Journal of Hazardous Materials 254–255 (2013) 325–335

Contents lists available at SciVerse ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Comparison of chlorine and ammonia concentration field trial data with calculated results from a Gaussian atmospheric transport and dispersion model

Timothy J. Bauer *

Naval Surface Warfare Center Dahlgren, Building 1480 Room 227, 4045 Higley Road, Suite 344, Dahlgren, VA 22448-5162, United States

HIGHLIGHTS

- Hazard area prediction requires expected value toxicity measures like toxic load.
- Rapid pressurized liquid releases can generate a stationary vapor cloud.
- Accurate source characterization improves downwind concentration profile predictions.
- Average meteorological conditions may not result in realistic dispersion estimates.
- Model predictions provide insight for commercial 1-ton chlorine tank hazard areas.

ARTICLE INFO

Article history:
Received 2 January 2013
Received in revised form 1 April 2013
Accepted 2 April 2013
Available online 9 April 2013

Keywords:
Jack Rabbit
Chlorine release
Ammonia release
Atmospheric transport and dispersion
Toxic hazard area

ABSTRACT

The Jack Rabbit Test Program was sponsored in April and May 2010 by the Department of Homeland Security Transportation Security Administration to generate source data for large releases of chlorine and ammonia from transport tanks. In addition to a variety of data types measured at the release location, concentration versus time data was measured using sensors at distances up to 500 m from the tank. Release data were used to create accurate representations of the vapor flux versus time for the ten releases. This study was conducted to determine the importance of source terms and meteorological conditions in predicting downwind concentrations and the accuracy that can be obtained in those predictions. Each source representation was entered into an atmospheric transport and dispersion model using simplifying assumptions regarding the source characterization and meteorological conditions, and statistics for cloud duration and concentration at the sensor locations were calculated. A detailed characterization for one of the chlorine releases predicted 37% of concentration values within a factor of two, but cannot be considered representative of all the trials. Predictions of toxic effects at 200 m are relevant to incidents involving 1-ton chlorine tanks commonly used in parts of the United States and internationally.

Published by Elsevier B.V.

1. Introduction

On January 6, 2005, a train wreck in Graniteville, South Carolina led to the rupture of a chlorine railcar and release of 54 tons of chlorine [1]. Over 5000 people in the lightly populated area were evacuated; over 500 people sought medical treatment; nine people died. This accident and others led to concern among city planners, emergency responders, the transportation and chemical industries, and the U.S. government about terrorist attacks on chemical railcars and tanker trucks transiting an urban area. A comparison by Hanna et al., of atmospheric transport and dispersion (ATD) model predictions suggested that lethal concentrations from large releases of chlorine (50+ tons) would persist within the toxic plume beyond 10 km downwind [2]; as discussed below, the issue involves source terms and toxicology rather than model physics. In contrast, the nine Graniteville deaths occurred within 1 km of the accident. The 1915 World War I Battle of Ypres, France included release of chlorine from several thousand laboratory (∼50 l) cylinders along a 4 mile-long trench, and deaths were again limited to within 1 km of the trench [3]. The over 2000 deaths in Bhopal, India from the December 3, 1984 release of 40 tons of highly toxic methyl isocyanate occurred within 3 km of the storage tank and were associated with high population density rather than lethal downwind distance [4].

To address the discrepancy between recorded toxic effects and model predictions, the U.S. Department of Homeland Security (DHS) Transportation Security Administration (TSA) assembled

* Tel.: +1 540 653 3091; fax: +1 540 653 8747.
E-mail address: timothy.bauer@navy.mil

0304-3894/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.jhazmat.2013.04.002

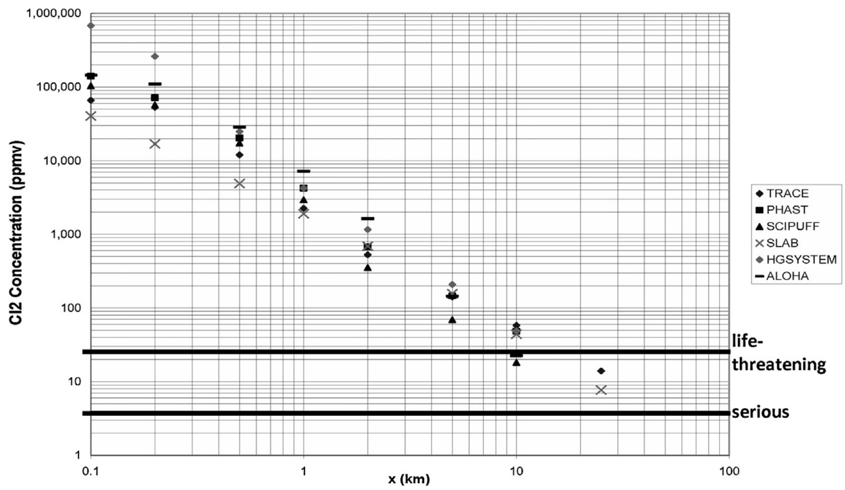

Fig. 1. Model predictions from Hanna et al., for a chlorine railcar accident with lines added for chlorine life-threatening and serious effects AEGLs. All predicted concentrations at 10 km downwind distance are near or above the life-threatening effects AEGL.

subject matter experts from the transportation and chemical industries, national laboratories, academia, emergency response organizations, and government agencies. Two knowledge gaps identified were: (1) characterization of the vapor source resulting from the liquid jet and (2) human toxic effects. These and other knowledge gaps were presented by Hanna [5] and documented by Britter et al. [6] Survivors of the Graniteville accident observed visible chlorine vapor persisting near the damaged railcar for at least two hours. The chlorine plume was also heavily influenced by the path of the Graniteville valley. ATD model methodology for large releases of toxic industrial chemicals (TICs) stored as pressurized liquids usually have the liquid jet entrain passing air and travel downwind as a long vapor plume; in some models, the plume must also accelerate from rest up to the ambient wind speed as the initial dense gas dynamics subside. The modeling approaches used for the model comparison agree with data from field trials, but field trial conditions were limited by available test sites and the requirement that wind direction remain steady and predictable for safety reasons; as such, field trials were conducted over flat desert terrain under fairly high wind speed [7]. A purpose of this study is to determine the importance of correct source characterization (cloud or plume diameter, depth, vapor flux and duration) in predicting downwind concentrations.

Bauer and Fox proposed a theory that large TIC masses of vapor and aerosol released over a short time period will pool into a large cloud at the release site and detrain vapor into the passing air over an extended time period [8]. The theory expands upon earlier work on dense gas releases in depressions. Briggs et al. conducted wind tunnel experiments measuring the sheltering effect of a V-shaped channel on dense gas evacuation [9]. Castro et al., used the same wind tunnel and channel to determine the flux of dense gas into the channel required for “pooling” as a function of air velocity [10]. Chemical concentration for a long duration vapor source (15+ min) versus a short duration plume (less than 5 min) will be lower and less toxic within the first kilometer downwind of the release where severe human toxic effects are likely to occur.

Downwind hazard areas and distances for human toxic effects have been based on chemical concentrations representing the Acute Exposure Guideline Levels (AEGLs) developed for the U.S. Environmental Protection Agency [11]. Fig. 1 displays ATD model predictions from the Hanna et al., comparison for a chlorine railcar accident with lines added for chlorine life-threatening and serious effects AEGLs [2]. All predicted concentrations at 10 km downwind distance are near or above the life-threatening effects AEGL. AEGLs are set for the most sensitive subpopulation rather than the average person [12]; however, for one-time acute exposures, the human body can slowly expel or otherwise counter a toxic chemical. According to the “toxic load” approach (Sommerville et al. [13]) high concentration received over short duration is more toxic than equivalent exposure of low concentration over long duration. Lowering vapor concentration at the release location can reduce the downwind hazard area. In Fig. 1, changing the source type and using toxic load values would both lower the concentration curves and raise the toxicity lines.

The Jack Rabbit Test Program is an important recent effort to generate data necessary to improve downwind hazard area estimation for pressurized liquid releases. It was funded by DHS TSA and conducted at Dugway Proving Ground, Utah during the period April 7, 2010 through May 21, 2010 [14]. The design included a 2-m deep circular pit of 50-m diameter with the chlorine or ammonia tank in the center; the pit shape was refined by Vik and Reif at the Norwegian Defense Research Institute using computational fluid dynamics modeling [15]. The purpose of the pit was to break up the flat desert terrain wind flow at the release location that previous field trials were subjected to. Five trials each were conducted with chlorine and ammonia involving the rapid release of 1 or 2 tons of pressurized liquid directed downward from 2-m height. The trials resulted in chlorine and ammonia pooling in the pit and releasing vapor into the passing air for the trials having low to moderate wind speeds, as predicted by Bauer and Fox’s criterion [8]. Examples of two 1-ton releases right after valve opening and after pooling are shown in Fig. 2. The pictures on the left show a very large and flat ammonia cloud extended well beyond the pit; the bubble surrounding the tank is from a boiling liquid pool. The pictures on the right show the green chlorine cloud filled the pit. Both clouds persisted in the pit for more than 30 min due to a very low wind speed (<1 m/s). The extensive data from sensors in the tank and pit and videos were used to characterize each cloud or plume for this study [16–18]. Hanna et al. recently conducted a similar study applying the Briggs and Castro equations to their own Jack Rabbit source characterization [19].

2. Methods

This study determines if the source characterization for the chlorine and ammonia releases of the Jack Rabbit Test Program can be used with an ATD model to correctly predict the concentration data measured by sensors at various distances and orientations