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November 2016 | Volume 169, Number 11

FEATURES


14


41


53


61

36 *Fire Engineering*'s 140th Anniversary
During the next year, we will take a look back at the rich and unique history of this landmark fire service publication by focusing decade by decade, starting from 1877, on stories that made history and helped shape and make the fire service what it is today. We will also show the evolution and changes of the publication from its humble beginnings as a journal "Devoted to the Interests of the Firemen of the Country." GLENN CORBETT AND ROB MALONEY

41 Preplanning for Incidents Involving Crude Oil Rail Shipments: Using the Military Planning Model as a Guide
The federal government predicts that trains hauling crude oil or ethanol will derail an average of 10 times a year over the next two decades, causing more than $4 billion in damage and possibly killing hundreds of people if an accident happens in a densely populated part of the United States. Will you be ready if it happens in your first-due area? Here is a proven and widely used planning model, which contains simple tools and techniques you can use to develop a coherent, thorough plan. It can also be used to preplan large-scale, complex, multiagency, fast developing emergencies such as a crude-by-rail incident. JERRY KNAPP

53 Preplanning for Incidents Involving Crude Oil Rail Shipments: The Crude Oil Unit Train (COUT) Plan
Although Lac Megantic, Quebec, was not well known to Lancaster (PA) emergency managers, a train derailment there that killed 47 people and destroyed several downtown blocks made the Lancaster County Emergency Management Agency reevaluate its own railroad preparedness. ERIC G. BACHMAN

61 The Jack Rabbit Tests: Catastrophic Releases of Compressed Liquefied Gases
Millions of tons of chlorine are shipped annually throughout the United States. Despite the excellent record of safe transportation, response to a bulk shipment disaster will challenge all emergency responders. The Jack Rabbit program is designed to understand the behavior and consequences of large-scale chlorine and anhydrous ammonia releases. GREGORY G. NOLL AND ANDY BYRNES

69 Radiation: A Primer for Emergency Responders
Is your department street smart when it comes to dealing with radioactive responses in the transportation setting? Although the safety practices outlined here apply to all incidents, they are particularly useful for incidents when radiation is used as a weapon of mass destruction. ROBERT SHELTON

76 Understanding the Photoionization Detector
This detector is useful for emergencies ranging from hazardous materials incidents to oil or gasoline spills, technical rescue, leaking cylinders or gas valves, and even to detect accelerants in arson cases. With proper training and maintenance, it can be a valuable tool in your toolbox. BRIAN CRIMMINS

The Jack Rabbit Tests: Catastrophic Releases of Compressed Liquefied Gases

BY GREGORY G. NOLL AND ANDY BYRNES

MILLIONS OF TONS OF CHLORINE are shipped annually throughout the United States. Despite the excellent record of safe transportation, bulk chlorine shipments represent a low-frequency/high-consequence response scenario that will challenge virtually all emergency response agencies. Compounding the vulnerabilities transportation emergencies present is the use of chlorine as a terrorist weapon in Iraq, Syria, and other Middle East countries. Knowing the behavior of chlorine in a large-scale release scenario is critical in applying a risk-based response (RBR) process for these scenarios, which is critical to successfully managing a hazardous materials incident. National Fire Protection Association (NFPA) 472, *Standard for the Competence of Responders to HM/WMD Incidents*, defines RBR as a systematic process in which responders analyze a problem involving hazmats; assess the hazards; evaluate the potential consequences; and determine appropriate response actions based on facts, science, and the incident's circumstances. Knowing the behavior of the container involved and its contents are critical in determining whether responders should and can intervene.

For emergency responders, below is an overview of the Jack Rabbit program, which is designed to help further understand the behavior and the consequences of large-scale chlorine and anhydrous ammonia releases. The program has involved the U.S. Department of Homeland Security (DHS)—Chemical Security Analysis Center (CSAC) (Table 1); the DHS Transportation Security Administration—Hazardous Materials Freight Rail Section; and the U.S. Department of Defense—Defense Threat Reduction Agency. Other stakeholders supporting this effort include the Chlorine Institute, the Association of American Railroads, the U.S. Fire Administration (USFA), and Transport Canada.

Table 1. Chemical Security Analysis Center (CSAC)

The CSAC was established in 2006 to identify and assess chemical threats and vulnerabilities in the United States. Associated with the U.S. Department of Homeland Security—Science and Technology Directorate, the CSAC is located at Aberdeen Proving Ground in Maryland, and its capabilities include the following:

- Conducting chemical hazard awareness, assessment, and analysis.
- Conducting science-based assessments of risks.
- Integration and analysis of chemical threat information and data.
- 24/7 reach-back capabilities in response to investigations and crises.
- Fusion of chemical information from different communities.

Fatal Chlorine Releases

On June 28, 2004, a westbound Union Pacific Railroad (UPRR) freight train bound for Arizona was traveling on the same main line track as an eastbound Burlington Northern—Santa Fe Railway Company (BNSF) freight train. At 0503 hours, the UPRR train struck the midpoint of the 123-car BNSF train as the eastbound train was leaving the main line to enter a parallel siding in Macdona, Texas. Forty rail units derailed, including the four UPRR locomotives, that train's first 19 cars, and 17 BNSF cars. As a result of the derailment and the subsequent pileup of railcars, a chlorine tank car was punctured. The car was a DOT-105 pressure container transporting 90 tons of liquefied chlorine at 37 pounds per square inch (psi) tank pressure; the tank car would ultimately release approximately 60 tons of chlorine. See Table 2 for chlorine's physical and chemical properties.

The escaping chlorine immediately vaporized into a chlorine vapor cloud that engulfed the accident area to a radius of at least 700 feet before drifting away from the site. The UPRR train's conductor and two local residents died as a result of chlorine gas inhalation. Twenty-three

Table 2. Chlorine Physical and Chemical Properties

Chemical Family:	Halogens
Formula:	Cl_2 (Diatomic molecule)
Physical:	Yellow/green gas
GHS Class:	Oxidizing gas
Four-Digit ID Number:	UN 1017
CAS Number:	7782-50-5
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 hydrochloric acid (HCl)
Flammability:	None
Boiling Point:	- 29°F
Odor Threshold:	0.3 parts per million (ppm)
TLV/TWA (8 hours):	0.5 ppm
IDLH:	10 ppm

High-level acute exposure signs: eye, nose, and throat irritation; salivation; dyspnea; violent coughing; vomiting; headache; chest pain.

civilians, six emergency responders, and the UPRR train engineer were also treated for respiratory distress or other injuries related to the collision and derailment.[1]

On January 6, 2005, in Graniteville, South Carolina, at 0239 hours, northbound Norfolk Southern Railway Company (NS) Freight Train 192, traveling about 47 miles per hour, encountered an improperly aligned rail switch that diverted the train from the main line onto an adjoining industry track, where it struck an unoccupied parked train (P22). As a result, both locomotives and 16 of the 42 freight cars of Train 192, the P22 locomotive, and one additional car derailed. The derailed Train 192 cars included three chlorine tank cars, one of which was breached and ultimately released 60 tons of chlorine. The train engineer and eight civilians died as a result of chlorine gas inhalation. Also, approximately 5,400 people residing within a one-mile radius of the derailment site were evacuated. More than 500 civilians complaining of respiratory difficulties were taken to local hospitals, and 75 were admitted for treatment.[2]

The Macdona and Graniteville incidents demonstrated that within minutes, releases of toxic inhalation hazard (TIH) gases from bulk containers can present significant response and safety challenges to emergency responders. During large-scale release scenarios, chlorine vapors could continue to be released for hours because of the process of autorefrigeration. In addition, the chlorine plumes were smaller than those predicted by computer models and raised questions on the effects of vegetation and organic materials on plume behavior. Finally, although both incidents were accident scenarios, they also raised issues from emergency responders and security officials as to the impact of an intentional large TIH release in an urban or highly populated environment.

These questions and real-world events involving terrorism-based chlorine releases in the Middle East drove the TSA and CSAC to initiate a series of full-scale test releases of chlorine and anhydrous ammonia to gather data and develop findings that could provide science-based guidance to the emergency planning and response communities.

(1) Jack Rabbit I: Rapid phase transition behavior. *[Photos by U.S. Department of Homeland Security (DHS)—Chemical Security Analysis Center (CSAC).]*

The Jack Rabbit Tests

The TSA and the CSAC began the Jack Rabbit Tests in 2010 to improve the understanding of rapid, large-scale releases of compressed liquefied TIH gases, focusing on anhydrous ammonia and chlorine, which account for approximately 75 percent of all domestic TIH shipments. All of the Jack Rabbit tests were conducted at the Dugway Proving Ground (DPG), a U.S. Army testing installation in Utah, approximately 85 miles southwest of Salt Lake City.

The three distinct testing phases are as follows:

1. Jack Rabbit I tests (2010) focused on one- and two-ton releases of chlorine and anhydrous ammonia.
2. Jack Rabbit II Phase 1 tests (2015) focused on five- to 10-ton releases of chlorine.
3. Jack Rabbit II Phase 2 tests (August-September 2016) focused on 10- to 20-ton releases of chlorine.

Jack Rabbit I Tests

Conducted in spring 2010, the Jack Rabbit I tests involved multiple successive one- and two-ton releases of chlorine and anhydrous ammonia from a standardized release container and within a standardized outside test area in various atmospheric conditions, including wind. The chemicals were released downward into a two-meter-deep depression with a radius of 25 meters.

The Jack Rabbit I tests were to study and improve the understanding of rapid large-scale releases (60 to 90 tons) of a compressed liquefied TIH gas from a railcar. Ten releases took place: two pilot tests of chlorine and anhydrous ammonia and four additional releases of each product. The chlorine dissemination device was a modified 500-gallon propane tank with a remotely controlled three-inch valve assembly on the bottom of the tank. The anhydrous ammonia dissemination device was a 1,000-gallon propane tank with a remotely controlled four-inch valve assembly.

The Jack Rabbit I test objectives were as follows:

- Develop and evaluate a mechanism for the controlled, rapid release of liquefied pressurized gases from containment to approximate the conditions hypothesized to generate a persistent vapor-aerosol cloud in a 90-ton railcar release.
- Characterize the vapor/aerosol cloud movement, behavior, and physiochemical characteristics and compare those characteristics with known observations and testing of large-scale releases of the testing materials.
- Determine if anhydrous ammonia can potentially act as a less expensive and less dangerous dense gas for studying the component phenomena of large-scale releases of dense gas TIH materials.
- Field and evaluate instrumentation used in studying the large-scale release of the testing materials, and develop and evaluate testing methodology for future additional and potentially larger-scale tests.

In February 2013, the USFA and CSAC hosted a meeting at the National Fire Academy (NFA) to review the Jack Rabbit I trials and assess the training value of the data and information to the emergency preparedness community. An Emergency Response Working Group (ERWG) of public and private sector subject matter experts was invited to analyze the data and findings, and determine what would be of most importance to the emergency response community.

Lessons Learned

- Within 250 meters of the release, the chlorine vapor cloud will stay low to the ground and may be influenced by obstacles and terrain.
- As the chlorine vapor cloud moves out to 250 to 500 meters, it will mix with the air and warm up. The vapor cloud will begin to rise and become less concentrated.
- At distances > 500 meters, the vapor cloud is often a well-mixed cloud and will flow easily with the wind, becoming neutrally buoyant.

Emergency Planning/Response Findings

- In low-wind environments, dense gas considerations dominate the initial behavior and movement of chlorine and anhydrous ammonia, especially when blocking or trapping terrain features are present—for example, a ground depression.
- Low-wind conditions will allow for some upwind movement of the vapor cloud.
- At higher wind speeds [> 3.5 meters/second/7.8 miles per hour (mph)], the wind clearly has an immediate and more prominent effect on how the material spreads and behaves after its release.
- The tests validated *Emergency Response Guidebook (ERG)* initial isolation zone distances. A review of chlorine incidents back to the 1930s showed that most fatalities had occurred within 250 meters of the release source and are limited at distances greater than 500 meters.
- During the chlorine trials, random "energetic releases" were observed in the pool of liquid chlorine on the ground (desert soil). Known as a rapid phase transition (RPT), these were observed with rapid one-ton and larger chlorine releases where the material impacts and can collect on the ground (photo 1). The RPT phenomenon was not observed during ammonia releases, but it has also been observed at liquefied natural gas (LNG) releases.
- Wind conditions more readily affected anhydrous ammonia, a lighter-than-air gas (vapor density = 0.6), than chlorine. Although it is more buoyant than chlorine, anhydrous ammonia also maintained its persistence and dense-gas characteristics for a significant time until it reached ambient temperatures. For example, during the first anhydrous ammonia trial release (one ton) under very low wind speed conditions (one mph or less), the condensed vapor cloud was visible and lingered near the tank for almost 45 minutes.

The Jack Rabbit I tests also raised a number of important additional questions for responders and planners and influenced the objectives of the Jack Rabbit II Phase 1 tests.

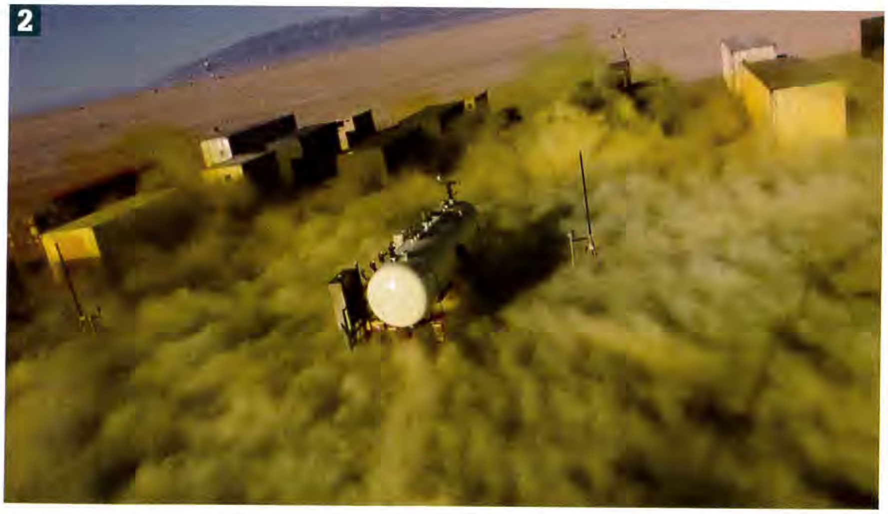
Jack Rabbit II Phase 1 Tests

In August and September 2015, field tests of larger-scale chlorine releases of five to nine tons were conducted to fill critical data and knowledge gaps for improved modeling and emergency response. The tests represented the largest and most comprehensive field study of a TIH chemical release behavior.

Jack Rabbit II test objectives included the following:

- Track and quantify downwind plume movement and chlorine concentrations to at least seven miles (11 kilometers). This distance was based on *ERG* (2012 edition) recommendations for a large night release scenario from a 90-ton chlorine tank car.
- Measure the key source term parameters for each trial. How will the chlorine behave as it exits the tank and impacts the immediate area around the breached tank? Parameters include mass flux, tank pressure and temperature dynamics, and phase distribution. These source term parameters are the foundational elements for the computer models used to project and predict plume movement within the emergency preparedness community (photo 2). Determine the level to which exposed materials may flash freeze when exposed to liquid chlorine and the impact of thawing. What is the physical nature of the pooled chlorine—a puddle or ice (liquid or frozen)?
- Determine if low wind speeds increase the probability of retrograde creep (i.e., upwind movement) of the vapor cloud. Specific questions included at what wind speed and distance are emergency responders safe in the upwind location? This would provide data to evaluate the validity of the initial isolation distances (3,000 feet/1,000 meters) contained in the *ERG* (2012).
- Determine the duration of "long-term off-gassing" and the possibility of secondary, postrelease cloud evolution if contaminated surfaces are disturbed—and to what degree.
- Determine the effects of obstacles and structures on vapor cloud movement and behavior. This would quantify outside and indoor chlorine concentrations and assess the effectiveness of sheltering-in-place in structures under varying conditions (e.g., the effect of heating, ventilation, and air-conditioning (HVAC); sealed windows; and multiple structure levels). Also, could emergency responders survive by sheltering inside emergency response vehicles?
- Determine a reliable vertical concentration gradient. Considering the vapor density of chlorine, can moving vertically either outdoors or in a structure increase the probability of survival?
- Examine the reactivity of chlorine with soil, vegetation, common building components, and urban surfaces. To what degree do common building materials and urban surfaces react with liquid and ultra-high concentrations of industrial chlorine?
- Determine if internal combustion engines (gas and diesel) can operate at high concentrations of chlorine and assess the probability of driving out of the plume as an emergency tactic.

To achieve these objectives, a series of five liquid chlorine releases were made from a 10-ton propane tank. Release quantities were between five and nine tons. The chlorine was disseminated through a six-inch opening in the tank bottom. Explosive bolts released a blind flange that released the entire tank contents in all five releases in a maximum of 50 seconds. The goal was to simulate a worst-case release scenario.



(2) Jack Rabbit II Phase 1: Initial liquid chlorine release through a six-inch breach.

The test grid consisted of the following elements:

- To simulate an urban area, a 400- × 400-foot pad was constructed, and more than 80 20-foot- and 40-foot-long intermodal containers and two mobile trailers were positioned to simulate buildings and structures. Thirteen rows of structures placed on the test grid included a set of stacked containers representing a three-story structure (photo 3).
- The 10-ton propane tank was positioned at the center of a 60-foot concrete pad that had a small one-inch-high lip around the outside and thermocouples installed within the concrete.
- Test boards with 16 common urban surfaces were placed at several locations throughout the test series. The boards were exposed to liquid or ultra-high concentrations of chlorine and observed for reactions and chlorine absorption.
- Vehicles, including three 1970-era pumpers, an ambulance, and three automobiles, were positioned downwind of the test grid and exposed to extremely high [> 10,000 parts per million (ppm)] chlorine concentrations. Detection equipment was positioned inside and outside the vehicles. Except for the final test in which the vehicles were placed adjacent to the concrete pad, the vehicles (with gasoline and diesel engines) downwind from the release tank continued to run even when exposed to these high concentrations.
- Beyond the urban test grid, downwind instrument stations were positioned on arcs at 200 meters, 500 meters, one kilometer, two kilometers, five kilometers, and 11 kilometers. The 11-kilometer (seven mile) distance was based on recommendations found in the *ERG* (2012) for a large, night-release scenario from a 90-ton chlorine tank car.
- Sensors and technologies used in support of the test project included the following:
  - ◊ Chlorine electrochemical sensors.
  - ◊ Photoionization detectors.
  - ◊ Ultraviolet visible spectroscopy.
  - ◊ Differential optical absorption spectroscopy.
  - ◊ Light detection and ranging.
- The upwind side of the urban test grid was monitored visually and with detection equipment to determine the level of "retrograde creep" in low-wind conditions.

Emergency Planning/Response Findings

Low-wind conditions allowed for some upwind movement of the vapor cloud.

- Liquid pooling (i.e., ice formation) was observed on the concrete pad and subsequently vaporized away over several minutes.
- Some movement of the chlorine vapor cloud over the one-story structures was observed. However, there was no visible cloud movement over the two- and three-story structures.
- There was significant channeling of the vapor cloud around the freight containers and structures. Where downwind movement was blocked, there was lateral movement of the vapor cloud until a downwind opening occurred.
- Initial release concentrations at the dissemination tank were more than 100,000 ppm. Vapors remained persistent in the immediate release area for as long as 20 minutes after the release. A visible vapor cloud generally persisted in the urban area of the test grid for more than 10 minutes after dissemination.
- Chlorine concentrations decreased rapidly with increases in height. However, standing on top of fire apparatus did not reduce concentrations to a safe level. As noted, there was no visible cloud movement over the two- and three-story structures.
- Much lower concentrations of chlorine were measured indoors compared to outdoors. In addition, sheltering-in-place inside the vehicles tested within 200 meters did not protect responders from lethal concentrations of chlorine (photo 4). Additional testing is required in this area.
- RPTs, as seen in Jack Rabbit I on the desert soil, were not observed on the concrete pad. This was consistent with expectations because the non-

(3) Jack Rabbit II Phase 1: Urban test grid.

(4) Indoor study structures (arrows).

permeable concrete was unable to accumulate the liquid chlorine.

- A long vapor cloud (estimated to be two kilometers long) was observed moving downwind after the vapor cloud cleared the test grid.
- No positive measurements of chlorine were observed at monitoring stations at more than 30 miles or more than 50 miles from the release point.

In April 2015, the USFA and the CSAC hosted a second meeting at the National Fire Academy to review the Jack Rabbit II Phase 1 trials and evaluate the data obtained for the emergency preparedness community. ERWG participants in the 2013 Jack Rabbit I tests suggested the following four objectives for the 2016 Phase 2 tests:

- Further study and classification of the RPT phenomenon.
- Providing an opportunity for additional National Institute for Occupational Safety and Health and NFPA studies regarding personal protective equipment contamination in a chlorine environment.
- Further study on the upwind movement of the chlorine vapor cloud to at least a distance of 500 meters.
- Further study on the use of emergency vehicles as an emergency measure for sheltering-in-place. Test considerations should include whether the vehicle is running or not, whether the vehicle HVAC is operational, and additional study on engine performance in high concentrations of chlorine.

The NFA and CSAC are now working jointly on ways to make the data obtained and the photo/video documentation available to the emergency responders. Options include NFA Coffee Break articles, emergency response magazine articles, technical presentations at hazmat response conferences, and stand-alone video packages for individual and department use. Utah Valley University Emergency Services will also host an academic site where the Jack Rabbit data will be available to emergency responders (http://www.uvu.edu/esa).

Jack Rabbit II Phase 2 Tests

The final phase of the Jack Rabbit test releases were completed in August and September 2016. Key elements included the following:

- Except for mobile buildings/trailers that remained in place for additional indoor sheltering-in-place experiments, all of the intermodal containers and structures were removed from the test pad.

- Six releases were made from the 10-ton tank using different release angle orientations. Researchers expected these differences to result in partial container releases and autorefrigeration. Angle orientations included 0° (straight up); 90° (horizontal); 135° (45° from the ground); and 180° (downward; same as in the Jack Rabbit II Phase 1 test releases).
- The final release was made from a 20-ton cargo tank at an angle orientation of 180° (downward). The cargo tank was explosively breached to create a six-inch diameter hole.

...

We want to provide the fire service and hazmat emergency responders with the most current information on the behavior of chlorine and other TIHs in large-scale release scenarios. As a low-frequency/high-consequen ce response scenario, critical considerations include the incident's location, the problem's overall size and scope, the need for rapid and effective public protective actions, and the need for responders to possibly operate in and around a highly toxic environment.

Apply the information and observations noted above as part of a risk-based response process. A critical element of this includes emergency responders establishing a relationship with their peers in the chemical and the railroad industries. ■

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