.50	0.50	0.50	0.50
AEGL 2	2.8	2.8	2.0	1.0	0.71
AEGL 3	50	28	20	10	7.1

Table 2. *EPA Acute Exposure Guideline Levels for Chlorine.*

TABLE 3 - INITIAL ISOLATION AND PROTECTIVE ACTION DISTANCES FOR LARGE SPILLS FOR DIFFERENT QUANTITIES OF SIX COMMON TIH (PIH in the US) GASES

	First ISOLATE in all Directions		Then **PROTECT** persons Downwind during											
			DAY						NIGHT					
			Low wind (< 6 mph = < 10 km/h)		Moderate wind (6-12 mph = 10 - 20 km/h)		High wind (> 12 mph = > 20 km/h)		Low wind (< 6 mph = < 10 km/h)		Moderate wind (6-12 mph = 10 - 20 km/h)		High wind (> 12 mph = > 20 km/h)	
	Meters	(Feet)	km	(Miles)	km	(Miles)	km	(Miles)	km	(Miles)	km	(Miles)	km	(Miles)
TRANSPORT CONTAINER	UN1017 Chlorine: Large Spills													
Rail tank car	1000	(3000)	9.9	(6.2)	6.4	(4.0)	5.1	(3.2)	11+	(7+)	9.0	(5.6)	6.7	(4.2)
Highway tank truck or trailer	600	(2000)	5.8	(3.6)	3.4	(2.1)	2.9	(1.8)	6.7	(4.3)	5.0	(3.1)	4.1	(2.5)
Multiple ton cylinders	300	(1000)	2.1	(1.3)	1.3	(0.8)	1.0	(0.6)	4.0	(2.5)	2.4	(1.5)	1.3	(0.8)
Multiple small cylinders or single ton cylinder	150	(500)	1.5	(0.9)	0.8	(0.5)	0.5	(0.3)	2.9	(1.8)	1.3	(0.8)	0.6	(0.4)

Figure 7. *2016 ERG (Pg. 355, Table 3) indicating 1,000m upwind and 11 km downwind at night in low wind for a rail tank car release of chlorine.* (PHMSA, 2016).

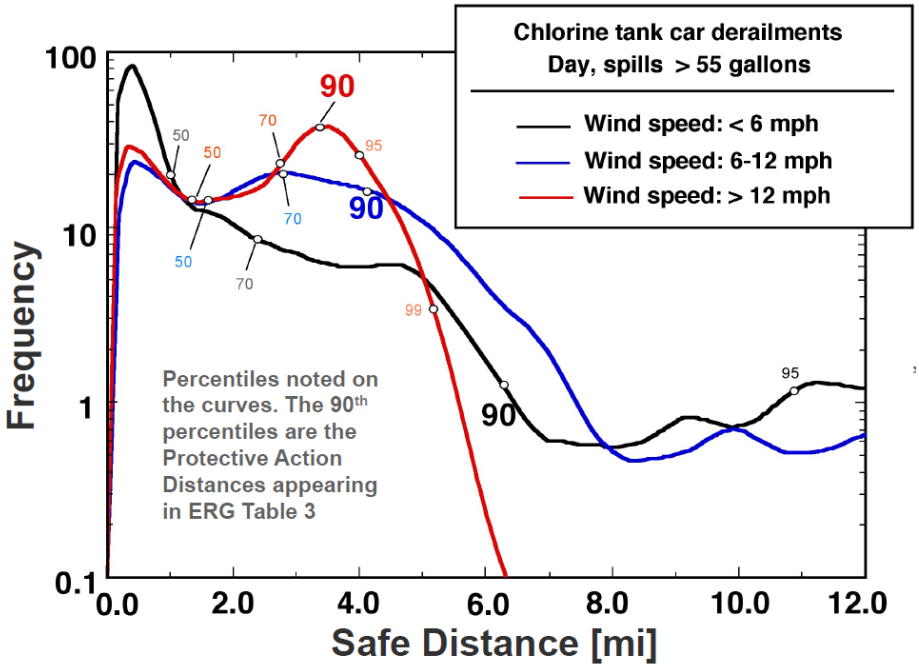

Figure 8. *Application of the 90th percentile analysis for daytime releases from railcars of chlorine in determining protective action distances in the ERG.*

Wind and terrain are key factors in making tactical decisions about upwind positioning. In the 2015 JRII Trials, barriers on the grid seemed to possibly influence greater upwind creep of the visible plume due to channeling – the "canyon" effect – from the energy of the jet release moving between the Conex boxes. See Figure 9. Much of the release energy in the 2015 JRII Trials was deflected laterally (east and west) due to the configuration of the Conex boxes on the grid. See Figure 10. Barriers such as solid fences, tree lines, buildings, and raised rail beds would certainly have a great influence on the upwind or lateral creep of the plume. Shifting winds and other environmental factors would also make the upwind environment less predictable.

Figure 9. *Release 4, 2015. Release energy and the effect of barriers.*

Figure 10. *Release 5, 2015. This is a diagonal view from the NW corner looking SE. Wind direction was almost directly centerline from the South at 182° and 2.7 m/sec. This view is showing the inclination for the plume to move lateral to the wind.*

During Release 5 in 2015, with barriers and with the lowest wind speed, a reading of 94 ppm (1.5 m above the ground on a ToxiRAE® II) was recorded at the firefighter mannequin located 100 m upwind. It was surrounded at the feet by a visible chlorine cloud. See Figure 11. It is important to note that this reading was significantly outside the higher range of the detector. Efforts to resolve this discrepancy with the manufacturer produced the hypothesis that it may have been a firmware issue, however, other possibilities exist. At 200 m upwind (.3 m above the

ground) on the same release, a MiniRAE® recorded 0 ppm. All other releases in JRII 2015 showed 0 ppm at 100 m upwind.

Figure 11. *Release 5, 2015. Retrograde creep of the visible plume against a 2.7 m/sec wind. The firefighter mannequin is 100m upwind as seen in the upper right corner.*

Figure 12. *Release 9, 2016. The small cone in the extreme bottom center of the screenshot is 50m upwind during this 20 ton release with a wind speed of 3.55 m/sec.*

2016 Release 9 Upwind Detection Maximum Concentrations								
Trial	Group	Location	Type	Serial Number	Elevation (m)	Height (m)	Elapsed Time to Max Concentration (minutes)	Max Concentration (ppm)
9	Field	100m MANNEQUIN	ToxiRAE	1358	1297.3	0.3	0.0	**0.2**
9	Field	100m MANNEQUIN	ToxiRAE	1395	1297.3	1.5	0.0	**0.0**
9	Field	50m CONE	MiniRAE	4717	1295.2	0.3	0.9	**2.8**
9	Field	50m CONE	ToxiRAE	1961	1295.2	0.3	0.0	**0.1**

Table 3. *Release 9, 2016. Maximum upwind concentration at 50 m and 100 m upwind.*

At first glance this data would lead you to believe that the ERG is too conservative in the upwind environment. In defense of the ERG, Dr. Brown makes the point that due to so many unpredictable variables including terrain, direction of the jet release and potential channeling effects, “conservative isolation and protective action distances are intentional to protect vulnerable populations” (Personal Communication, August 7, 2017). The UVU Team supports the approach and the upwind distances that are found in the current ERG regarding rail tank car releases of chlorine.

Figure 13. *Release 9, 2016. A UVU ToxiRAE® and a DPG MiniRAE® detector at the 50m cone upwind.*

Figure 14. *Release 9, 2016. A UVU and DPG ToxiRAE® detectors at the 100m mannequin upwind.*

During the JRII 2016 Trials, without barriers on the grid, no appreciable upwind creep was observed. See Figure 12. The farthest the visible cloud traveled upwind was ~35 m during the 20 ton Release 9. On all other releases the visible cloud did not move upwind farther than the concrete pad ~20 m. Table 3 shows the maximum concentration on the upwind side for Release 9. All other releases showed 0 ppm at 100 m upwind. See Figures 13 & 14.

The Effects of Chlorine on Vehicle Infiltration and Performance

In order to more accurately assess the interior environment that the detection devices would occupy, the exact infiltration/exfiltration rates (they are the same) under various conditions needed to be established. See Figure 15. Dr. Woody Delp confirmed that SF_6 (Sulfur Hexafluoride), an inert gas, is used to determine the amount of air going through the vehicle or structure (ACH). The ACH will largely dictate the ratio of the indoor/outdoor peaks. See Figure 16. The sorptive loss, when using chlorine gas, comes more into play when determining how long dangerous concentrations will persist inside a vehicle or structure.

There were no large changes in ventilation rates from trial to trial. The ACH stayed steady during repeated exposures to chlorine. It is worth noting that the test team could not test all ventilation conditions post-trial as the electrical systems in the vehicles were compromised and behaved erratically over the course of the trials.

The data provided by LBL shows that vehicles have the lowest possible ACH when the vehicle and the air ventilation systems are off. See Figure 17. The five vehicles used in JRII 2016 ranged from 1994-2008, a good representation of current road models. New cars have similar ACH as the cars in the JRII Trials according to Dr. Delp. In all cases, with a vehicle closed up tight and the air off, ACH averaged 1.6. With the vehicle running and the recirculation mode on, the ACH rate was at least three times greater.

Figure 15. *A typical vehicle co-location set up with ToxiRAE®, MiniRAE® PID (11.7) and UV Canary and capture camera.*

Figure 16. *Dr. Delp from LBL injects a vehicle with SF_6 to determine the exfiltration rate (ACH).*

ACH Values	Off	Fresh Air	Recirculation
 1	1.1 – 1.2	153 (doors open)	N/A
 2	2.1	81 - 91	81 - 91
 3	1.6	108 - 152	108 - 152
 4	2.1	180 - 250	9.3
 5	1.44	111 - 136	3.9

BERKELEY LAB

Figure 17. *Air Changes per Hour (ACH) for vehicles in differing modes. LBL.*

With some variations in air flow design, the general take-away is that if a person is trapped in an approaching plume, and there is no way to drive lateral to the wind, it is best to turn the vehicle off which ensures that ventilations systems are off, roll up all the windows tightly, and call for help. Attempting to drive through a plume in a moving vehicle, with the ventilation system on, especially in fresh air mode, or the windows down, the ACH are significantly greater and less survivable.

JRII in 2015 and again in 2016 proved that gasoline and diesel engines will likely run in ultra-high concentrations of chlorine (240,000ppm – 24% in Release 5, 2015). If emergency responders find themselves in a position of danger they should move laterally to the wind and the plume at the highest rate of speed that considers safety. The engine of the vehicle, whether gasoline or diesel, should continue to run. Note that the JRII trials did not test either engine type under load (high rpm) but they did remain running at idle which presents the probability that they will remain operational. Responders should roll up windows, stop ventilation/fan systems, and don SCBA if possible. Move fast, act fast, and retreat to an area of safety. Experience with real world accidental releases (Macdona, TX chlorine and Minot, ND ammonia) have shown that getting out of a vehicle or structure and attempting to exit the area on foot is not a safe alternative. Once through the plume, all windows should be rolled down completely and the vehicle ventilated with systems turned up to high speed. This takes the contaminated inside air from 1.6 ACH to over 125 ACH in seconds.

The JRII 2015 trials proved that in areas where emergency responders may find themselves 100–500 m (300–1,500 feet) downwind will not be able to “get above” a dense gas by climbing on top of the apparatus to safety. ToxiRAE® data at 100m and 500m downwind showed that the area on top of an apparatus (5m or 15 feet above ground level) was at least five times IDLH at 49.9 ppm in these cases. At 49.9 ppm the detector locked. In summary, it is not a safe tactic to climb on top of the apparatus. See Figure 18. Donning SCBA as soon as possible is the best tactic when engulfed in a high concentration. Wind shifts, poor visibility, inaccurate dispatch information, or inappropriate decision making may lead responders into such a situation. The best emergency tactic is to get out of the area as quickly and safely as possible or shelter-in-place inside the vehicle, don SCBA if possible, and transmit your location.

Figure 18. *Release 2, 2015. Firefighter mannequin on top of an engine simulating an escape from a plume. Visible plume in the background. 49.9 ppm at the nose level, 100 m downwind.*

Due to repeated exposures to ultra-high concentrations of chlorine, the vehicle's electrical systems, wiring, connectors, slides, and controls were adversely effected and became erratic over time. Metal surfaces under the dash were visibly corroded with rust and exhibited a color change after the first exposure. There is no evidence that exposures affect the rubber door seals or other plastic surfaces in the ventilation system. Other electronic devices such as a fire service radio and cell phone were exposed and, though still operational immediately after the exposure, suffered internal metal component corrosion instantaneously which will likely affect performance in the future. See Figures 19a and 19b.

Figure 19a. *Before exposure (left) and after one exposure (right). Notice the immediate corrosion.*

Figure 19b. *Before exposure (left) and after one exposure (right). Notice the immediate corrosion.*

The ALOHA® Plume Model vs. Data from the JRII Trials

One of the key objectives of the trials were to assess the efficacy, reliability and accuracy of the Areal Locations of Hazardous Atmospheres (ALOHA®) plume model with its variants vs. the ground truth of the JRII data. All nine releases were calculated by UVU Team member Hank DuPont and further analyzed by atmospheric modeling experts. Given the known inputs provided by the JRII Trials, ALOHA® was consistent in the way it depicted the output of the model. The inherent limitations of single point atmospheric data input to the model does not allow for adjustments of the plume calculations as it moves downwind over long distances. As seen in releases 1-5 in 2015, the construction of barriers in the path of the plume had a significant effect

on the upwind and downwind behavior of the plume. ALOHA® does not account for these steering effects and meanderings within its 10 km range. The user needs to be cognizant of the limitations of the model and how it depicts the output. Releases 6-9 in JRII 2016 were unabated over flat terrain for which the model would theoretically be more accurate. Data analysis from these releases leads to the conclusion that the ALOHA® model is qualitatively sound.

Hank DuPont explained that the ALOHA® model had the option for the JRII release point openings. There are three options in ALOHA®: circular hole, rectangular opening, or pipe or valve. The release tank for JRII used a 6" short pipe or valve setting for Releases 6-8 and for Release 9 the model used a 6" hole (Personal Communication, Hank DuPont, August 8, 2017).

The reality is that in an emergency responders will not have the luxury of collecting release point parameters in a timely manner, putting any model output in doubt when it comes to real-time predictability. This issue is not exclusive to ALOHA®. In support of this, Hanna et al. stated:

> …it is very important to point out that knowledge of the hole size is critical… If the models needed to be applied in an emergency situation, it is likely that the visible cloud would obstruct the hole and the hole size could not be accurately estimated by persons at the scene. Furthermore, it is expected that, for hole diameters greater than about 10 cm, most of the mass in the tank would be released within the first few minutes, before emergency personnel arrived on the scene. Also, because emergency responders are involved in assessing safety and keeping persons away from the site, it is unlikely that a model will be run by them during the initial period (2008, p. 15).

A major limitation when using ALOHA® is that only one wind direction can be used for input in the model. Shifting winds can be a huge variable in assessing the upwind and downwind hazard regarding public protection. Topography will also effect the model as ALOHA® only predicts on a flat surface. Source data determines the accuracy of the output. This will be the most difficult information for responders to collect and input into the model. Any unknowns that are entered as input such as flow rate or size of the opening will affect the outcome. Many variables that are unknown to the responder running the model may make the ALOHA® output questionable in an emergency setting. Source data is critical. Without knowledge or accuracy the model is only as good as the source data you have. The UVU Team advises caution with tactical decisions based on a model when the source data is questionable.

In comparing the actual JRII data to the ALOHA® model, there is insufficient data to definitively say that the model aligned overall. Wind shifts are not model problems. The flat sterile terrain and lack of vegetation at DPG produced data that is not transferrable to urban and other common environments. In addition, no extrapolation has been offered for the largest JRII release of 20 tons to a fully loaded railcar release of 90 tons of chlorine.

Qualitatively, the model was in alignment. Dr. Delp was impressed with ALOHA® predictions on Releases 6, 7, and 9 from a qualitative point of view. See the model comparisons between ALOHA®, RAILCAR, and the Hazard Prediction and Assessment Capability (HPAC)

models in Figure 20. "HPAC was developed by the US Defense Threat Reduction Agency (DTRA) to model chemical, biological, radiological, and nuclear agents" (DHS & NIST, 2011).

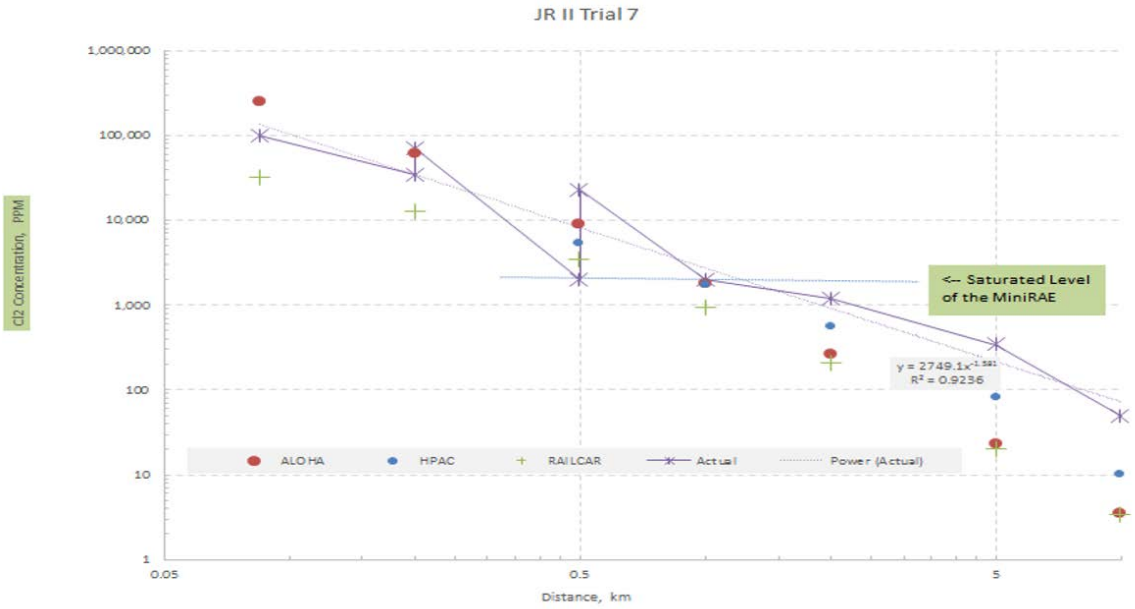

Figure 20. *Release 7, 2016. Plume model comparison with actual JRII release data.*

The strength of ALOHA® is using it as a planning/forecasting tool. Responders need to understand the limitations and capabilities of the model. The ERG is designed for the first 30 minutes and ALOHA® can provide additional information after those initial 30 minutes of response. ALOHA® can then provide a model for out to 60 minutes. There are currently two operator options when running ALOHA® for compressed liquefied gases; the Traditional release-dispersion and the RAILCAR release. The latter has a run setup prompt that can be rejected per the operator's judgment and thus obtain the Traditional output for a dense gas.

ALOHA® plots depict an averaged plume. This averaging over time creates the elliptical shape of the output plume. See Figure 21 for the RAILCAR variant of the release. The line graphs generated by ALOHA® also depict the initial large release (spike) and trailing effect of the mist pool (line graph trailing off to a lower concentration). See Figures 22 and 23 for the RAILCAR and Traditional releases, respectively. The spike and trailing vapor releases are reflected in the instantaneous "mushroom" cloud shape of a catastrophic release as seen from the UVU UAV during Releases 7 and 9 in JRII 2016 which was typical of all of the releases. See Figures 24a and 24b depicting a few minutes after the tank emission ended. Other models with more real time local weather (especially wind) inputs create a more accurate plume shape. These models are not commonly available to most emergency response agencies.

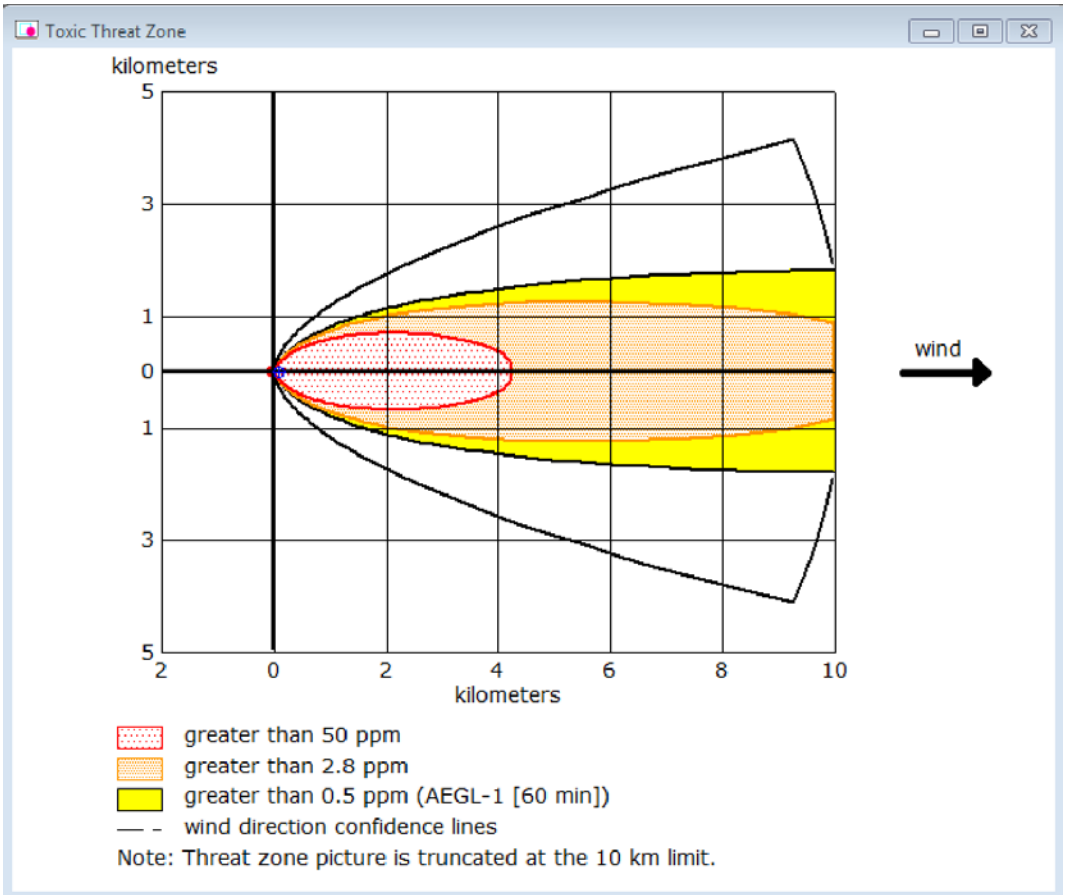

Figure 21. *ALOHA® RAILCAR model results at 1 hour for the 20 ton Release 9 in 2016. The contours are the peak concentrations predicted at some time in that 1 hour.*

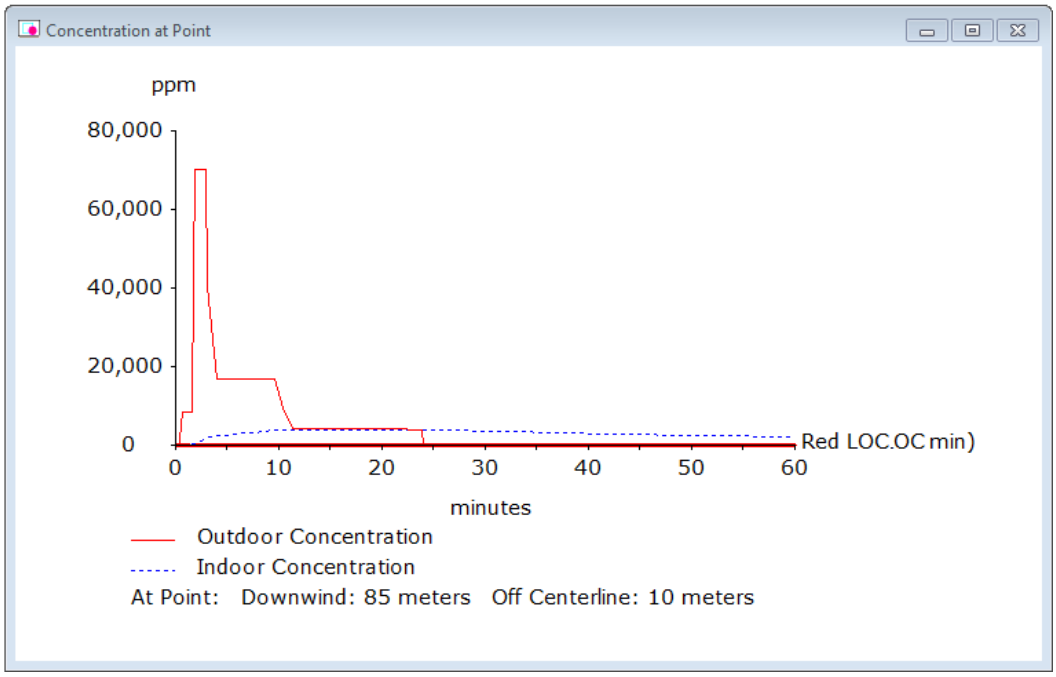

Figure 22. *Corresponding ALOHA® concentration graph for 20 ton Release 9 in 2016 using RAILCAR. Note that the peak occurred ~two minutes after the release started.*

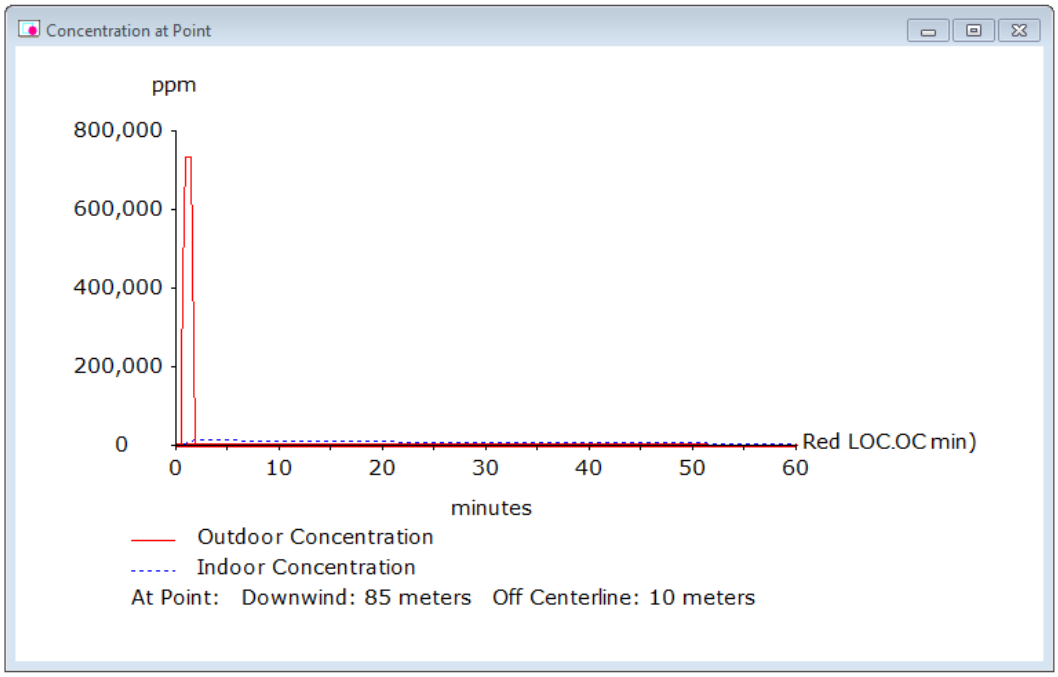

Figure 23. *Corresponding ALOHA® concentration graph for 20 ton Release 9 in 2016 using Traditional ALOHA® Tank. Note that traditional heavy gas is not taking into account the mist pooling effect and the large difference in the concentration predictions compared to RAILCAR.*

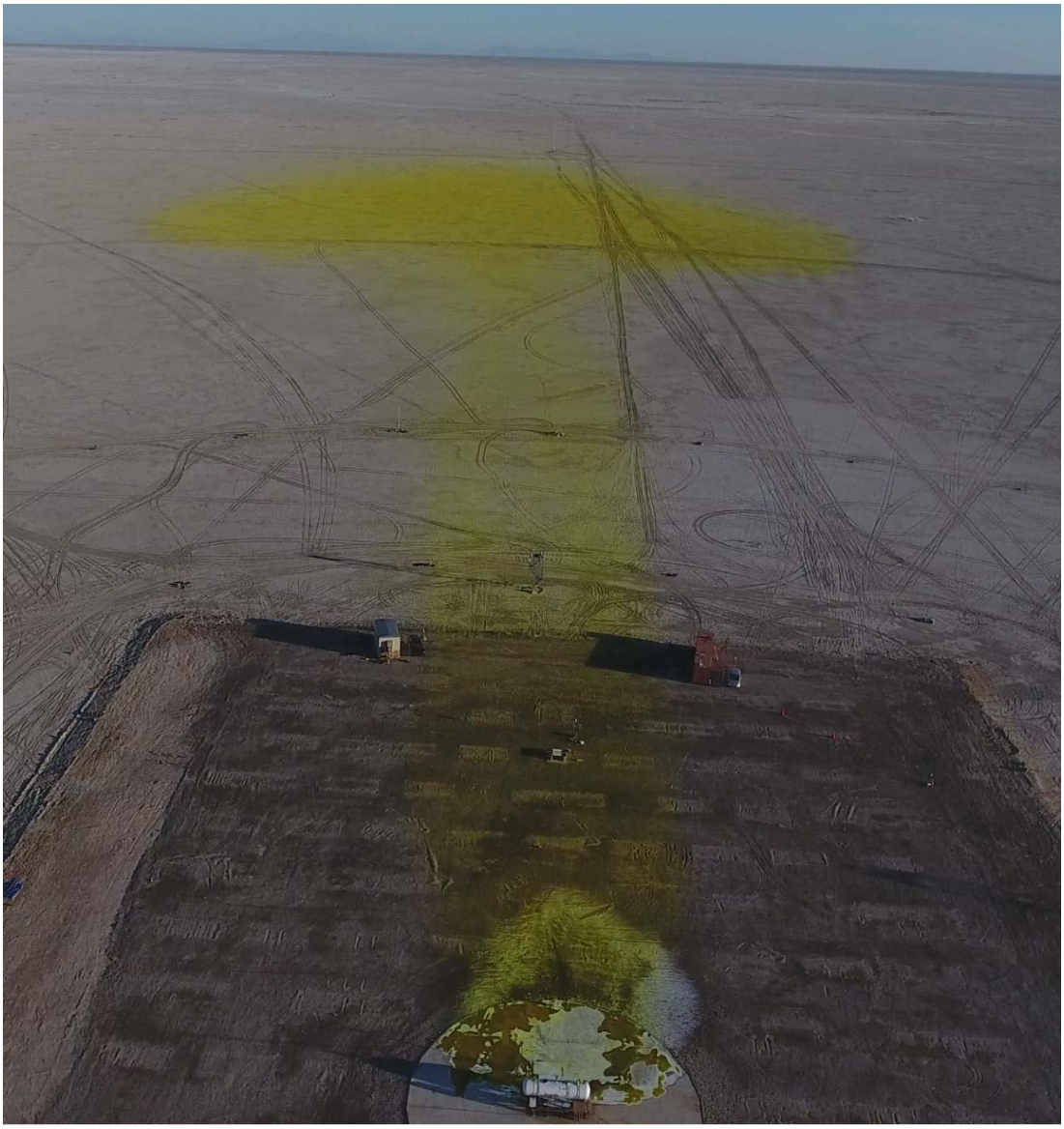

Figure 24a. *Release 7, 2016. Aerial view depicting the "mushroom" shaped cloud formed by a catastrophic release and subsequent vapor trail from the mist pool.*

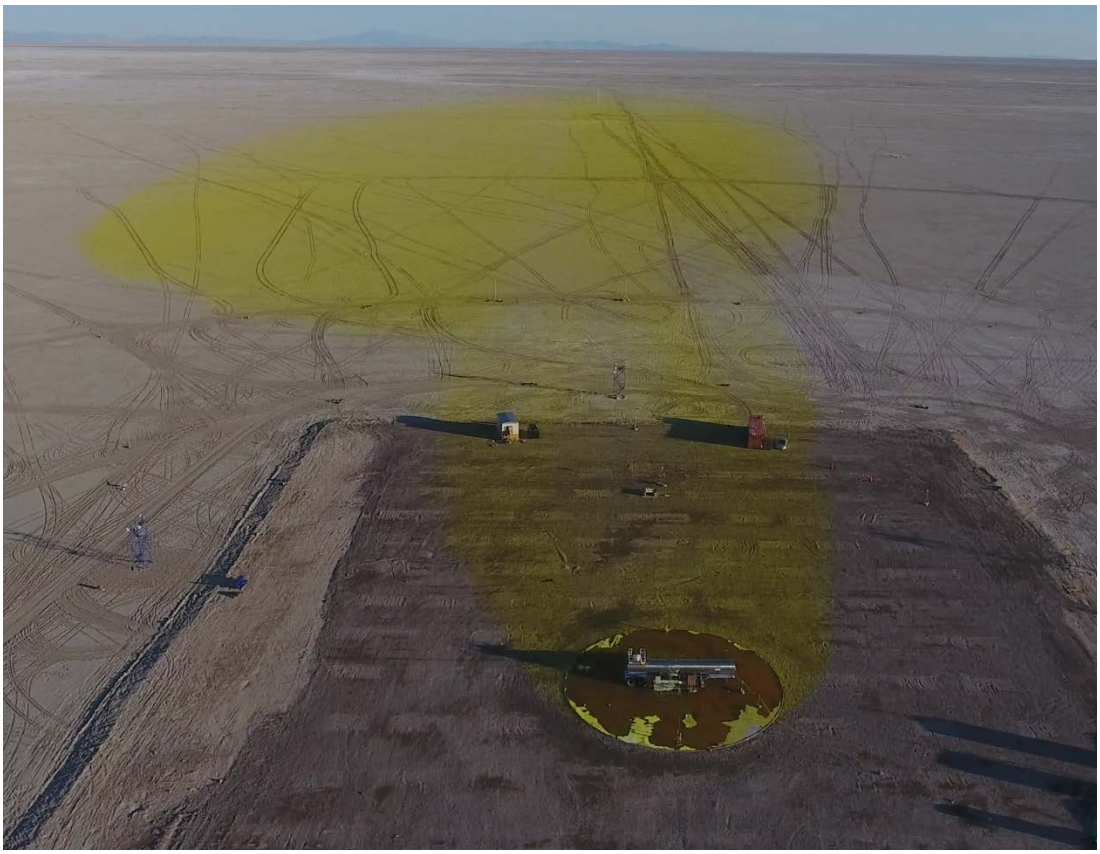

Figure 24b. *Release 9, 2016. Aerial view depicting the "mushroom" shaped cloud formed by a catastrophic release and subsequent vapor trail from the mist pool.*

The likely wind direction variations and meandering during the one hour ALOHA® prediction period widens the labeled contours where peak concentrations can occur. This again has to do with single input atmospheric data, and must be taken into account during the interpretation of the model's output. Also, the model was run for all of the releases in both RAILCAR and Traditional ALOHA® Tank modes. Distinct differences were noted from the source outputs. RAILCAR was seen to depict the releases in a truer fashion, as was seen by the UVU UAV video. The mist pooling effect that RAILCAR takes into account significantly increased release times. The visible trail behind the main body of the plume was evident and validated the mist pooling effect. The Traditional ALOHA® Tank algorithm depicted the releases in a very short time frame without taking into account trailing vapor concentrations that would actually be present for an extended time.

From the National Oceanic and Atmospheric Administration (NOAA) website regarding the RAILCAR model:

> This latest update to the program includes new data from several sources, including revised public exposure guidelines for toxic releases. ALOHA® 5.4.5 also includes a new alternative source strength model to estimate how chemicals escape from tanks over time. The new model is called RAILCAR, and it was developed by the Naval Surface Warfare

> Center, Dahlgren Division. The RAILCAR model was developed based on the results of the Jack Rabbit Test Program, which involved a series of field tests performed in 2010 in order to better estimate how [anhydrous] ammonia and chlorine escaped from transportation tanks. The RAILCAR model simulates the release of pressurized liquid from a transportation or storage tank as a result of damage to the tank. RAILCAR predicts that pressurized liquids will not only form dense vapor clouds, but will pool at the release location under certain incident and meteorological conditions. The portion of the RAILCAR model that estimates the source strength associated with releases that form stationary clouds or "mist pools" is now available in ALOHA® 5.4.5. (NOAA, 2015)

Standard ALOHA® has two separate dispersion models incorporated into the application. A Gaussian distribution case predicts how gases that are neutrally buoyant disperse downwind, assuming the highest concentrations occur along the vertical and horizontal axes of the plume. See Figure 25. Traditional ALOHA® also uses a heavy gas model based on the generally accepted Dense Gas Dispersion (DEGADIS) model. ALOHA® chooses which model to run based on property information for a particular chemical. ALOHA® chooses heavy gas for chlorine initially, but also incorporates Gaussian distribution into the model's output as the gas moves downwind. See Figure 26. Air is mixed into the cloud, diluting it and making it less dense-acting, more like a neutrally buoyant gas. When the cloud has been diluted sufficiently (below 1% or 10,000 ppm), the model then utilizes Gaussian distribution predictions. For small releases this can occur within a short distance of the release point and may occur much farther downwind for larger releases. Hanna et al., observed, "The Gaussian plume model is more applicable to continuous releases" (Hanna et al., 2008, p. 8).

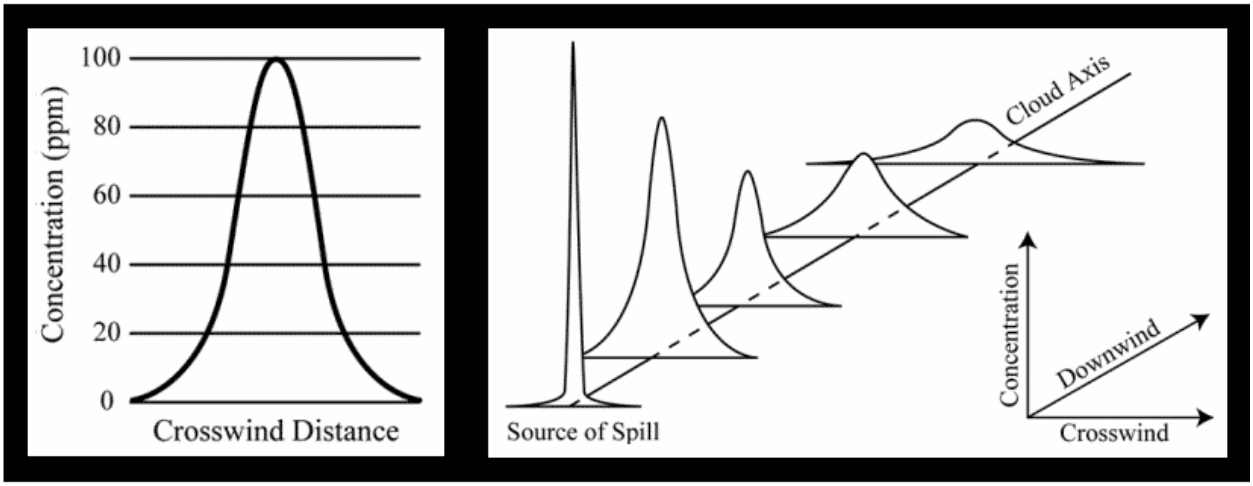

Figure 25. *Gaussian distribution. (EPA, 2007)*

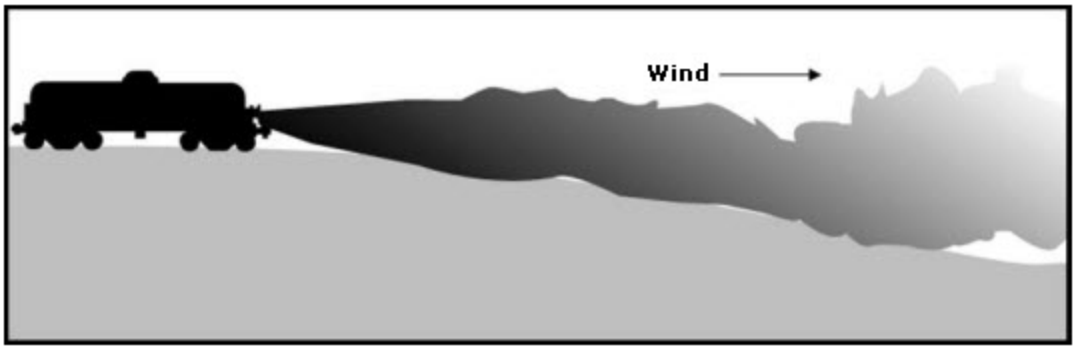

Figure 26. *Heavy gas distribution and transition into neutrally buoyant. (EPA, 2007)*

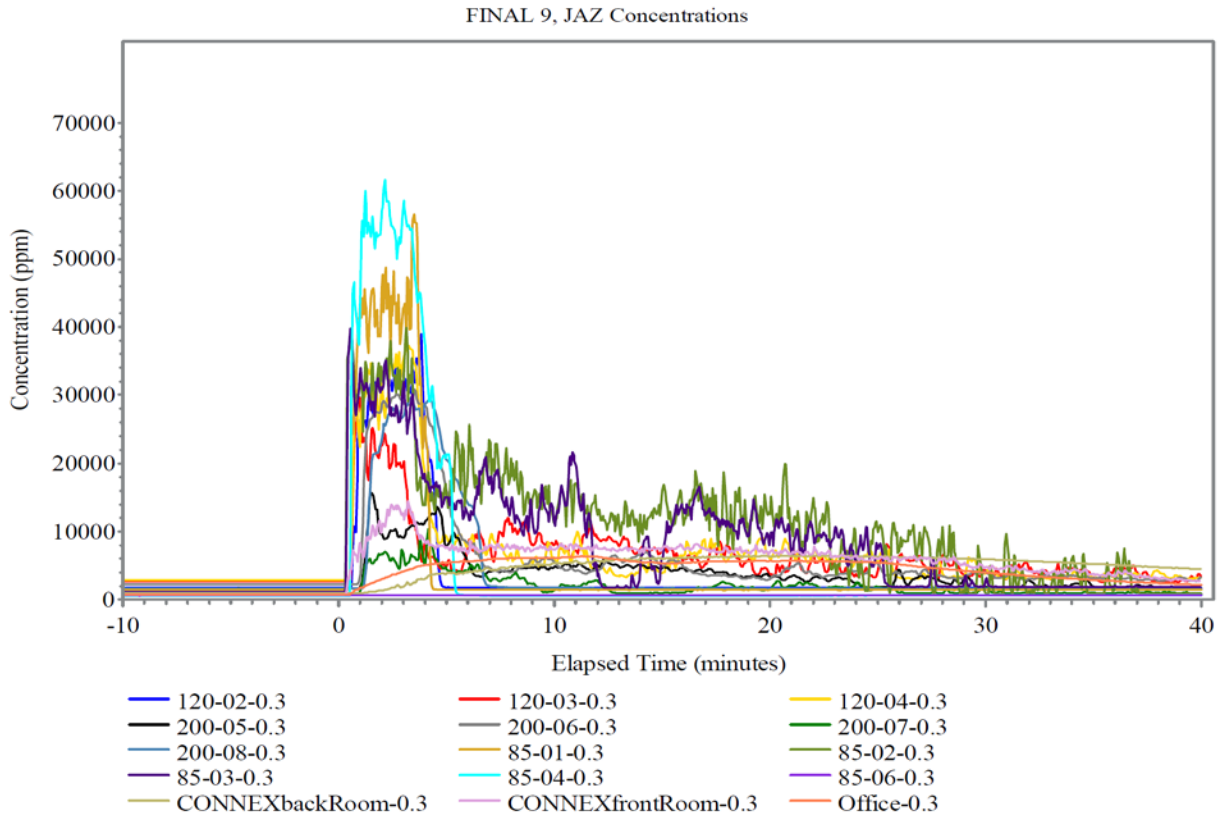

Figure 27. *Outside concentrations for the 20 ton Release 9 in 2016 as recorded by JAZ® instruments.*

Comparing Figures 22 and 27, the quantitative results from the ALOHA® RAILCAR prediction was in line with the outside ground level concentrations recorded by JAZ® instruments on the grid. The addition of the RAILCAR algorithm into ALOHA® has improved the way the model deals with the effects of "mist pooling". There is strong evidence of this occurring during the JRII Trials, and the visuals are stunning. The stark differences between

Traditional ALOHA® Tank vs. RAILCAR outputs tell the story and demonstrate that the RAILCAR model is a superior model in these cases.

Reliability of a PID (11.7eV) During the JRII Trials

During the JRII Trials in 2016, the UVU Team used the RAE Systems MiniRAE® 3000 Photoionization Detector (PID). The PID technology with an 11.7eV lamp was able to detect chlorine in real time with reasonable accuracy and repeatability in broad chlorine concentration ranges. It is important to note that the PIDs used for the infiltration studies were calibrated to 100 ppm isobutylene to align with the instruments that emergency responders are likely to have at an incident. This provided for a wider variance in the PID reading compared to the actual concentration. The graph in Figure 28 was produced by Dr. Russell Allred during testing at DPG in JRII 2016. After running for nine hours post calibration, the instrument was consequently exposed to 50, 290, 500, and 1000 ppm of chlorine (Allred, 2016).

Regarding exterior/interior concentration comparisons Dr. Delp from LBL observed that, "the UV Canary instruments came in a bit 'hotter' than the JAZ® by about 20%". He goes on to comment, "The data is clear that the PID unit with the 11.7eV bulb inside the vehicles did see the chlorine and it correlated very well with the UV Canary®" (Personal Communication, Dr. Delp, August 7, 2017). Delp was "uncomfortable" assigning a true conversion factor (CF) for the PID exposed to high concentrations of chlorine due to questionable UV Canary® data. RAE Systems® Consumer Electronics Division confirmed that a good CF to use with a PID and an 11.7eV lamp calibrated to IBE when exposed to high concentrations of chlorine would be ~10:1 (Personal Communication, Viktor Konovalov, RAE Systems® August 3, 2017).

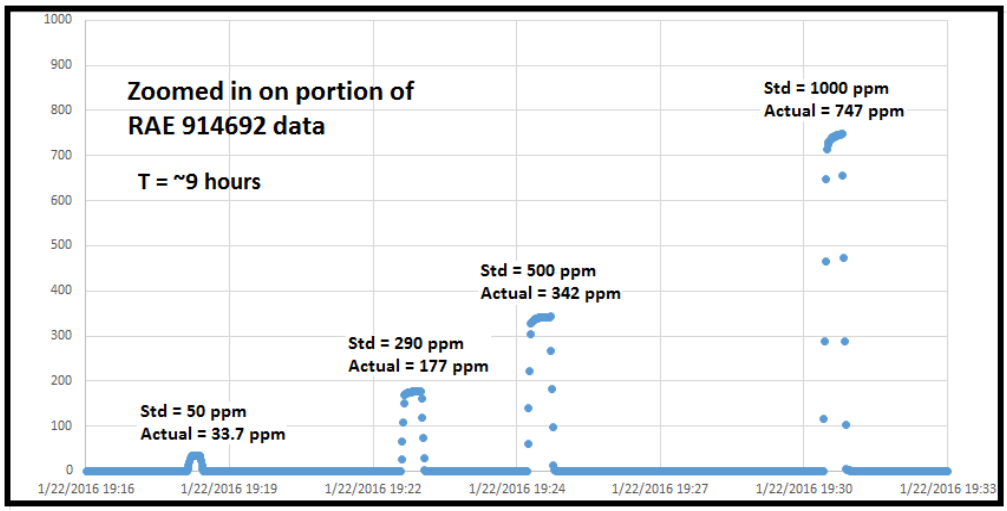

Figure 28. *After a nine hour burn-in time a PID was exposed to varying concentrations of chlorine at DPG* (Allred, 2016).

The term "burn-in time" is used to explain that a PID lamp must be run for a given time in order to secure greater accuracy and stability. This is especially true for the 11.7eV bulb required to detect chlorine, which has an Ionization Potential (IP) of 11.48eV. It cannot be detected using a more commonly carried 10.6eV PID bulb. There is some debate on the proper burn-in time. Sitting idle, the lamp does degrade due to its hygroscopic properties. The energy of the lamp depends on the gas used to fill the lamp and the crystal used as the transmission window. The 11.7eV lamp is made of Lithium Fluoride filled with Argon gas and the 10.6eV lamp is made of Magnesium Fluoride filled with Krypton gas. The 11.7eV lamp degrades at a much faster rate than the 10.6eV lamp. When a PID lamp matures, the response stabilizes and the decay over a work cycle (at least eight hours) is less than 20% of the initial reading after calibration.

Dr. Allred from DPG stated:

> RAE Systems recommended that the 11.7eV lamps be "burned in" for 10 hours prior to use. This "burn in" procedure basically involves installing the lamp into the instrument and allowing it to run (i.e., in sampling mode so lamp is on) for 10 hours. During testing, all lamps used had been burned in. However, it was of interest to determine how necessary the "burn in" was, and if the length of time could be shortened. (Note that loss of response during run-time can be attributed to loss of excitation energy of the lamp).
>
> To characterize this 'burn in' effect, twelve instruments were fitted with new 11.7eV lamps. Each of the instruments was then turned on and a 2-point calibration was performed. The two points were 0 ppm (zero air) and 500 ppm chlorine (balance N_2). Subsequently, each instrument was challenged (bumped) with 500 ppm chlorine intermittently for approximately six hours; After six hours, the instruments were re-calibrated and the experiment continued; The figure [X] above displays the typical behavior observed for each of the RAEs. Note that the temperature throughout the experiment was maintained at 20-21 ^{o}C (2016). See Figure 29.

The UVU Team accepts the 10 hour burn-in time in sample mode as recommended for PID 11.7eV lamps in order to stabilize the response. Dr. Allred stated, "Once lamps are well-used or well-'burned in', it would be anticipated that instrument response be more stable" (Allred, 2016).

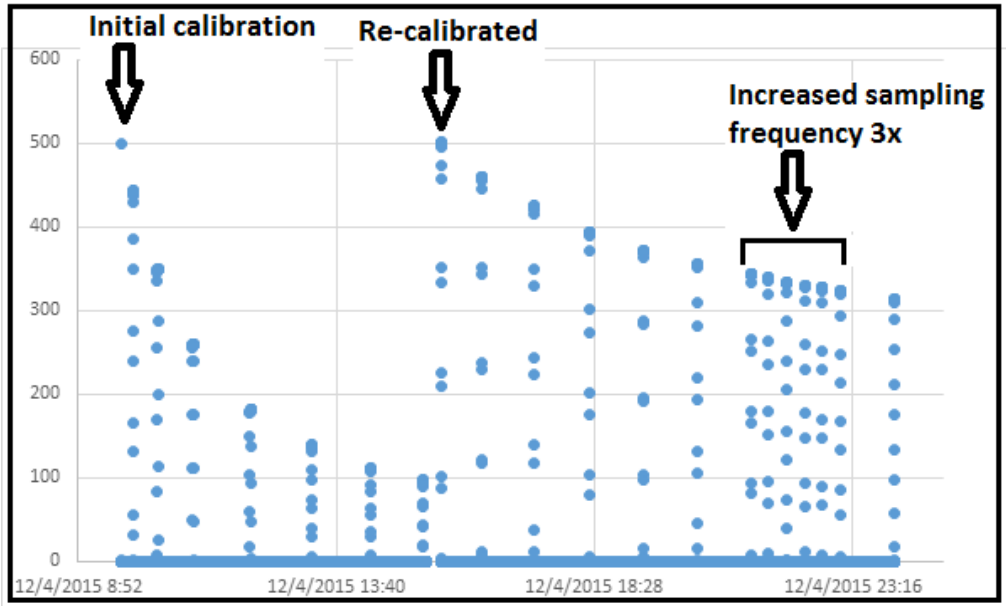

Figure 29. *Typical MiniRAE® 3000 PID behavior after burn-in time and recalibration* (Allred, 2016).

Comparisons made using data readings from different types of instrument technology is problematic and requires thorough experiment preparation. For example, electrochemical sensors may work only at low chlorine concentrations (up to 50 ppm) while a PID and UV Canary® are able to measure data in a much broader range. The data extracted from Releases 7 and 9, 2016, clearly depict this limitation. See Figure 30. In order to verify the relationship between the two technologies, a camera was used in the JRII 2016 trials to capture the PID and electrochemical responses simultaneously. The electrochemical sensors seemed to respond accurately at lower concentrations, however, they would lock out at 49.9 ppm while the PID continued to provide a reading at much higher concentrations. The instruments responded as predicted within their calibration limits. Figure 31 depicts the moment the PID catches the highest reading for Release 7 inside of a vehicle. During the same release, at the moment the electrochemical sensor locked out at 49.9 ppm, the PID was reading 29.6 ppm.

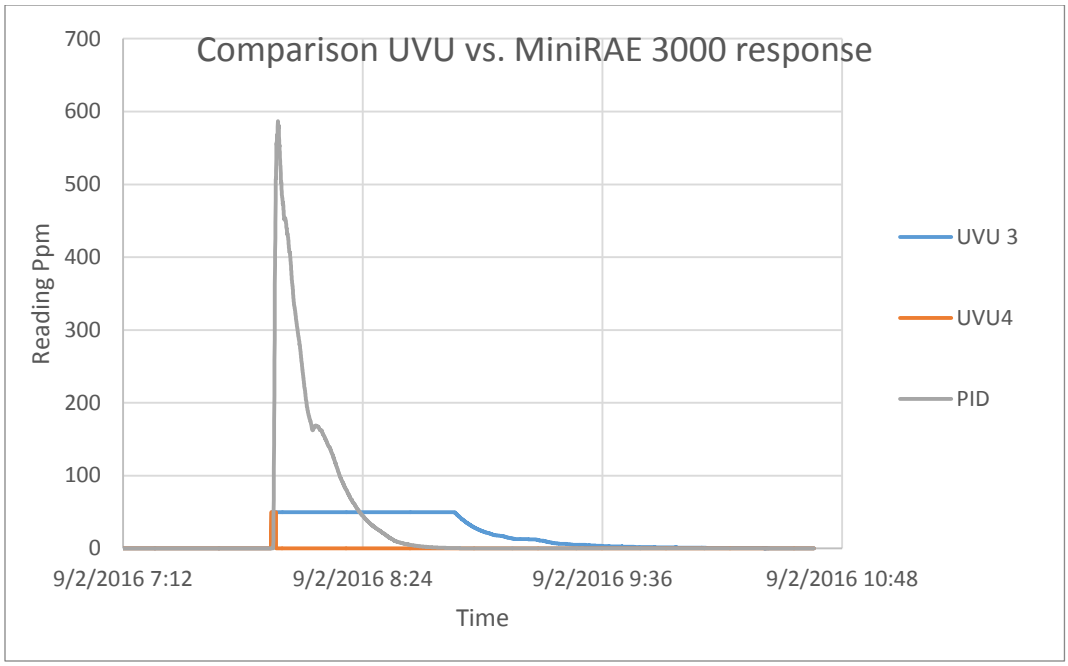

Figure 30. *Release 7, 2016. Comparison data of UVU electrochemical ToxiRAE® and a MiniRAE® PID with an 11.7eV bulb.*

Figure 31. *Release 7, 2016. A camera captures the maximum concentration inside vehicle #1 at 441.6 ppm on the PID and 49.9 ppm locked on the electrochemical sensor. Visible chlorine cloud outside.*

Dr. Delp and Dr. Sohn from LBL conducted exfiltration (air leakage) studies in 2016 using chlorine gas to confirm the accuracy of the SF_6 representative gas in determining ACH. The UVU Team took the opportunity to experiment once again with the two technologies. Both technologies, PID and electrochemical, responded to the chlorine exposure as expected. A PID was placed inside the vehicles during the test. The PID provided visual displays which were consistent with ~10:1 conversion factor (actual concentration of chlorine vs reading) in higher concentrations. Prior to the final test, the PID was calibrated and then placed next to a new PID with an 11.7ev lamp at the door of the vehicle. The readings of the two instruments were within 2 ppm of each other. See Figure 32. Unfortunately, the data from the new PID during the testing was not evaluated due to issues with the downloading process of the ProRAE Studio® Software.

There is significant data to support the application and limitations of PIDs with 11.7eV bulbs when exposed to various concentrations of chlorine. This data has been evaluated by interested parties and its usefulness in the emergency response community should be presented to national SME's. A surprising finding from the JRII test was the resiliency of UVU PID #12. It was repeatedly exposed to high concentrations of chlorine and continued to recalibrate and was put back into service. There was noticeable discoloration to the wand and a battery error message appeared after Release 8, 2016.

The most popular PID calibration gas standard is isobutylene. There are tables of correction factors (CF) applied to a reading in order to eliminate sensitivities to different gases in comparison with IBE, which converts the instrument reading to an actual concentration. (RAE Systems® PIDs use volatile organic compound (VOC) as the reading on the monitor for concentration). This approach is working well for 10.6eV PID lamps. The JRII Trials were used to evaluate IBE as the preferred gas for the calibration of PIDs with 11.7eV lamps.

Once calibrated with IBE, the instrument shows a CF = 1 at start up (RAE Systems® TN-106). With higher concentrations of chlorine this value changed significantly and reached a CF of 10 to12. This degradation makes proper comparisons difficult between instruments regarding accurate measurements.

Starting in 2017, RAE Systems® has changed the calibration gas to propane for PIDs with 11.7eV lamps. This narrows the CF range for chlorine to ~0.3 to ~0.5. Of course, the best calibration gas is the target gas which is why DPG calibrated their 150 PIDs to chlorine for the JRII Trials. They used a two-point calibration (span 500 ppm) or 3-point calibration with a span 1 value of 10 ppm and a span 2 value of 500 ppm to capture data from the release. DPG did produce a document outlining the calibration procedures and reliability of the PIDs as part of the metadata created for the JRII Project (Chang & Mazzola, 2017).

Figure 32. *PID side by side comparison. The left PID (UVU #12) was exposed multiple times to high concentrations and then recalibrated and challenged by a new, never exposed PID on the right. Left PID reads 41.4 ppm, right PID reads 43.8 ppm (glare).*

Once properly calibrated, a PIDs response is not limited by single exposures to high chlorine concentrations. In addition, repeated exposures at lower concentrations (10 ppm) of chlorine generates reasonable responses with only a slight decay over an eight hour workday. Standard recalibration of the instrument returns the reading to its desired initial state. Figure 33 is a graph showing a PID instrument that was exposed to 10 ppm of chlorine for seven hours. Before exposure, the instrument was calibrated to 10 ppm chlorine. The instrument had a burned-in 11.7eV lamp with approximately 80 hours of aging. Data showed that over the seven hours of exposure, the reproduction of the 10 ppm reading dropped only 10% (Allred, 2016).

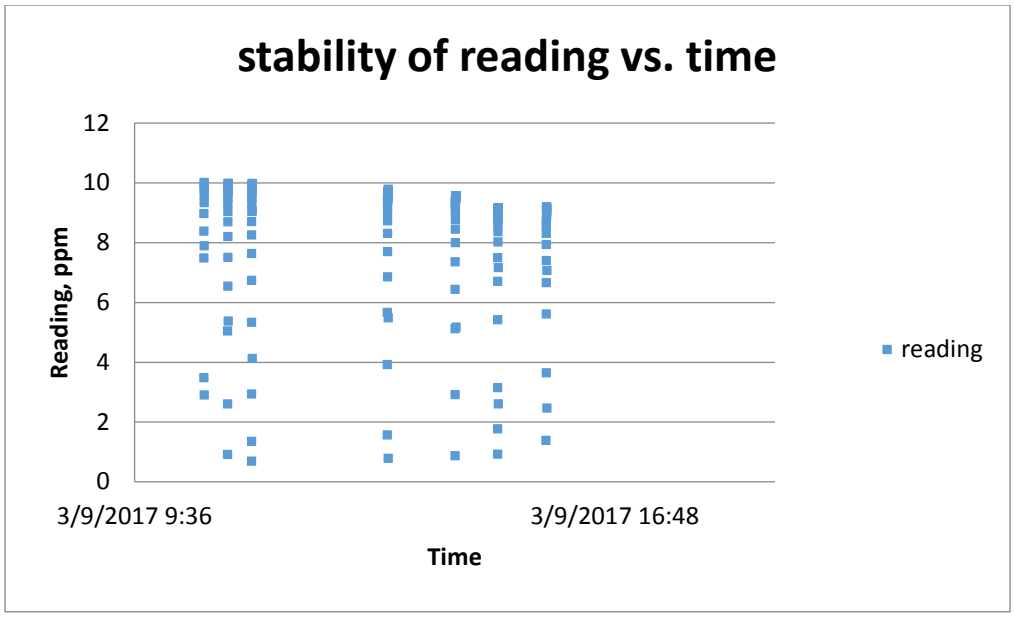

Figure 33. *PID with an 11.7eV bulb with 80 hours of running time dropped only 10% in accuracy over a seven hour exposure.*

UV Canary® instruments were co-located inside the vehicles with PID and electrochemical technology. Inside the structures, LBL researchers co-located UV Canary® and JAZ® instruments and determined that the absolute calibrations are probably within +/- 25% of the true value. The PID data correlated very well with the UV Canary® data. A simple scaling factor brings the data together. An effort was made by Dr. Delp of LBL to reconcile the PID response and the UV Canary® response as depicted in Figures 34a and 34b by applying a scaling factor (for the two data sets this factor is between 6 and 11). Delp did not specify a multiplier that would work under all conditions (Personal Communication, August 7, 2017).

The camera recorded all instrument responses in real time. The interior concentrations for the first 15 minutes of Release 8 (zero degree release) revealed less than 2 ppm readings on the PID and the electrochemical sensors. After the secondary release (dump valve) of the "super-cooled" chlorine remaining in the tank, the readings on the instruments inside the vehicles mirrored the previous trials (a "super-cooled" liquid is below its freezing point but still in a liquid state).

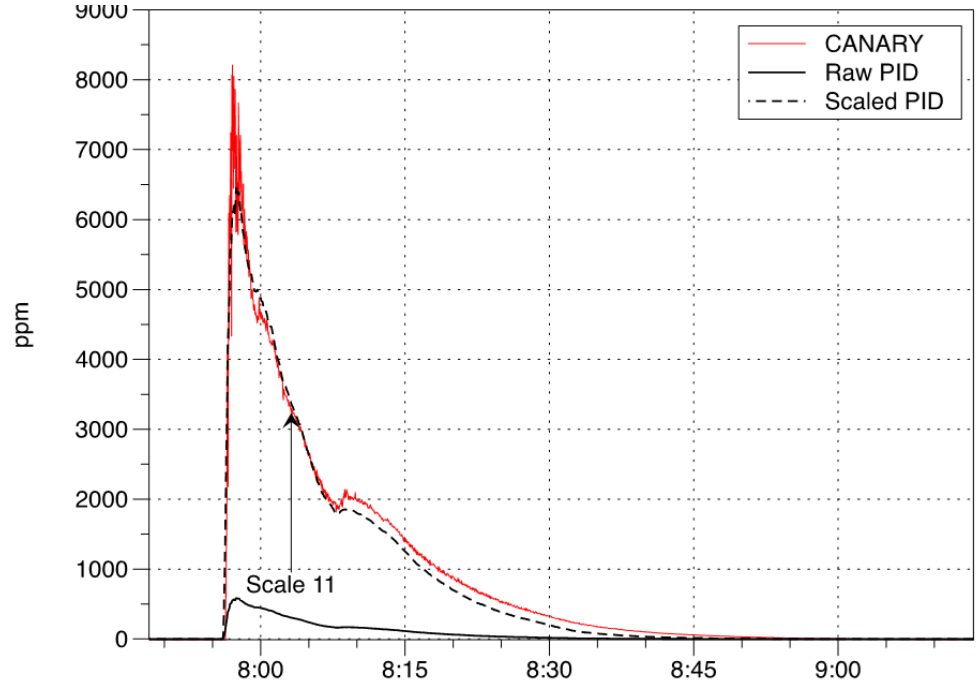

Figure 34a. *Release 7, 2016. Scaled comparisons between detector technologies and a multiplier determined by LBL in order to align the instruments.*

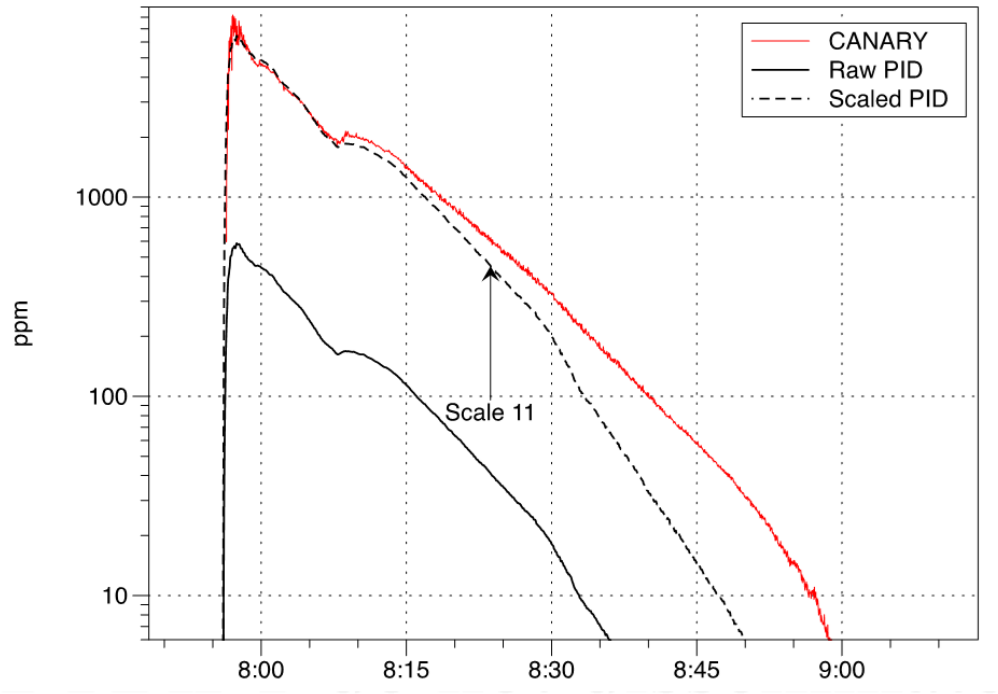

Figure 34b. *Release 7, 2016. Scaled comparisons between detector technologies and a multiplier determined by LBL in order to align the instruments.*

Significance of UVU Aerial Video During the JRII Trials

In 2016, Utah Valley University obtained permission to fly a UAV in the DOD restricted airspace of the US Army Dugway Proving Ground in order to obtain overhead views and documentation of the plume behavior from high elevation. The operator used a DJI® Phantom 4 model UAV. Flight times were approximately 25-28 minutes depending on the requirements of the mission. The UAV was operated at an unobstructed distance of ~2 miles at the Incident Command Post (ICP) and was directed via video feed from an Android® tablet.

Based upon the conditions of the test release, each UAV video mission provides unique video files that can be used by the researchers and the scientific community to address test objectives. Each UAV video leaves its own particular noteworthy impression depending on the perspective of the viewer. All of the UVU aerial video files will have tremendous potential impacts for the scientific and responder communities that will be analyzed for years to come. Dr. Mike Sohn from the Lawrence Berkeley Laboratory stated he thought the UVU aerial video "a highly impactful outcome from the JR Project" (Personal Communication, August 7, 2017).

The UVU aerial video files will also have significant impact on atmospheric and plume modeling applications. Current plume dispersion models do not depict what was observed 400 feet above the plume. This needs to be reconciled in the software to closer reflect the behavior seen in the video (see the ALOHA® discussion on pp. 25-34).

Emergency responders will likely not change the way they tactically approach a catastrophic chlorine release based upon the JRII aerial video files. However, the observations in the video files related to the speed, lifting behavior, visual aspects, and density of the plume are key elements in applying risk-based response processes, especially as it pertains to the evaluation and selection of public protective actions. Emergency responders will gain an appreciation of the speed and scope of a release when they view the videos.

The concentrations at the edge of the visible vapor cloud are difficult to determine unless specific releases are examined and unless a detector was in the vicinity. Concentrations within the visible downwind vapor cloud were ~30,000-80,000 ppm and were clearly higher closer to the release point. Concentrations varied with the shape and speed of the visible vapor cloud. From a testing perspective, it is recognized that the downwind detection array is significantly different than what emergency responders would be able to employ, especially early in the incident timeline. In any case, if the cloud is visible, the concentrations are likely thousands of times the IDLH for chlorine (10 ppm).

Figures 35 through 38 depict the four 2016 JRII releases and an interesting aspect of each. The aerial video, when in combination with the ground video, give an individual the perspective that could only be appreciated by having both views. See Figure 39.

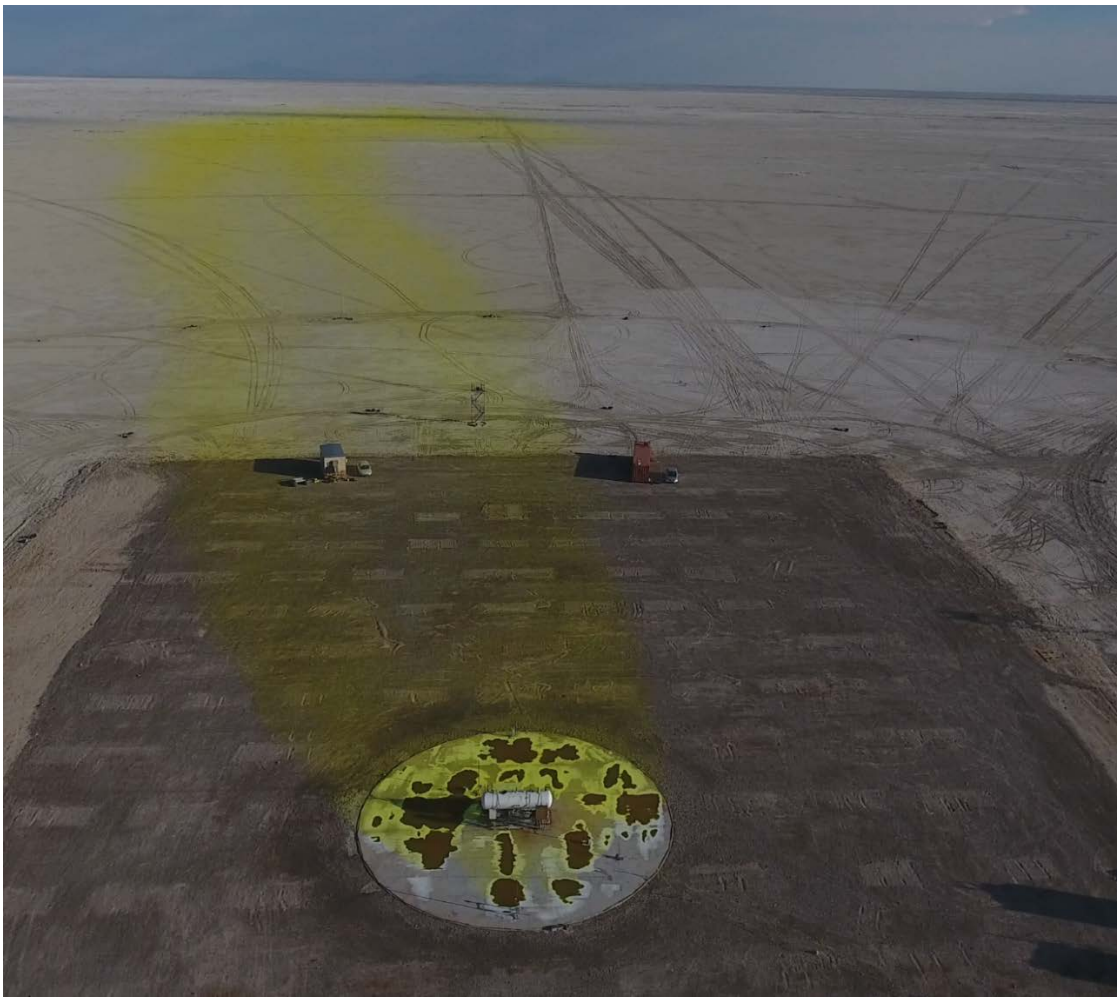

Figure 35. *Release 6, 2016. Interesting downwind plume behavior and the liquid pooling on the pad. Visible plume trails denote higher concentrations in an uneven mixture of the vapor as the main body of the release travels downwind well ahead of the remaining "tail" of the plume.*

Figure 36. *Release 7, 2016. 135° downward angle and high wind speeds contributed to a spectacular visual of the plume's energetic activity and its behavior when encountering the structures on the grid.*

Figure 37. *Release 8, 2016. The vertical plume and the subsequent ground shadow was somewhat unanticipated and, coupled with ground video, provided a 3-D type of visual effect. Concentrations inside the vehicles were surprisingly low as the chlorine landed on the pad downwind.*

Figure 38. *Release 9, 2016, 20 tons. Seconds after the release. The UAV provided upwind and downwind angles of the largest of the plumes and depicted the best view of the release behavior found in no other video. Compare with Figure 39.*

Figure 39. *Release 9, 2016, 20 tons. Seconds after the release from 5 m elevation and 85 m downwind. Compare to the same time as seen from the UAV in Figure 38.*

Auto-refrigeration Behavior and its Impact on the JRII Trials

Release 7, 2016, 135° down, was a 10 ton release. Estimates were that ~10 % of the liquid remained in the tank after the liquid biphasic jet completed its release. When the pressure equalized inside and outside the tank opening there was ~168 gallons of liquid remaining (11.87 lbs/gal). Release 8, 2016, zero degrees straight up, was also a 10 ton release that left a residual liquid quantity of ~70% inside the tank or ~1,180 gallons. This remaining super-cooled liquid would have cooled to at least its boiling point of -29° F. This is most likely the condition inside the tank based on the SME team's considerable experience with auto-refrigeration.

No visible ice formation on openings or solidification of the remaining liquid after the initial release in either case was observed. Interesting is the DPG Infrared (IR) video depicting temperature differentiations in the tank. See Figure 40-43. Ice formation is seen in accidental chlorine release case history but was not observed at JRII. Humidity is a factor in ice formation. The Utah desert and Louisiana in the summer have a tremendous difference in the water content of the air, for example. Hazmat teams routinely use thermal imaging cameras which play a role in establishing the liquid line inside containers based on the IR image. This technology is already found in most fire/hazmat organizations.

UVU aerial video captured a close up of the vertical opening in Release 8 after the vertical release and before the liquid dump valve was activated. There was no visible ice formation at the opening on top of the tank. See Figure 44.

The JRII Trials using DPG IR video of the tank show that the physical condition inside the tank is sub-cooled. Bottom valve releases, of the remaining chlorine, confirmed the physical nature of the chlorine was liquid rather than solid. Predictions cannot be made universally due to the countless variations in the individual release conditions of the environment, the tank, and the product.

Figure 40. *DPG IR image from video at four seconds after the vertical release.*

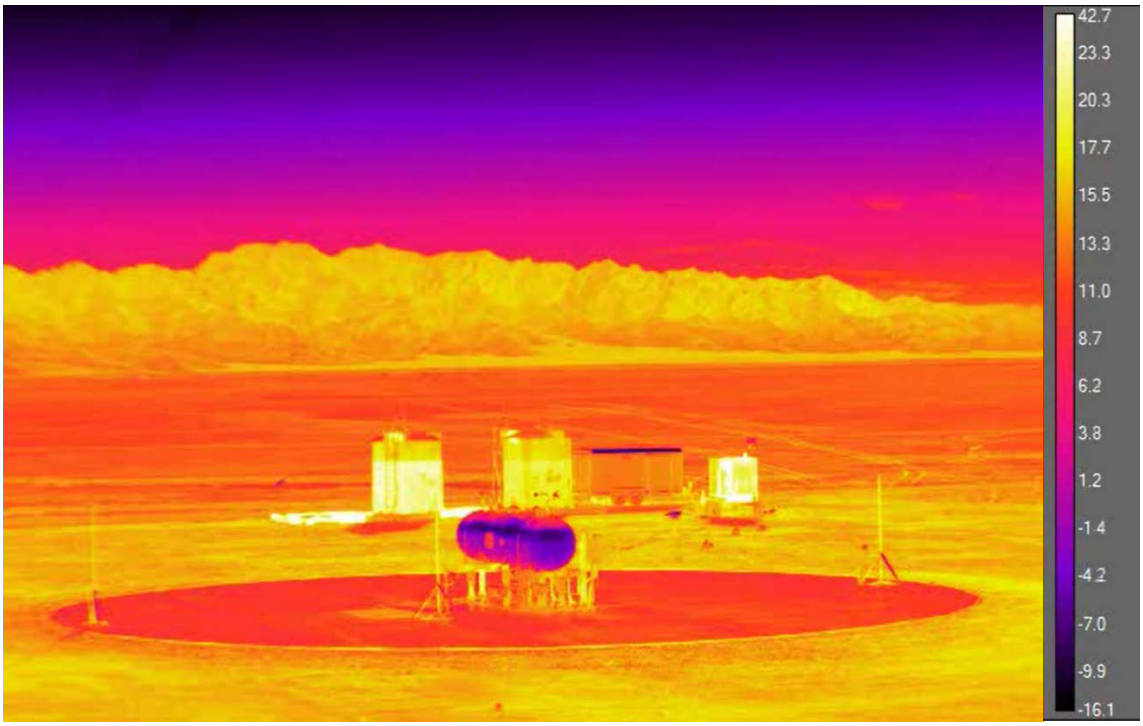

Figure 41. *DPG IR image from video at 60 seconds immediately after the vertical release stopped.*

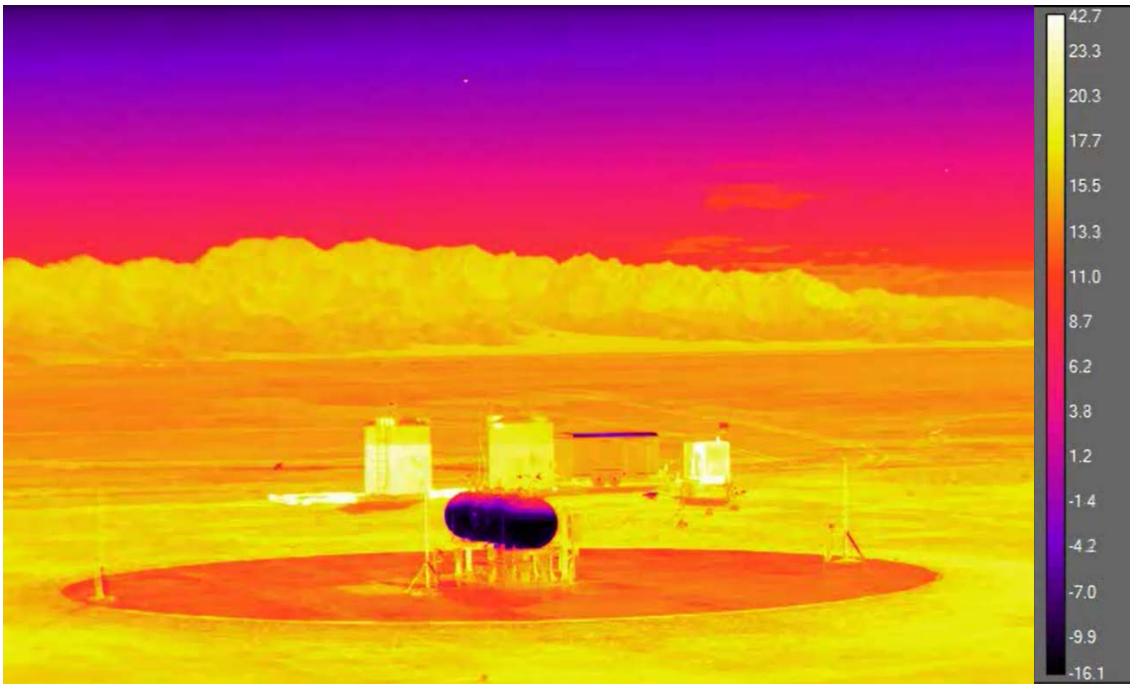

Figure 42. *DPG IR image from video at 11:30 min. post release and prior to the dump valve opening at ~15:35 min.*

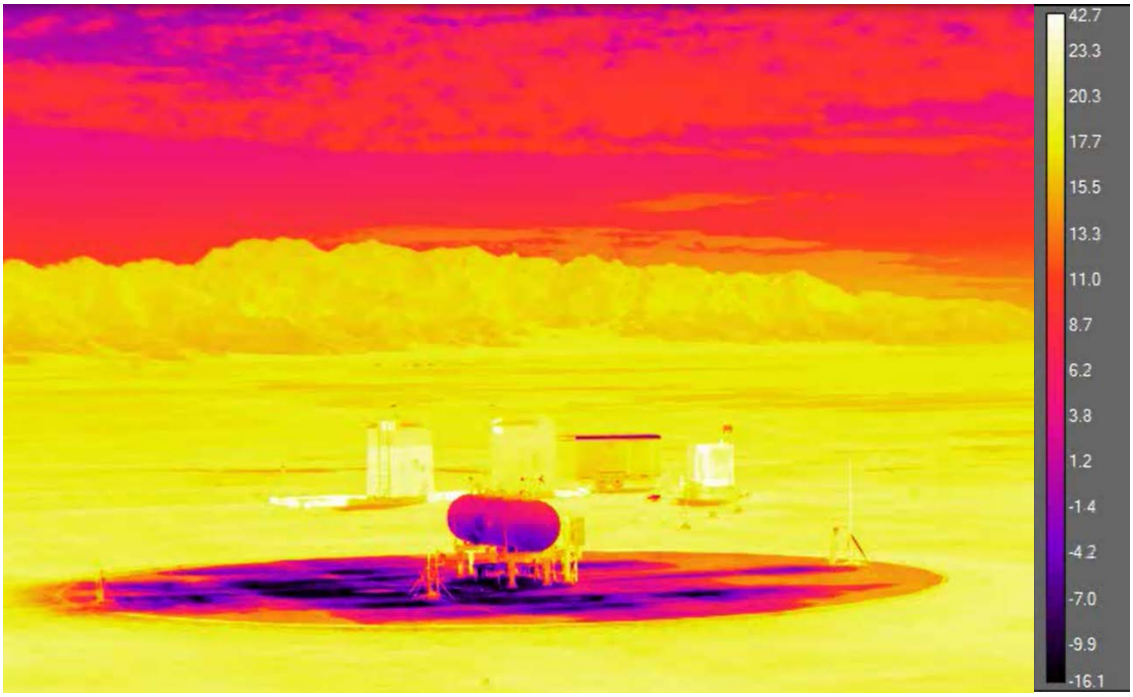

Figure 43. *DPG IR image from video at 50 min. post release and ~35 min. after the dump valve release.*

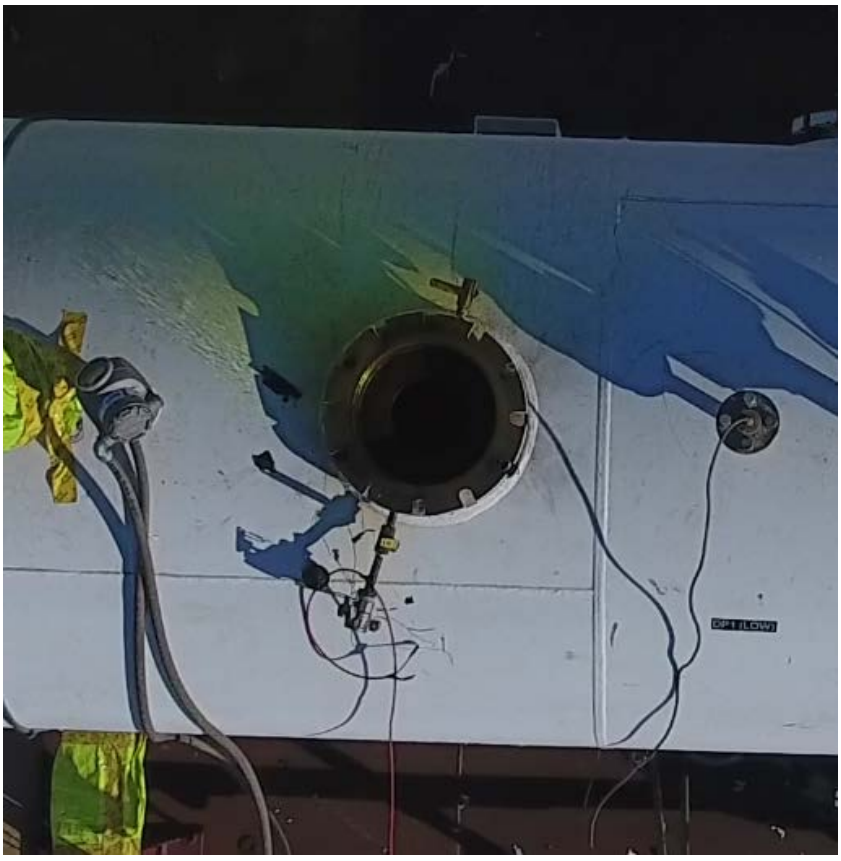

Figure 44. *UVU Aerial shot from ~10 feet above the opening on Release 8 showing no visible ice accumulation.*

PPE Performance During the JRII Trials

No significant data or observations were derived at JR beyond the data which has already been established by manufacturers and testing agencies regarding chlorine challenges to chemical protective fabrics. No new information was obtained that would counter or add to the current body of knowledge. The National Fire Protection Association (NFPA) standards that specifically test against chlorine include:

- NFPA 1991, *Standard on Vapor Protective Ensembles for Hazardous Materials Emergencies and CBRN Terrorism Incidents* (2016 edition)
- NFPA 1994, *Standard on Protective Ensembles for First Responders to Hazardous Materials Emergencies and CBRN Terrorism Incidents* (2017 Edition, to be released in September 2017)

NFPA 1991 challenges materials and interfaces at a 100% gas challenge. NFPA 1994 challenges materials and interfaces at 10,000 ppm (1%) for Class 1, 350 ppm for Classes 2 and 2R, and 40 ppm for Classes 3 and 3R. This approach balances the need for chemical protection with physiological and physical comfort.

Dr. Christina Baxter, CEO of Emergency Response TIPS LLC, and chairperson of the NFPA 1991 and 1994 Technical Committees on Chemical Protective Clothing made the following statement: [See Figure 45]

> The JR data provides excellent examples of real-world scenarios where the JR data can be applied to the selection of the appropriate PPE. In the absence of readings from the release point to the 500 meter point, an NFPA 1991 ensemble with the optional liquefied gas capability would be suitable. The measured sensor readings demonstrate that an NFPA 1994 Class 1 ensemble would be sufficient for operations between 500 and 5000 meters from a catastrophic release. An NFPA 1994 Class 2 ensembles is suitable for the 5000 – 10,000 meter range and the Class 3 ensembles would be suitable for the areas at greater than 10,000 meters. (Personal Communication, Christina Baxter, August 9, 2017)

Figure 45. *Left: Blauer® Manufacturing's Multi-Threat Ensemble. NFPA 1994 Class 2 performance as well as NFPA 1992 and Right: Blauer® Manufacturing's XRT Ensemble. NFPA 1994 Class 3 performance.*

Note: Blauer® Manufacturing's Multi-Threat Ensemble: Certified to the NFPA 1994 Standard for Class 2 performance as well as NFPA 1992 for splash protection. Appropriate for use with approved SCBA systems in environments where liquid and vapor challenges are at IDLH concentrations. Blauer® Manufacturing's XRT Ensemble: Certified to the NFPA 1994 Standard for Class 3 performance. Appropriate for use with approved APR/PAPR systems in environments where the liquid or vapor challenges are at or below IDLH concentrations.

No chemical or thermal PPE studies were conducted during JRII in 2016. During Release 5, 2015, a new set of firefighter bunker pants was exposed to ultra-high concentrations of chlorine vapor without immediate visible effects on the fabric. Two years later the fabric appears new but has not undergone standardized physical tests or chemical laboratory analysis. The metals parts on the pants – snaps, zippers and rivets – are all significantly corroded, however, they are functional. See Figure 46.

Figure 46. *Release 5, 2015. Corroded metal parts on turnout pants exposed to ~24% chlorine concentration.*

It is clear that firefighter turnout gear would not be an adequate substitute for chemical protective clothing during a large scale chlorine release incident. On this point, Dr. Baxter emphasized:

> This is further backed by laboratory experiments which demonstrate that chlorine does not degrade skin at the lower concentrations of 30 and 250 ppm, but does begin to degrade the skin's integrity at 500 ppm. After 10 minutes of skin exposure to a 500 ppm concentration, the chlorine will begin to build up within the skin. Therefore, any response to chlorine events should consider the use of chemical protective clothing such as that described within NPFA 1991 and NFPA 1994. (Personal Communication, August 9, 2017).

Rapid Phase Transition (RPT) Behavior During the JRII Trials

The term "Rapid Phase Transition", or RPT, was used by the scientists at the Chemical Security Analysis Center at DHS at the first Jack Rabbit Meeting of SME's at the National Fire

Academy in Emmitsburg, Maryland, in 2013. RPT defines the physical change from liquid to gas in the soil which has been impregnated by a liquid release and frozen over by the cooling effect of a decompressing gas as its volume expands. The liquid then transitions to a gas under the frozen surface of soil and liquid product until the pressure builds and is then rapidly released. This phenomenon was only seen in JR 2010. See Figure 47.

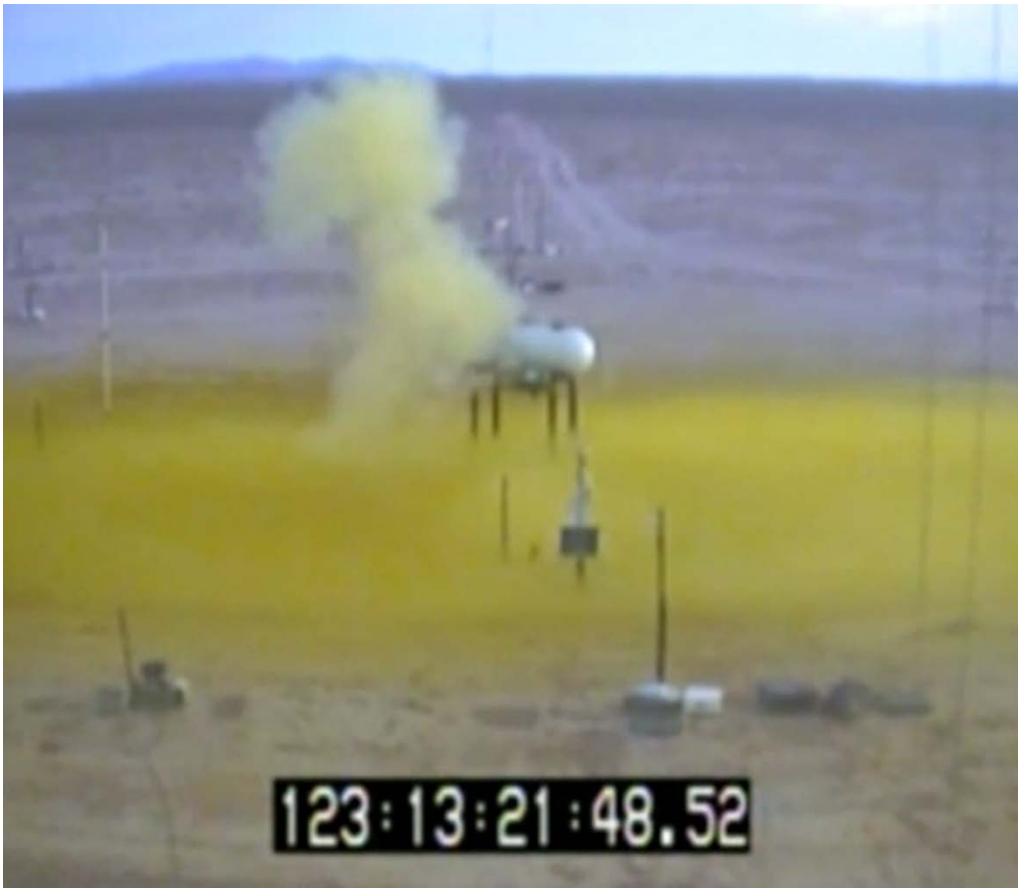

Figure 47. *JRI Trial 5, May, 2010. Typical RPT event at +46 seconds post release. RPTs were observed randomly until ~five to ten minutes after release.*

RPT's were not seen in any of the 2015 or 2016 JRII Trials most likely due to the releases occurring on a concrete pad or loose gravel rather than soil. The environmental conditions in 2010 involved surface water (rain the night before), a previous ammonia exposure in the soil, and the current chlorine release. Two main theories are physical and chemical reactions. Mark Whitmire, the lead scientist working on behalf of the Department of Homeland Security, Chemical Security Analysis Center, who conducted the research on RPT's, said, "I have absolutely no doubt that the phenomenon is indeed a 'rapid phase transition' and is a physical event, not a chemical reaction" (Personal Communication, August 7, 2017). Whitmire stated that he has found this same reaction in liquid releases of bulk Liquefied Petroleum Gas as well.

The surface composition at the release site plays a significant role in the likelihood of an RPT occurring. In JRII 2016 an experiment on a smaller scale was designed by Whitmire. A series of two gallon buckets of various soil types and organic matter were inserted into a steel table and exposed to liquid chlorine in the dump valve secondary release of Release 8 in 2016 without any observed RPT events. In spite of this attempt to recreate an RPT through experimentation in 2016, the phenomenon was not duplicated in JRII.

The liquid release from Release 7 in 2016 left the pad in the direction of the liquid jet and made contact with the gravel surface of the grid causing visible liquid contact and freezing conditions. No RPT events were recorded on video. This could be due to the porosity of the gravel, similar to rail bed ballast.

The JRII Project did not endeavor to determine the likely force exerted by a RPT event. The JRI 2010 RPT's raised soil and visible cloud ~20 feet into the air. The energy and impact of such a reaction can only be speculated upon without further study.

While the UVU Team feels that it is important for responders to be aware of RPT's, it is not critical to spend excessive training time to explain. While interesting, the probability of RPT's occurring does not appear to be significant. During the JR 2010 trials, RPT's occurred in close proximity to a liquid pool of chlorine and within ~5-10 minutes post release. It is highly unlikely that hazardous materials emergency response teams would be operating in or near a liquid pool within that time frame.

Effect of Chlorine on Common Urban Surfaces

One of the emergency response objectives that originated in the JR meeting at the NFA in 2013 was determining what effect, if any, chlorine would have on common urban surfaces found in most communities. An experiment was designed around small scale representative samples attached to what was called a "witness board". Twelve boards were built, two for each test. The chosen materials were based on a majority decision of the UVU Team. The samples were arranged in four rows of four materials as shown in Table 4 and Figure 48.

Telephone Pole	**Railroad Tie**	**Aged Asphalt**	**New Asphalt**
Asphalt Shingle	**Polyvinyl Fence**	**Bare Wood**	**Galvanized Steel**
Bare Copper	**Bare Aluminum**	**Painted Aluminum**	**Bare Steel**
Rubber Tire	**Hose Coupling**	**Fire Hose**	**Nylon Rope**

Table 4. *Witness board composition.*

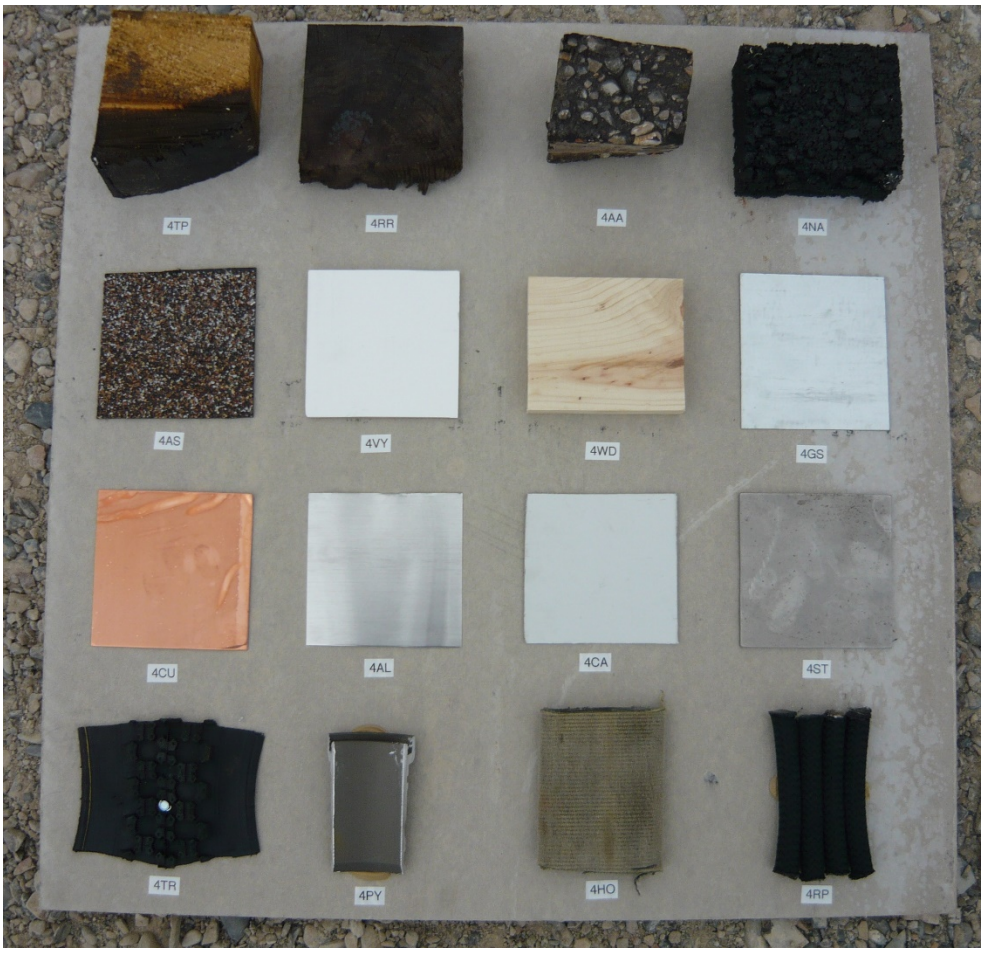

Figure 48. *A typical witness board prepared for a release in JRII 2015.*

Boards were placed on the grid separated by an arbitrary distance in order to expose at least one to the greatest concentration. Cameras were employed on each board to capture any reactions. In all of the testing done and video captured, no overt reactions were noted other than an immediate “smoking” on exposure in a railroad tie sample that may be attributed to vaporization of chlorine.

One notable reaction exception was Release 5, 2015, when witness board #10 was exposed to liquid chlorine directly from the release. The board was located ~15m from the release point. Cameras captured a cold, vaporous green cloud enveloping the board and subsequent liquid on the board which continued to boil off as the surrounding area was covered in frosty layers of ice. The only result was that heavy hydrocarbons dissolved and metals were corroded to a higher degree than exposure to gas only. See Figure 49.

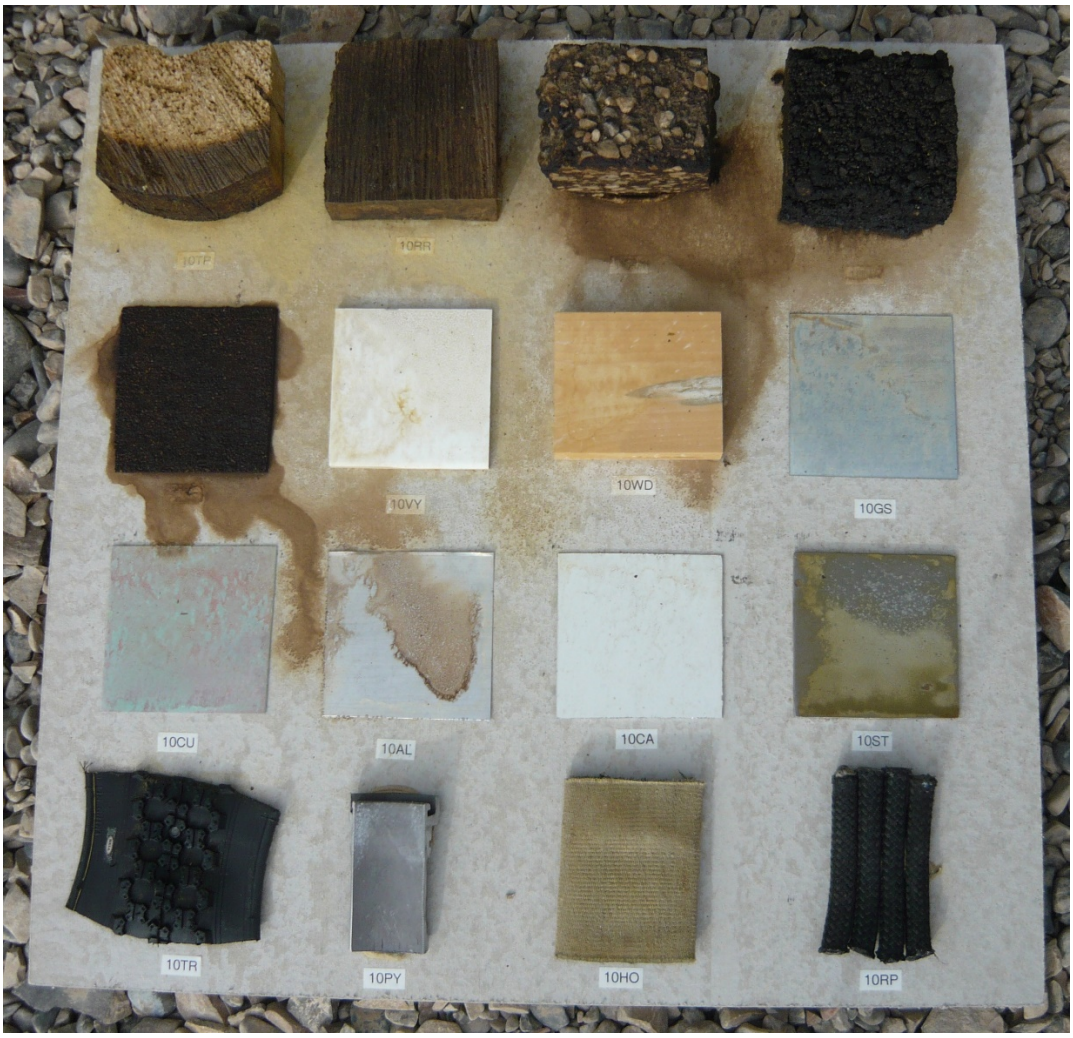

Figure 49. *Release 5, 2015. Witness board #10 after complete evaporation of the liquid chlorine exposure. Note the dissolving hydrocarbons and metal corrosion.*

The board in Figure 49 looks almost identical today (Aug. 2017) as it did immediately after exposure in 2015 therefore, it may be implied that no further or deeper corrosion will occur after the initial corrosive effects have taken place. A final observation is that urban surfaces exposed to ultra-high concentrations of gas and even liquid chlorine will not react immediately, however, they may suffer long-term corrosion and degradation especially bare copper and bare carbon steel which showed immediate corrosion. See Figure 50.

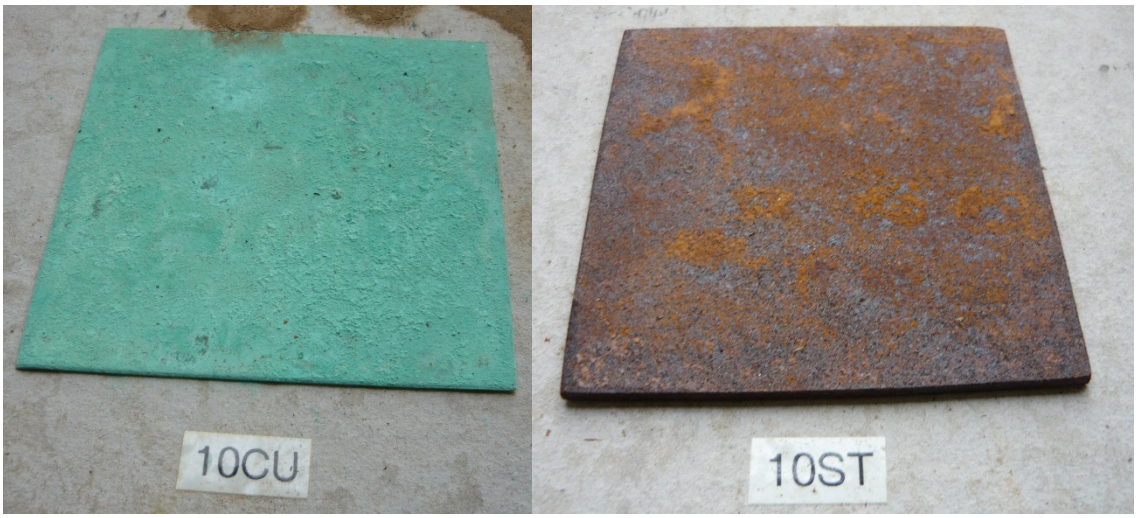

Figure 50. *Corrosive effects of chlorine on Copper (left) and Bare Carbon Steel (right) observed 24 hours post exposure.*

Regarding residual contamination with chlorine, Mark Whitmire from CSAC conducted follow-up examinations of the urban surfaces during the 2015 JR Trials using portable x-ray fluorescence. After exposure, samples were tested within one to two hours on average. Results were that chlorine did not adhere to surfaces or it desorbed from any porous materials almost immediately. The chlorine left no appreciable contamination on or in common urban surfaces. Referring to the concrete release pad where the greatest concentrations of chlorine had occurred Whitmire states, “There is only nominal change in chlorine concentration on the concrete surface where liquid chlorine had previously washed over it” (Whitmire & Schneider, 2016, p. 26).

Conclusion

The Jack Rabbit Project was impactful for the emergency planning and response communities in that it provided a basis for scientific validation of long practiced hazmat strategies and tactics. The effect of TIH materials on communities and response organizations are understood at a higher level. The melding of the emergency responder objectives and the scientific approach to experimentation to meet those objectives delivered credibility and consensus in their conclusions. Emergency responders should base their decisions on the facts, science, and circumstances of the incident. Some limitations exist in the outcomes of this report and will require further study to fully understand. In any case, involving future research, representatives of the emergency planning and response communities should be involved in the planning and execution of the research.

For more information about the JR Project see: http://www.uvu.edu/esa/jackrabbit .

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References

Advanced Technical and Educational Consultants Inc. (ATEC). (April, 2013). *Jack rabbit trials I: Training value analysis meeting.* U.S. Fire Administration; National Fire Academy.

Allred, R. (January, 2016) *MiniRAE 3000 chlorine lab study.* US Army Dugway Proving Ground, Dugway, UT.

Byrnes, A., Matthew, D. (Nov. 11, 2016) *Jack rabbit II phase II 2016: Findings and observations*. McKinley Group, Rockville, MD. U.S. Fire Administration; National Fire Academy.

Chang, J. & Mazzola, T. (February, 2017). *Correction of 2016 JR II miniRAE data*. [PowerPoint Presentation]. Final JR 2016 Data. US Army Dugway Proving Ground, Dugway, UT.

Environmental Protection Agency (EPA). (February, 2007) *ALOHA User's manual.*

Hanna, S., Dharmavaram, S., Zhang, J., Sykes, I., Witlox, H., Khajehnajafi, S., Koslan, K. (April 7, 2008). *Comparison of six widely-used dense gas dispersion models for three recent chlorine rail car accidents*. Process Safety Progress, American Institute of Chemical Engineers, Vol. 27. Issue 3. Pages 248-259.

McKinley Group. (Aug. 1, 2016) *Jack rabbit II phase I trials: Training needs assessment and analysis.* McKinley Group, Rockville, MD. U.S. Fire Administration; National Fire Academy.

National Oceanic and Atmospheric Administration (NOAA). (July 10, 2015) *New RAILCAR source strength model available in ALOHA 5.4.5.* Retrieved Aug. 29, 2017 from: https://response.restoration.noaa.gov/about/media/new-railcar-source-strength-model-available-aloha-545.html

Nicholson, D., Hedrick, A., Lian, N., Schmidt, E., (2017). *Final test report for jack rabbit (JR) II.* WDTC-SPD-FTR-001, US Army Dugway Proving Ground, Dugway, UT. 120 pp.

Pipeline and Hazardous Materials Safety Administration. (PHMSA). Department of Transportation. Research and Special Programs Administration Department of Transportation. (2016). *2016 emergency response guidebook: a guidebook for first responders during the initial phase of a dangerous goods/hazardous materials transportation incident.* Washington, D.C.: U.S. Dept. of Transportation, Pipeline and Hazardous Materials Safety Administration

US Department of Homeland Security (DHS) & National Institute of Standards and Technology (NIST). (June, 2011). *Modeling simulation of hazardous material releases for homeland security applications*. DHS/NIST Workshop in Homeland Security and Modeling & Simulation, June 14-15, 2011.

Whitmire, M. & Schneider, J. (February, 2016) *Evaluation of portable x-ray fluorescence for the determination of chlorine in the environment after chlorine releases at jack rabbit II*. US Department of Homeland Security, Chemical Safety Analysis Center. CSAC-16-004

Appendix A – Test Control Logs for JRII 2015 & 2016

(Nicholson, Hedrick, Lian, & Schmidt, 2017)

Trial	Date	Time 1 h:m:s	Stop 1 h:m:s	Time 2 h:m:s	Stop 2 h:m:s	Cl2 Lbs.	Size	Wind from	Wind Speed m/sec	Temp °C	RH %	Pressure mbar
2015												
1	8/24	13:35:45	13:36:43	n/a	n/a	9940	6”	147°	2.0	17.7	39.2	873.5
2	8/28	15:24:21	15:25:10	n/a	n/a	17969	6”	158°	4.2	22.7	33.6	875.12
3	8/29	13:56:55	13:57:31	n/a	n/a	9947	6”	169°	3.9	22.5	30.3	870.97
4	9/1	14:38:50	14:39:33	n/a	n/a	15366	6”	183°	2.3	22.5	26.9	869.26
5	9/3	13:28:19	13:29:09	n/a	n/a	18304	6”	182°	2.7	22.2	26.5	866.53
2016												
6	8/31	14:23:35	14:24:30	n/a	n/a	18460	6”	160°	2.3	22.0	21.6	871.1
7	9/2	13:56:00	13:57:20	14:07:08	14:09:20	19989	6”	160°	4.54	18.88	56.17	868.48
8	9/11	15:01:45	15:04:42	15:17:16	15:26:27	20020	6”	175°	2.18	14.75	26.49	873.31
9	9/17	14:05:30	14:10:21	n/a	n/a	39000	6”	164.6°	3.55	10.48	43.26	875.65

Release Point	Orientation from Vertical
6	180°
7	135° / 180°
8	0° / 180°
9	180°

Appendix B – Chemical and Physical Properties of Chlorine

Formula	Cl_2 (Diatomic molecule)
Physical	Yellow/Green Gas
Ionization Potential	11.48 eV
Four Digit ID Number	UN 1017
Primary Hazard Class	2.3 Inhalation Hazard
Vapor Density	2.48
Vapor Pressure	6.8 ATM @ 70° F
Expansion Ratio	460:1
Solubility	None
pH	< 1 reacts with water to form HCl
Flammability	None
Boiling Point	- 29° F
Odor Threshold	0.3 ppm
TLV/TWA (8 hours)	0.5 ppm
IDLH	10 ppm