

HOSPITAL RESPONSE TO CHEMICAL TERRORISM:

Personal Protective Equipment, Training, and Operations Planning

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ABSTRACT

Background: Hospitals removed from the immediate site of an incident involving a hazardous materials release, including chemical warfare agents, must develop emergency response plans (ERPs) to protect healthcare professionals if the hospital anticipates receiving potentially contaminated victims. The ERP must address OSHA, EPA and JCAHO requirements.

Methods: The VHA convened groups to develop a hazard and exposure assessment, identify actions for compliance with existing regulatory standards, and review site and operational planning issues. Exposure modeling results were used to derive relationships between operational parameters (time and distance from sites/sources) and potential exposure for healthcare workers.

Results: According to exposure modeling, level C personal protective equipment is adequate to protect hospital staff away from the chemical release site. Decontamination runoff and contaminated clothing should also be controlled to limit exposure.

Conclusions: Development and coordination of ERPs must include the local emergency planning committee, with clear assignment of tasks, locations, and training in order to prevent exposures to healthcare workers.

Key Words: Personal Protective Equipment; Hospital Emergency Response Plans; Chemical Warfare Agent

INTRODUCTION

Hazardous materials incidents have prompted the establishment of Occupational Safety and Health Administration (OSHA) and Environmental Protection Agency (EPA) standards [OSHA 1995a; USEPA 1989] as well as standard medical practices for incident response and surveillance of exposed workers [Favata and Gochfeld 1989; Gochfeld and Favata 1990; Melius 1986; Udasin, et al. 1991]. Although protocols have been developed for emergency medical response [Bronstein and Currance 1994], such guidelines are of little use for emergency room personnel as they do not provide any practical instructions on hospital-based procedures. Chemical release incidents are thought to be possible through many different scenarios and present numerous challenges to the facilities responsible for the treatment of victims. The accidental release of harmful materials in transportation events are frequent sources of exposure [Binder 1989; Hall, et al. 1994] and adverse health effects. In addition, chemical incidents related to terrorist acts may involve not only known chemical warfare agents (CWA) [IOM/NRC 1999], but the opportunistic use of commonly used and transported toxic industrial chemicals [ATSDR 2001a]. The possibility of such activities forces hospitals to develop emergency response plans (ERPs).

To aid in the development of emergency medical planning, detailed information is available on appropriate responses for both weapons of mass destruction (WMD) [ATSDR 2002; Lake, et al. 2000; Rogers, et al. 1990; SBCCOM 2002; Sidell, et al. 2002] and general industrial chemicals [ATSDR 2001a]. One relevant publication [Bronstein and Currance 1994] provides personal protective equipment (PPE) level guidance for chemical responses. The Agency for Toxic Substances and Disease Registry (ATSDR) [ATSDR 2002] recommends a “high level” of

PPE, i.e., self-contained breathing apparatus, be used at the scene of the release and in hospital emergency rooms when dealing with contaminated patients (refer to Table I for details of PPE levels). However, the emergency pocket card from the National Institute for Occupational Safety and Health (NIOSH) [NIOSH 2003] suggests that a lower level may be used where the exposure levels are known to be acceptable. The promulgation of new emergency planning guidelines by the Joint Committee on Accreditation of Healthcare Organizations (JCAHO) [JCAHO 2003] emphasizes the need for appropriate hospital action.

In the course of developing ERPs for chemical releases, including terrorist attacks, specific issues have arisen that warrant further attention [Brennan, et al. 1999; Huff 1991; Kirk, et al. 1994]. MacIntyre et al. [MacIntyre, et al. 2000] identified several areas in need of clarification or additional discussion, including victim decontamination, decontamination of wastewater, PPE level, and training. Discussion has focused on the level of PPE needed to protect healthcare workers as they treat contaminated patients [CDC 1997], including recent recommendations on the use of level B in emergency rooms [ATSDR 2001a; NIOSH 2003]. Appropriate training is an issue of particular concern, as some groups have argued that “contaminated patients” trigger the provisions of the Hazardous Waste Operations and Emergency Response Standard (HAZWOPER) [OSHA 1995a] as promulgated by OSHA. Although the need for hospital-specific guidelines addressing the issues of decontamination and PPE is recognized, the way in which local area and hospital operational strategies affect the level of PPE has not been scrutinized. Finally, discussions within several hospital systems suggested uncertainty about appropriate medical surveillance and clearance for work.

As a large integrated healthcare system, the Veterans Health Administration (VHA) must provide a certain level of central policy guidance for facilities. The system consists of 142 hospital systems (many with multiple campuses), 800 clinics, and 200 nursing homes around the United States, with approximately 210,000 healthcare workers. To identify and define needed resources, the VHA convened groups to develop a hazard and exposure assessment, identify actions for compliance with OSHA and EPA standards, review site and operational planning issues, and resolve medical testing issues. A detailed description of this process is available [Fedele, et al. 2003].

MATERIALS AND METHODS

Hazard identification

Hazards covered under the current assessment initially incorporated the traditional weapons of mass destruction identified as likely agents in the US Army Chemical Casualty Care Handbook [USAMRICD 2000]. Documentation such as the Army Field Manual 3-9, *Potential Military Chemical/ Biological Agents and Compounds* [US Army 1990] points out that industrial chemicals that are commonly transported may also be used as weapons. Therefore, situations relevant to several industrial chemicals [ATSDR 2001b; Binder 1989; Hall, et al. 1994] were also considered in the assessment. These agents represent a broad range of physical characteristics (vapor pressure), toxicology (dermal, systemic, respiratory effects), and exposure routes (dermal, inhalation).

Personal Protective Equipment: background

HAZWOPER activities require appropriate levels of PPE [Melius 1986] for defined conditions (refer to Table I for itemized list of equipment). However, the equipment is not easily compatible with medical operations [Bronstein and Currence 1994; Stopford 2001]. The self-contained breathing apparatus (SCBA) required for levels A and B adds 35 to 45 lbs to the back, creating physical instability and constraints due to weight and the added cardiovascular load. In warmer climates, heat illness also becomes a very serious concern [Beckett, et al. 1986; Favata, et al. 1990; Ferguson and Martin 1985; Paull and Rosenthal 1987]. In addition, SCBA precludes working for longer than permitted by the content of two containers, according to traditional operations guidance. Given time requirements for changing cylinders, individuals may work, at most, two 45-minute periods. The gloves used in levels A and B interfere with manipulation of

intravenous solutions and intubation in the absence of frequent drills. Visibility constraints resulting from protective face shields can further compromise the efficiency of medical personnel in level A or B equipment. Level C consists of air purifying respirators, inner and outer gloves, and chemical protective suits. Gloves may be less cumbersome than other constituents of protective equipment but are still not tight enough to support fine-motor manipulation in the absence of frequent practice.

The authors reviewed statutory language and compliance interpretations of pertinent standards from OSHA and EPA in order to identify constraints on planning.

Exposure modeling and operations

The authors identified conceptual models and derived equations to estimate source strengths and airborne concentrations of the chemical agent at a location removed from the site of release (please refer to Appendix for modeling details). The possibility of exposure to personnel at a healthcare facility arises as contaminated patients essentially become secondary sources of exposure. Many of the parameters involved in the determination of exposure are probabilistic in character. Therefore, Monte Carlo simulations were performed in order to obtain the estimates of time-integrated exposure concentration. Design Engineering's Crystal Ball 2000 Professional [Werckman, et al. 2000], a macro package for Microsoft Excel, was utilized in this effort. The modeling results and planning reconsiderations were then used to derive relationships between operational parameters (time and distance from sites and sources) and potential exposure for healthcare workers. Iterations using assumptions concerning exposure, operational planning, and control strategies identified critical "forcing" elements and produced guidelines for management.

The development of event operations and staging strategies is as important as the selection of PPE in reducing risk to healthcare workers. Potential sources, complicating parameters, and geographical relationships must be considered in the development of plans. For example, decontamination staff downwind of arriving victims may encounter a secondary exposure source. Exposure would arise from evaporation of agent from victims' clothing prior to disrobing and showering. Worst-case conditions are used to estimate an upper bound of exposure; if recommended decontamination procedures are followed, this scenario would be highly unlikely.

Medical programs

The medical program content herein was defined by reviewing the pertinent standards and professional guidelines; considering the levels of protection and decontamination required for effective medical care; and reviewing the scientific literature on appropriate medical surveillance.

RESULTS

Agents of interest and concern

Internal discussions and reviews of existing documentation previously described [ATSDR 2001b; Fedele, et al. 2003; Stopford 2001; US Army 1990; USAMRICD 2000] have identified agents of potential concern which encompass a broad range of physical characteristics (such as vapor pressure), toxicology, and exposure routes. Table II presents examples of CWAs with corresponding characteristics; water has been included as a reference. While the list is not all-inclusive, toxic industrial chemicals of interest also generally fall within the range of parameters described in Table II.

Statutory requirements and decontamination

Facilities may encounter two concerns as they plan chemical agent response. First, they must ensure adequate protection of their own employees under OSHA standards. Second, they must consider the effects on the environment under EPA statutes.

The requirement to use an SCBA during emergency response found in HAZWOPER Standard 29 CFR 1910.120(q)(3)(iv) [OSHA 1995a] applies to employees under the site specific Incident Command System (ICS) who are engaged in emergency response with the intent of handling or controlling the release and may be exposed to a hazardous substance presenting an inhalation hazard. OSHA has not yet determined how 1910.120 will apply to off-site hospitals and health care facilities. A review of existing compliance letters and interpretations suggests that all hospitals likely to treat victims of chemical incidents, especially involving WMD agents, must require the use of level B PPE when handling potentially contaminated victims. However,

based on the current study, PPE requirements for healthcare workers involved in patient decontamination and triage should be less stringent for several practical reasons. First, the primary source of chemical agent -- the terrorist device or transportation accident -- will no longer contribute to exposures. This assumption is valid in situations where the medical facility is not the site of incident. This notion further implies that the hospital workers responsible for treating contaminated victims will generally not be "at the scene." Finally, the time elapsed since exposure will have led to a reduction in the level of patient contamination, e.g. due to evaporation (or off-gassing) from the contaminated patient [Westin, et al. 1998].

As described in several OSHA standard interpretation and compliance letters, hospital personnel who decontaminate patients should be trained to first responder operations level (OSHA 1910.120(q)(6)(ii)) [OSHA 1992; OSHA 1999]. Health care workers' primary activities in such a situation would be clinical care and decontamination. Their inhalation and dermal exposures are likely to be substantially lower than those of the emergency responders actively participating at the site of the chemical release. OSHA is unable to define the contamination levels of patient(s) presented at hospitals post-release, and, therefore, whether level A, B, or C is the most appropriate level of protection [OSHA 2002b]. OSHA does not explicitly require the use of level B or A [OSHA 2002a], but compels hospitals to conduct a risk assessment to identify the types and levels of exposures likely in the workplace [OSHA 2002b]. If personnel are exposed to residual off-gassing from patients rather than to the active dispersal of a chemical agent, the risk assessment should focus on potential exposures given these specific circumstances.

In addition to the protection of employees under OSHA guidelines, the medical facility must also manage any possible adverse effects on the environment. The EPA issued a Chemical Safety Alert [USEPA 2000] to address the possibility of environmental degradation from contaminated runoff. Under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) § 107 (d) (1), the “Good Samaritan” provision protects emergency responders at the scene of the incident if they pollute through spilling decontamination water in response to imminent hazards. Such “Good Samaritan” language may protect emergency responders but does not absolve the need for emergency planning. If a healthcare facility recognizes the risk of such events and plans to receive patients, that facility must contain contaminated runoff (i.e. from decontamination showers and other cleanup efforts).

Site Operations Planning

Tasks for healthcare workers and others include security and crowd-control, decontamination, triage, and treatment in various settings. Clinical treatment guidelines after diagnoses are clear, and tools are widely available. In a true emergency, clinicians are unlikely to refer to textbooks. No clinical algorithms have been published to guide non-clinicians, but specific treatment is needed only for chemical asphyxiants (cyanide) and cholinesterase inhibitors (nerve agents) [ATSDR 2001c]. VHA assembled these instructions onto a “chemical agents” pocket card, in line with the format for its Clinical Practice Guideline support tools [VHA 2002]. Although VHA has distributed these to each physician and mid-level provider, the pocket card can also be downloaded from the internet at <http://ccl.rutgers.edu/chemcard/>.

Even though the clinical treatment guidelines are clear, discussions did reveal confusion regarding planning for decontamination, triage, and treatment at the local level. Despite the

availability of literature on the subject [Cox 1994], clothing removal in general has not been considered to be an essential first step in many settings. This important oversight can lead to unnecessary and preventable exposure to emergency transport personnel due to the presence of the secondary source, e.g. evaporation of a chemical agent from the clothes and skin of a contaminated individual [Torngren, et al. 1998]. Additionally, site operations planning must address decontamination runoff and contaminated clothing control as potential sources of secondary exposure [USEPA 2000]. Since planning for such incidents should be coordinated, the local emergency planning committees (mandated under CERCLA) provide an ideal setting to develop and plan coordinated responses and training that reinforces source control.

Chemical exposure incidents or terrorist events are likely to occur in high-density settings, such as crowds, public transportation, or stadiums. Traditional hazardous materials approaches define the site of such a release as a “hot zone”, or areas within a defined perimeter around an active release. “Warm zones” have lower level contamination and therefore necessitate lower levels of PPE. These conditions differ from those in hospitals, the “lukewarm” or “yellow” zones, where residual contamination of patients may pose a risk (see Figure 1 for a detailed illustration of these “zones”). The possibility exists that hospitals will be the direct site of a chemical attack and would therefore become a “hot zone.” Clearly, this scenario requires fundamentally different approaches and is not the situation addressed in the present study. Experience suggests that patients may arrive through planned or unplanned routes. In the former case, patients will likely have undergone some form of decontamination, although some of these patients may be incapacitated. In the latter situation, self-referred patients will seek aid wherever they perceive it to be available.

Modeling Results and Operational Impact

The modeling outcomes (details provided in Appendix) suggest several important operational implications. First the major predictors of exposure to healthcare personnel are (1) the time elapsed since exposure in the “hot” zone and (2) the amount of material remaining on the person. For all agents except sarin, doses delivered through airborne routes (i.e., off-gassing) five minutes *after leaving the scene should be negligible if clothing was removed at the scene* (see Table II). Recognition of an event, identification of transportation means, and transportation to a healthcare facility are not expected to take less than five minutes even under ideal circumstances. Only agents with a vapor pressure similar to water, such as sarin, might still volatilize from the skin and clothing at a sufficiently slow rate to place healthcare workers at risk after relatively short periods of time [Mioduszewski, et al. 1998]. Thus, source material needs to be removed from the victim as soon as possible, and the source material must be safely stored in approved HAZMAT containers away from the healthcare workers.

In mass casualty settings, many survivors have appeared in healthcare facilities through non-standard routes, bypassing the planned transportation pathways. It is likely that potentially contaminated patients, whether minimally exposed and healthy, or heavily exposed and acutely ill, will arrive in healthcare settings without clothing removal. Patients with heavy exposures and chemical loadings that may cause immediate health effects will be severely ill and would likely appear only in small numbers. Conversely, agents with very high characteristic times of evaporation (see Appendix for definition of the time constant τ), or low vapor pressure, may pose a hazard to patients but will not likely pose a threat to health care workers.

Second, as clothing is likely to contain a large fraction of the delivered dose, the clothing that remains on the victim, or that is not properly stored, is the next most important predictor of dose. If clothing is removed in the “hot” or “warm” zone, secondary exposures will be substantially lower. If not, clothing is a secondary source in the decontamination zone, and it requires an explicit exposure control strategy. This requires clothing removal and control immediately upon arrival at the decontamination scene (for example, preparing explicit instructions and planning an efficient delivery system). Some personal items, such as wallets, photographs, plastic glasses frames, etc. may absorb agents in a way that prevent decontamination and each must be discarded immediately. Valuables, such as wedding rings and precious stones, can likely be decontaminated. Facilities must plan to distinguish between items that can be decontaminated and those that should be discarded. Clothing must be stored in controlled settings away from people during activities. Plastic bags (3 or 6 ml) are likely to provide adequate protection for transport to storage but should not be relied upon for containment of agent. Therefore, a centralized HAZMAT storage container must be available near (but at a safe distance from) the actual decontamination and triage area for all bagged materials. Finally, waste disposal and site clean-up must follow strict hazardous waste operations protocols.

Third, during patient decontamination, both showering and effluent runoff may function as secondary sources of exposure; both require control. EPA mandates planning for runoff control [USEPA 2003]. Containment is necessary if real contamination is expected. Similarly, if serious contamination is anticipated, ventilation of the decontamination facility is necessary. Where such facilities are permanent hospital infrastructure, extra care must be taken to assure that no cross-contamination occurs in other parts of the facility, through drift from positive

pressure, re-entrainment into air intakes, or inadvertent recirculation. Portable units, including tents, have substantial advantages for terrorist events since cross-contamination is less likely. A schematic of the recommended approach to patient receipt, clothing removal, decontamination and triage is shown in Figure 1.

Understanding exposures requires the use of “near field” microscale models rather than regulatory atmospheric dispersion models [Bacon 2000; Fernando, et al. 2001; Georgopoulos 2002; Kukkonen, et al. 2001; OFCM 1999; ORD 2002]. There are no existing simple/regulatory models valid to the 1 m scale in a realistic setting, i.e. near buildings, with moving vehicles, people, etc. In fact, understanding the dynamic patterns of sources and resulting concentrations in complex outdoor and indoor microenvironmental settings requires Computational Fluid Dynamics (CFD) techniques that account for local mechanical and convection effects on the transport and deposition of contaminants [Bennett, et al. 2000; Hayashi, et al. 2002; Winters and Chenoweth 2002]. Not only do site operations and layout affect exposures, but human movement and posture will also affect contaminant transport patterns. For example, the “human plume” resulting from a thermal gradient producing convective turbulence, would likely enhance the release agent and move it along the body at about 50 L/s with a vertical speed of about 0.25 m/s [Settles, et al. 2001; Settles, et al. 1996] for a standing person.

Several aspects of local site layout can also affect predicted exposures. Orientation of the patient, i.e., lying vs standing, affects concentrations. Upright patients release concentrations along a longer pathway, yielding higher exposures to healthcare workers. The closeness of patients to each other, and up- and/or down-drafts of wind will influence exposure. The chaotic nature of

emergencies would most likely prevent the control of exposure via proper placement of stretchers and patients.

Medical Surveillance

Workers performing assessment and clean-up operations at hazardous waste sites and emergency response to hazardous substance releases have undergone medical surveillance examinations since several environmental disasters in the early 1980s. The practices evolved from an early document [NIOSH/OSHA/USCG/EPA 1985] and were initially codified in OSHA's Interim Final HAZWOPER Standard issued in 1986 [Melius 1986]. (OSHA's final standard, a revision of the Interim Final, was issued in 1989 and became final in 1990.) Practices have evolved since then and have been defined for a program to manage demilitarization of chemical warfare agents, namely the Chemical Stockpile Emergency Preparedness Program (CSEPP) [FEMA 2003]. Medical programs for hazardous materials handling serve two purposes: (a) fitness to work and (b) adverse health effect monitoring [Favata and Gochfeld 1989; Gochfeld and Favata 1990; Melius 1986; Udasin, et al. 1991]. OSHA defines requirements under HAZWOPER work (29 CFR 1910.120(q)(9) [OSHA 1995a]) for emergency responders.

Working in chemical protective suits with powered air-purifying respirators (PAPRs) generates three specific concerns: first, individuals working in chemical protective clothing appear to be at increased risk of heat illness, especially in hot climates. Physical conditioning and acclimatization appear to have few documented benefits [McLellan and Frim 1994] and are not likely to serve as a useful element to a hospital response program. Second, chronic diseases associated with impaired autonomic sensitivity warrant scrutiny [Beckett, et al. 1986]. Third, PAPRs, by themselves, really have no physiological contraindications, as there is no added

resistance such as described for negative pressure respirators [Hodous, et al. 1986]. However, discomfort from air streams passing the face may be severe enough to prevent effective work. This represents a psychological response that, together with claustrophobia, may preclude participation in a program. The weight of equipment is negligible, so that the cardiovascular concerns that arise with the use of SCBA in levels A or B are insignificant for level C PPE. In general, therefore, neither pulmonary nor cardiac contraindications should preclude wearing level C PPE, but heat illness monitoring programs are necessary. Of course, OSHA's Respiratory Protection Standard requirements for medical evaluation (29 CFR 1910.134 (e)) call for a medical assessment using a defined questionnaire or its equivalent and a follow-up assessment where appropriate [OSHA 1995b]. Spirometry is not a necessary element of such examinations although there are clearly defined responses and conditions under which it is appropriate.

Equally important is surveillance of health endpoints. Routine screening for pulmonary, dermal, neurological, and gastrointestinal effects represents important baseline documentation. Routine blood testing for such programs generally defines hematologic and hepatic functioning. Body-mass index, as a major contributor to liver test abnormalities, must be recorded. Biological monitoring for the many potential agents is impossible. After the fact, documentation of exposure, particularly for individuals who develop symptoms, should be an integral part of the incident resolution. For many, serial laboratory determinations, such as used for the documentation of cholinesterase inhibition and recovery [Coye, et al. 1987] are appropriate.

DISCUSSION

Based upon the current study, level C PPE will protect health care workers under the defined conditions and assumptions, i.e., the hospital itself was not the target of the terrorist attack and personnel are performing patient decontamination in the “luke-warm” zone, away from the site of the release. Still, use of level C requires prior planning and protocols at the facility as overexposures are possible. The following constraints must be addressed in planning:

Local: facility level

- Staff involved in handling potentially contaminated patients must have a clear understanding of the hazards of agents, broad syndromes associated with exposure, and treatment implications (pocket cards, emergency responders’ guides). They must have training in PPE and local plans (HAZWOPER ((q)(6)(ii)).
- Medical surveillance must address fitness to work and define baseline medical conditions. Blood and urine should be collected at the end of an incident to define levels of appropriate biological markers of exposure
- Level C ensembles (chemical protective suits, inner and outer gloves, and PAPRs) are adequate to protect healthcare workers away from the release of agents and after a 10-minute lag time.
- The HAZWOPER standard, and JCAHO planning, require a written ERP which should include the decontamination plan, PPE level, and emergency equipment.
- Local emergency response plans (HAZWOPER (q)(1) , (q)(2)) must focus on integrated site layout and operational strategies. A decontamination plan requires site layout that identifies a receiving area before the hospital, that focuses on rapid disrobing and

decontamination, and local storage of bagged source material (Figure 1). Prior to considering the location of staging and holding areas, their relationship to the emergency room/ambulatory care access site, and the intricacies of security and crowd control are essential to the success of decontamination. Clear, fast, and simple instructions broadcast by megaphone, to individuals or groups, are essential.

- Facilities must provide fans for air movement across disrobing / holding areas and in decontamination tents.
- Hospital staff in level C ensembles is inadequately protected to handle HAZMAT containers storing clothing and other items, and will not be trained in HAZMAT removal protocols. This work **MUST** be done by others.
- Bleach decontamination of corpses is likely to allow the deceased to be handled in a normal manner [Blewett, et al. 1992].

Local: area emergency planning committees

It is essential that local committees agree on protocols that require the removal of clothing prior to transport to healthcare facilities. This exposure reduction strategy will benefit emergency medical technicians and ambulance drivers and the receiving healthcare workers. This is the single most important control tactic. All responders must be trained to recognize that prompt removal of contaminated clothing is essential once victims have been removed from the site of ongoing release and before transport to a healthcare facility.

National level

EMT triage guidance should exist for the clinical presentations used by front-line workers. This is crucial for rapidly-acting nerve gases and chemical asphyxiants like cyanide. In general, other

agents require decontamination and supportive treatment but do not clearly benefit from additional pharmacologically justified treatment. Once detection equipment exists that is sensitive and reliable enough to guide exposure assessment and management, such front-line algorithms may be less important. First responders should distinguish basic syndromes (cholinergic toxidrome, chemical anoxia, mucosal irritants) and relay critical information on likely agents to the receiving healthcare facility.

LIST OF ACRONYMS

ATSDR	Agency for Toxic Substances and Disease Registry
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CBRNE	Chemical Biological, Radiological Nuclear and Explosive Materials
CSEPP	Chemical Stockpile Emergency Preparedness Program
CWA	Chemical Warfare Agent
D2PC	U.S. Army Personal Computer Program for Chemical Hazard Prediction
DOD	Department of Defense
EMT	Emergency Medical Technician
EOHHS	Environmental and Occupational Health Sciences Institute
EPA	Environmental Protection Agency
ERP	Emergency Response Plan
HAZMAT	Hazardous Material
HAZWOPER	Hazardous Waste Operations and Emergency Response
ICS	Incident Command System
JCAHO	Joint Commission on Accreditation of Healthcare Organizations
MMRT	Metropolitan Medical Response Team
NIOSH	National Institute of Occupational Safety and Health
NIST	National Institute for Standards and Technology
OSHA	Occupational Safety and Health Administration
PAPR	Power Air-Purifying Respirator
PPE	Personal Protective Equipment
SBCCOM	US Army Soldier and Biological Chemical Command

SCBA	Self Contained Breathing Apparatus
USAF	United States Air Force
VHA	Veterans Health Administration
WMD	Weapons of Mass Destruction

List of Symbols

$\frac{dm}{dt}$	evaporative flux of chemical agent [mg/m ² -min]
C_{vol}	volatility of chemical agent [mg/m ³]
v_{evap}	evaporation transfer rate [m/min]
m_0	mass deposition [mg/m ²]
τ	time constant of evaporation process [min]
A_w	area of column of air [m ²]
A_p	surface area of patient contaminated with agent [m ²]
u_w	wind velocity [m/min]
C	vapor concentration downwind of contaminated patient [mg/m ³]
CT	integrated exposure concentration [mg-min/m ³]
t_s	start time for integration [min]
LD_{50}	dose lethal to 50% of exposed population [mg]
LCt_{50}	concentration lethal to 50% of exposed population after 1 min exposure [mg-min/m ³]

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DISCLAIMER

The opinions, findings, and conclusions presented by the authors are not necessarily those of OSHA. Any mention of materials or products does not imply an endorsement by OSHA.

REFERENCES

- Arnold JL, Lavonas E. 2003. CBRNE - Personal protective equipment (<http://www.emedicine.com/emerg/topic894.htm>). e medicine.
- ATSDR. 2001a. List of chemical protocols in managing hazardous materials incidents, vol. 3 Atlanta, GA: Agency for Toxic Substances and Disease Registry.
- ATSDR. 2001b. Managing hazardous material incidents (MHMI). Volumes 1, 2, and 3 Atlanta, GA: Agency for Toxic Substances and Disease Registry (ATSDR), U.S. Department of Health and Human Services, Public Health Service.
- ATSDR. 2001c. Managing hazardous material incidents. Vol 3. Hospital Emergency Departments: Management Guidelines for Acute Chemical Exposures Atlanta, GA: US Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Regulation.
- ATSDR. 2002. Nerve Agents: Tabun (GA) CAS 77-81-6; Sarin (GB) CAS 107-44-8; Soman (GD) CAS 96-64-0; and VX CAS 5078269-9 Atlanta, GA: Agency for Toxic Substances and Disease Registry (ATSDR).
- Ayyub BM, McCuen RH. 2002. Probability, statistics, and reliability for engineers and scientists, 2d edition: CRC Press.
- Bacon DP. 2000. Chapter 4: Real time modeling and emergency response forecast. In: Boybeyi Z editor. Mesoscale Atmospheric Dispersion Southampton: WIT Press. p 171-192.
- Beckett WS, Davis JE, Vroman N, Nadig R, Fortney S. 1986. Heat stress associated with the use of vapor-barrier garments. *J Occup Med* 28: 411-414.
- Bennett JS, Feigley CE, Khan J, Hosni MH. 2000. Comparison of mathematical models for exposure assessment with computational fluid dynamic simulation. *Appl Occup Environ Hyg* 15: 131-144.
- Binder S. 1989. Deaths, injuries, and evacuations from acute hazardous materials releases. *Am J Public Health* 79: 1042-1044.
- Bjorn E, Nielsen PV. 1996. Exposure due to interacting air flows between two persons. *Proceedings of Roomvent '96, 5th International Conference on Air Distribution in Rooms* Yokohama, Japan. p 107 - 114.
- Bjorn E, Nielsen PV. 2002. Dispersal of exhaled air and personal exposure in displacement ventilated rooms. *Indoor Air* 12: 147-164.
- Blewett WK, Arca VJ, Rowan WA, Jones DW, Aleman R. 1992. Evaluation of a mortuary affairs collection point-decontamination: US Army Dugway Proving Ground.
- Brennan RJ, Waeckerle JF, Sharp TW, Lillibridge SR. 1999. Chemical warfare agents: Emergency medical and emergency public health issues. *Ann Emerg Med* 34: 191-204.
- Brockman JE. 1998. Removal of sarin aerosol and vapor by water sprays Albuquerque, NM: Sandia National Laboratories.
- Brohus H. 1997. Measurement of personal exposure using a breathing thermal manikin. *Proceedings of Ventilation '97, The 5th International Symposium on Ventilation for Contaminant Control, Global Developments in Industrial Ventilation* Ottawa, Canada. p 781-791.
- Bronstein AC, Currence PL. 1994. Emergency care for hazardous materials exposure, second edition St. Louis, MO: Mosby Lifeline.

- CDC. 1997. Personal protective equipment program (<http://www.cdc.gov/od/ohs/manual/pprotect.htm>): Centers for Disease Control and Prevention.
- Chen Q, Xu W. 1998. A zero-equation turbulence model for indoor airflow simulation. *Energy Build* 28: 137-144.
- Cox RD. 1994. Decontamination and management of hazardous materials exposure victims in the emergency department. *Ann Emerg Med* 23: 761-770.
- Coye MJ, Barnett PG, Midtling JE, Velasco AR, Romero P, Clements CL, Rose TG. 1987. Clinical confirmation of organophosphate poisoning by serial cholinesterase analyses. *Arch Intern Med* 147: 438-442.
- Fan Y. 1995. CFD modelling of the air and contaminant distribution in rooms. *Energy Build* 23: 33-39.
- Favata EA, Buckler G, Gochfeld M. 1990. Heat stress in hazardous waste workers: evaluation and prevention. *Occup Environ Med* 5: 79-91.
- Favata EA, Gochfeld M. 1989. Medical surveillance of hazardous waste workers: ability of laboratory tests to discriminate exposure. *Am J Ind Med* 15: 255-265.
- Fedele P, Georgopoulos P, Liroy P, Shade P, Hodgson M, Deitchmann S, Longmire A, Beatty J, Scott M. 2003. In-hospital response to external chemical emergencies: personal protective equipment, training, site operations planning, and medical programs (Draft Report) (http://www.vethealth.cio.med.va.gov/OSHTerr/ppeREPORT_FINAL_DRAFT_2003.04.16.pdf): ECBC, OSHA, NIOSH, VHA, and UMDMJ.
- FEMA. 2003. What is CSEPP? Washington DC: Federal Emergency Management Agency (FEMA), Office of National Preparedness.
- Ferguson JS, Martin WF. 1985. An overview of occupational safety and health guidelines for Superfund sites. *Am Ind Hyg Assoc J* 46: 175-180.
- Fernando HJS, Lee SM, Anderson J, Princevac M, Pardyjak E, Grossman-Clarke S. 2001. Urban fluid mechanics: Air circulation and contaminant dispersion in cities. *Environmental Fluid Mechanics* 1: 107-164.
- Fulco CA, Liverman CT, Sox HC. 2000. Chapter 5: Sarin. In: Fulco CA, Liverman CT, Sox HC editors. *Gulf war and health, Volume 1* Washington DC: Institute of Medicine, National Academy Press.
- Georgopoulos P. 2002. Human exposure modeling framework in support of emergency events: Source to dose. ORD Workshop: Environmental Monitoring and Modeling Associated With National Emergencies Research Triangle Park, NC: US Environmental Protection Agency - Office of Research and Development.
- Gochfeld M, Favata EA. 1990. Medical surveillance of hazardous waste workers: conclusions and consensus. *Occup Med* 5: 151-155.
- Grotte JH, Yang LI. 1998. Report of the workshop on chemical agent toxicity for acute effects Alexandria, VA: Institute for Defense Analyses.
- Hall HI, Dhara VR, Price-Green PA, Kaye WE. 1994. Surveillance for emergency events involving hazardous substances -- United States, 1990-1992. *Morbidity and Mortality Weekly Report. CDC Surveillance Summ* 43: 1-6.
- Hatch KL, Wilson DR, Maibach HI. 1987. Fabric-caused changes in human skin: in vivo stratum corneum water content and water evaporation. *Textile Research Journal* 57: 583-591.

- Hayashi T, Ishizu Y, Kato S, Murakami S. 2002. CFD analysis on characteristics of contaminated indoor air ventilation and its application in the evaluation of the effects of contaminant inhalation by a human occupant. *Build Environ* 37: 219-230.
- Hodous TK, Boyles C, Hankinson J. 1986. Effects of industrial respirator wear during exercise in subjects with restrictive lung disease. *Am Ind Hyg Assoc J* 47: 176-180.
- Huff JS. 1991. Lessons learned from hazardous materials incidents. *Emerg Care Q* 7: 17-22.
- Hurst CG. 1997. Chapter 15 - Decontamination. *The textbook of military medicine. Part I. Warfare, wweaponry and the casualty.* p 351-360.
- IOM/NRC. 1999. *Chemical and biological terrorism: Research and development to improve civilian medical response* Washington DC: Institute of Medicine, National Academy of Sciences.
- JCAHO. 2003. *Emergency management standards - EC.1.4 aand EC.2.9.1* Oakbrook Terrace, IL: Joint Commission on Accreditation of Healthcare Organizations.
- Jenkins RA, Buchanan MV, Merriweather R, Ilgner RH, Gayle TM, Moneyhun JH, Watson AP. 1992. *Protocol for determination of chemical warfare aagent simulant movement through porous media:* Oak Ridge National Laboratory.
- Karayannis A, Panagopoulos J, Koras A. 1997. Prediction of wind patterns in an urban environment. *PHOENICS Users Conference Seville.*
- Karlsson E, Huber U. 1996. Influence of desorption on the indoor concentration of toxic gases. *J Hazard Mater* 49: 15-27.
- Kirk MA, Cisek J, Rose SR. 1994. Emergency department response to hazardous materials incidents. *Emerg Med Clin North Am* 12: 461-481.
- Kukkonen J, Riikonen K, Nikmo J, Jappinen A, Nieminen K. 2001. Modelling aerosol processes related to the atmospheric dispersion of sarin. *J Hazard Mater* 85: 165-179.
- Lake WA, Fedele PD, Marshall SM. 2000. *Guidelines for mass casualty decontamination during a terrorist chemical agent incident:* U.S. Army Soldier and Biological Chemical Command (SBCCOM).
- Larson RC, Odoni AR. 1981. *Spatially distributed queues and the M/G/1 queueing system (Section 4.7).* Urban Operations Research Englewood Cliffs, NJ: Prentice Hall.
- MacIntyre AG, Christopher GW, Eitzen Jr E, Gum R, Weir S, DeAtley C, Tonat K, Barbera JA. 2000. *Weapons of mass destruction events with contaminated casualties: effective planning for health care facilities.* *JAMA* 283: 242-249.
- McLellan TM, Frim J. 1994. Heat strain in the Canadian forces chemical defence clothing: problems and solutions. *Can J Appl Physiol* 19: 379-399.
- Melius JM. 1986. Medical surveillance for hazardous waste workers. *J Occup Med* 28: 679-683.
- Mioduszewski RJ, Reutter SA, Miller LL, Olajos EJ, Thomson SA. 1998. *Evaluation of airborne exposure limits for G-agents: Occupational and general population exposure criteria* Proving Ground, MD: Edgewood Research and Development Engineering Center, US Army Chemical and Biological Defense Command.
- NIOSH. 2001. *Letter to all respirator manufacturers, attachment A:* National Institute for Occupational Safety and Health.
- NIOSH. 2003. *NIOSH emergency response ccard for sarin:* Centers for Disease Control and Prevention.
- NIOSH/OSHA/USCG/EPA. 1985. *Occupational safety and health guidance manual for hazardous waste site activities (also referred to as the "Four-Agency Document").*

- NPPTL. 2003. Statement of standard for chemical, biological, radiological, and nuclear (CBRN) full facepiece air purifying respirator (APR) - revised April 4, 2003 Pittsburgh, PA: National Personal Protective Technology Laboratory, Centers for Disease Control - National Institute for Occupational Safety and Health.
- OFCM. 1999. Directory of atmospheric transport and diffusion consequence assessment models Washington, DC: Office of the Federal Coordinator for Meteorological Services and Supporting Research.
- Ohbu S, Yamashina A, Takasu N, Yamaguchi T, Murai T, Nakano K, Matsui Y, Mikami R, Sakurai K, Hinohara S. 1997. Sarin poisoning on Tokyo subway. *South Med J* 90: 587-593.
- ORD. 2002. ORD workshop: Environmental monitoring and modeling associated with national emergencies. US Environmental Protection Agency - Office of Research and Development Research Triangle Park, NC.
- OSHA. 1992. Compliance interpretation letter to Howard Levitin, MD (http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=20911): Occupational Safety & Health Administration (OSHA).
- OSHA. 1995a. Regulations (standards - 29 CFR). Hazardous waste operations and emergency response: U.S. Department of Labor, Occupational Safety and Health Administration.
- OSHA. 1995b. Regulations (standards - 29 CFR). Respiratory protection Washington DC: U.S. Department of Labor, Occupational Safety and Health Administration.
- OSHA. 1999. Compliance interpretation letter to Daniel Burke, Safety Coordinator, St John's Mercy Medical Center (http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=22710): Occupational Safety & Health Administration (OSHA).
- OSHA. 2002a. Compliance interpretation letter to Francis Roth, Loss Prevention, Princeton Insurance, September 5 (http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=24516): Occupational Safety & Health Administration (OSHA).
- OSHA. 2002b. Compliance interpretation letter to Kevin Hayden, NJ EMS, Department of Law and Public Safety, September 30 (http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=24523): Occupational Safety & Health Administration (OSHA).
- Paull JM, Rosenthal FS. 1987. Heat strain and heat stress for workers wearing protective suits at a hazardous waste site. *Am Ind Hyg Assoc J* 48: 458-463.
- Raber E, Jin A, Noonan K, McGuire R, Kirvel RD. 2001. Decontamination issues for chemical and biological warfare agents: how clean is clean enough? *Int J Environ Health Res* 11: 128-148.
- Rogers GO, Watson AP, Sorensen JH, Sharp RD, Carnes SA. 1990. Evaluating protective actions for chemical agent emergencies: Oak Ridge National Laboratory, Prepared for the US Department of the Army and the Federal Emergency Management Agency (FEMA).
- SBCCOM. 2002. Guidelines for cold weather mass decontamination during a terrorist chemical agent incident: U.S. Army Soldier and Biological Chemical Command (SBCCOM).
- Settles GS, Ferree HC, Tronosky MD, Moyer ZM, McGann WJ. 2001. Natural aerodynamic portal sampling of trace explosives from the human body. FAA 3rd International Symposium on Explosive Detection and Aviation Security Atlantic City, NJ.

- Settles GS, Gowadia HA, Strine SB, Johnson TE. 1996. The natural aerodynamic sampling of trace explosives from the human body. In: Makky WH editor. Proc. of the 2nd FAA Symposium on Explosives Detection Technology and Aviation Security Technology Conference Atlantic City, NJ. p 65-70.
- Sidell FR, Patrick WC, Dashiell TR, Alibek K, Layne S. 2002. Jane's chem-bio handbook Alexandria, VA.
- Stopford B. 2001. Responding to the threat of bioterrorism: practical resources and references, and the importance of preparation. *J Emerg Nurs* 27: 471-475.
- Topp C, Nielsen PV, Heiselberg P. 1997. Evaporation controlled emission in ventilated rooms. Proceedings of Healthy Buildings/IAQ '97 Washington DC. p 557-562.
- Tornngren S, Persson SA, Ljungquist A, Berglund T, Nordstrand M, Hagglund L, Rittfeldt L, Sandgren K, Soderman E. 1998. Personal decontamination after exposure to simulated liquid phase contaminants: Functional assessment of a new unit. *J Toxicol-Clin Toxic* 36: 567-573.
- Udasin IG, Buckler G, Gochfeld M. 1991. Quality assurance audits of medical surveillance programs for hazardous waste workers. *J Occup Med* 33: 1170-1174.
- US Army. 1990. Potential military chemical/ biological agents and compounds Washington, DC: U.S. Army, Navy and Air Force.
- USAMRICD. 2000. Field management of chemical casualties handbook Aberdeen Proving Ground, MD: U.S. Army Medical Research Institute of Chemical Defense (USAMRICD), Chemical Casualty Care Division.
- USEPA. 1989. CFR Title 40 - Protection of environment. Chapter 1, Subchapter J - Superfund, emergency planning and community right-to-know programs, part 311 - Worker protection. Washington DC: U.S. Environmental Protection Agency.
- USEPA. 1997. Exposure factors handbook Cincinnati, OH: US EPA, National Center for Environmental Assessment.
- USEPA. 2000. First responders' environmental liability due to mass decontamination runoff: USEPA Office of Solid Waste and Emergency Response.
- USEPA. 2003. Chemical safety alert. First responders' environmental liability due to mass decontamination runoff: U.S. Environmental Protection Agency.
- VHA. 2002. Chemical terrorism pocket cards, 2nd edition: Veterans Health Administration, Office of Quality and Performance.
- Welty JR, Wicks CE, Wilson RE. 1984. Fundamentals of momentum, heat, and mass transfer. John Wiley and Sons: New York, NY.
- Werckman C, Hardy T, Wainwright E, Sargent R. 2000. Crystal Ball 2000 user manual Denver, CO: Decisioneering, Inc.
- Westin SN, Winter S, Karlsson E, Hin A, Oeseburg F. 1998. On modeling of the evaporation of chemical warfare agents on the ground. *J Hazard Mater A* 63: 5-24.
- Winters WS, Chenoweth DR. 2002. Modeling dispersion of chemical-biological agents in three dimensional living spaces Albuquerque, NM: Sandia National Laboratories.
- Yokoyama S, Kakuta N, Mizuta Y, Mabuchi K. 2002. Simulations of airflow and substance concentration around a human body. *J Physiol Anthropol Appl Human Sci* 21: 215-222.
- Zhu Z, McKnew MA, Lee J. 1992. Effects of time-varied arrival rates: an investigation in emergency ambulance service systems. Proceedings of the 24th Conference on Winter Simulation Arlington, VA: ACM Press.

Table I. Description of the levels of Personal Protective Equipment (PPE) as well as any inherent limitations.

Level	Elements	Protects against	Usual time required to put on and remove PPE	Maximal period available to work	Constraints
A B	Fully encapsulating for vapor barriers Self-contained breathing apparatus	All unknown agents	15 minutes	two periods of approximately 60 minutes ("featherweight" bottles, with bottle replacement time needs)	Cardiovascular risk; exercise limitations; physical instability; heat stress Visibility constraints in face shields (fogging; perimeter vision) Glove use (palpation, fine motor manipulation)
C	Negative pressure respirator or powered, air-purifying respirator Splash-protecting suits	Splash of liquids Some airborne hazards	1-5 minutes	8 hour shift with rest breaks for heat illness management (This is also a factor of the change schedule for the cartridge and varies by chemical compound.)	Heat illness Glove use (palpation, fine motor manipulation)
D	No respirator				

Table II. Summary of the properties of chemical warfare agents (CWA) and selected toxic industrial chemicals. Properties such as volatility (C_{vol}) and evaporation time constant (τ) indicate how quickly an agent will evaporate upon dissemination. The relative toxicity of an agent is given by its lethal concentration (vapor) or dose (liquid).

Agent Symbol	Agent	Cvol (25°C) (mg/m ³)	MW (g/mol)	τ^* (min)	τ^* (hr)	LCt50 (mg • min)/m ³	LD50 (mg)	LD50/100g
Cl	Chlorine	25000000	71	0.04	0.000667	19000		
CG	Phosgene	10000000	99	0.1	0.001667	3200		
AC	Hydrogen Cyanide	1080000	27	0.925926	0.015432	2000		
MIC	Methyl isocyanate	≈1000000	57.1	≈1	0.016667	2000-5000	60- 200mg/kg	
--	Water	22900	18	43.66812	0.727802			
GB	Sarin	22000	140	45.45455	0.757576	35	1700	59
GD	Soman	3900	182	256.4103	4.273504	35	350	286
HD	Sulfur Mustard	920	159	1086.957	18.11594	1000	1400	71
GA	Tabun	610	162	1639.344	27.3224	70	1500	67
GF	GF	581	180	1721.17	28.68617	35	350	286
VX	VX	10	267	100000	1666.667	15	5	20000

* See appendix for definition of the characteristic time constant τ .

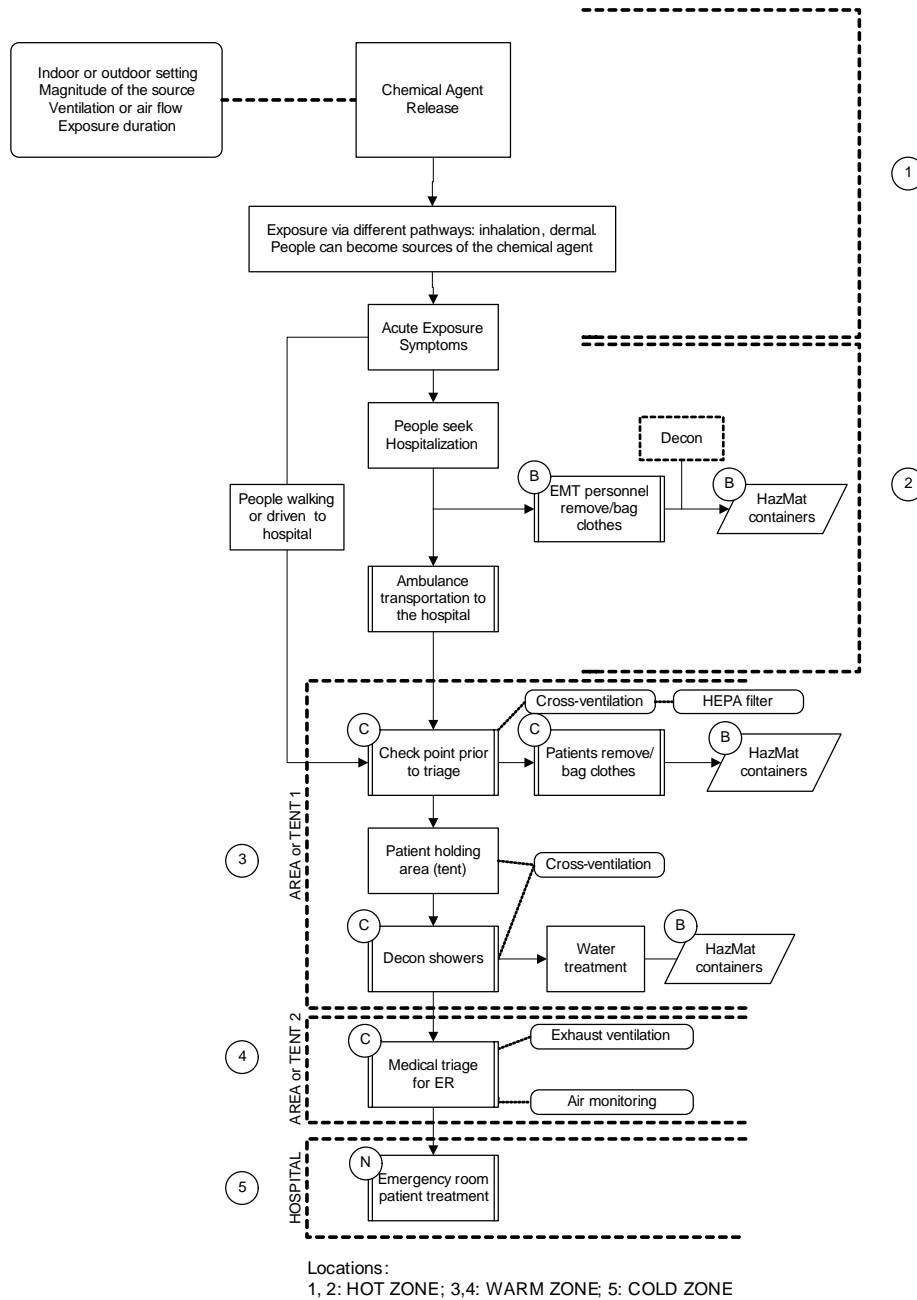


Figure 1. Emergency response steps for survivors of chemical attack seeking medical attention at hospital ER. The “hot” zone represents the site of the CWA release, while the “cold” zone is the area with no expected contamination. As the contaminated patients arrive at the ER (i.e. the “warm zone”), they become sources of contamination for the medical personnel. Exposure is limited by use of appropriate PPE.

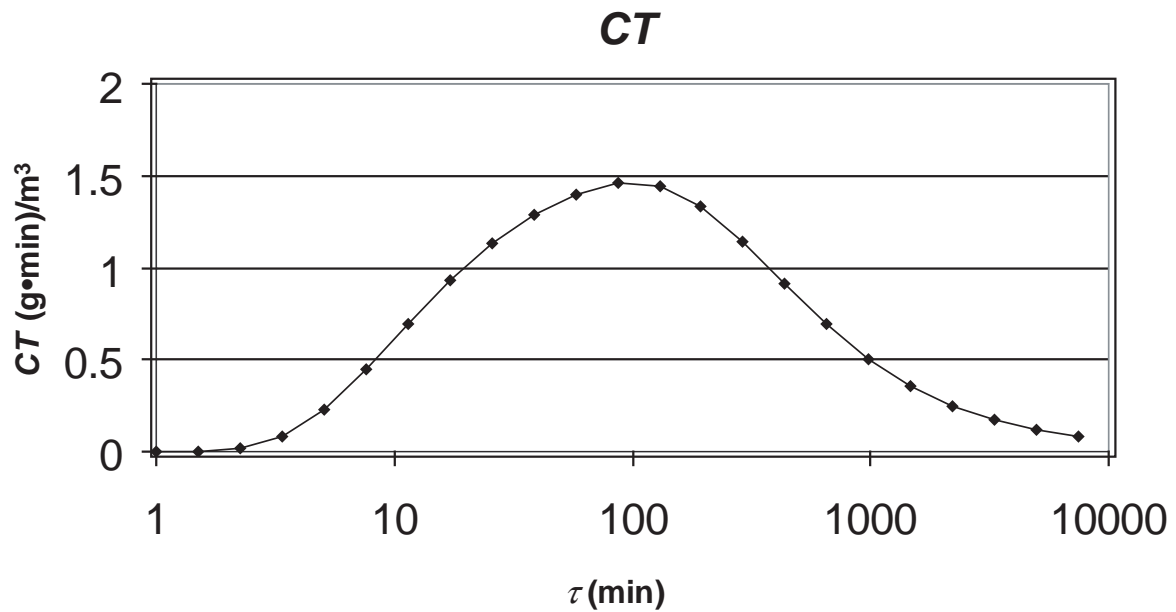


Figure 2. Total integrated exposure concentration (CT) of CWA for medical personnel as a function of the evaporation time constant (τ). The time-integrated exposure concentration is the sum of exposure concentration as contaminated patients file past decontamination staff. When τ is small the majority of the agent evaporates prior to arrival at the hospital; for agents with a larger τ , little agent will evaporate not only during transport, but throughout the decontamination process.

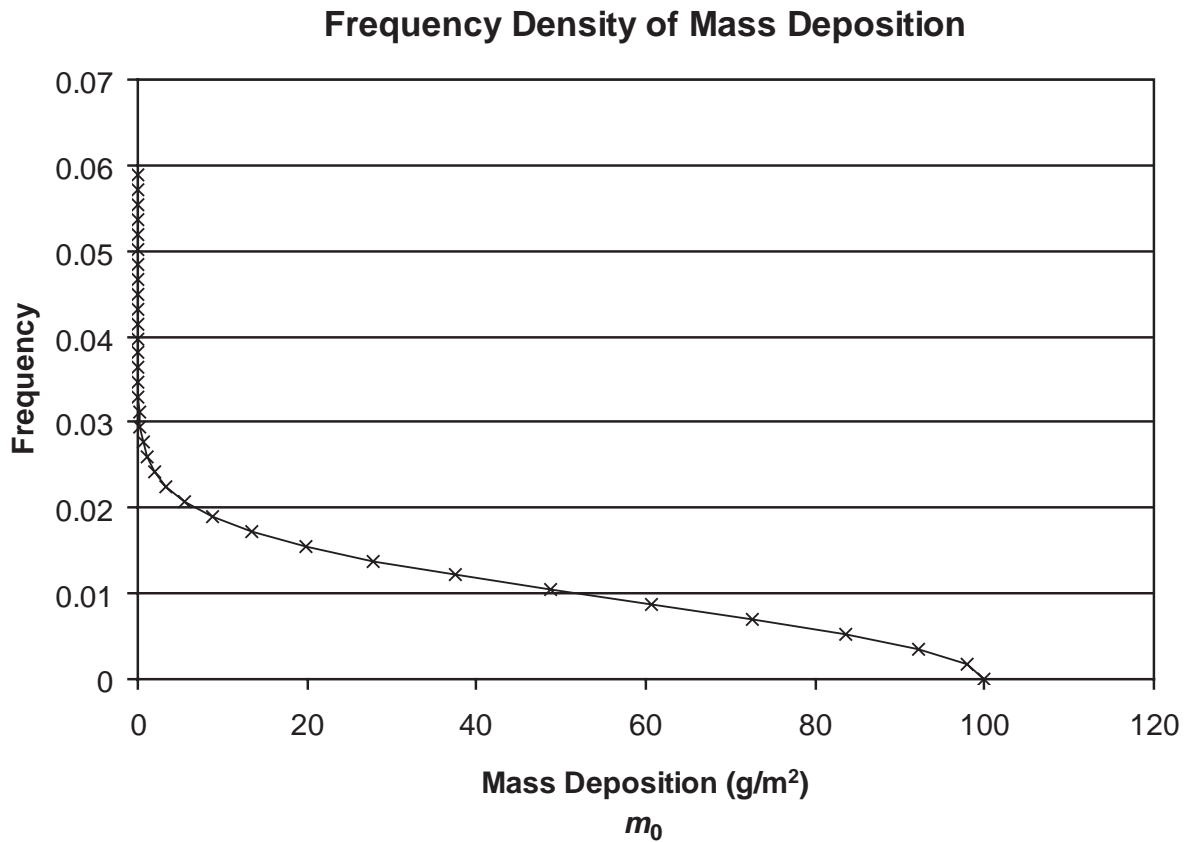


Figure 3. Frequency density of initial mass deposition (m_0) of sarin onto victims. This distribution describes the frequency with which victims will be contaminated with a specific amount of sarin. This situation depicts a uniform density of people where the likely mass deposition of the CWA increases as the radial distance increases from the dissemination device.

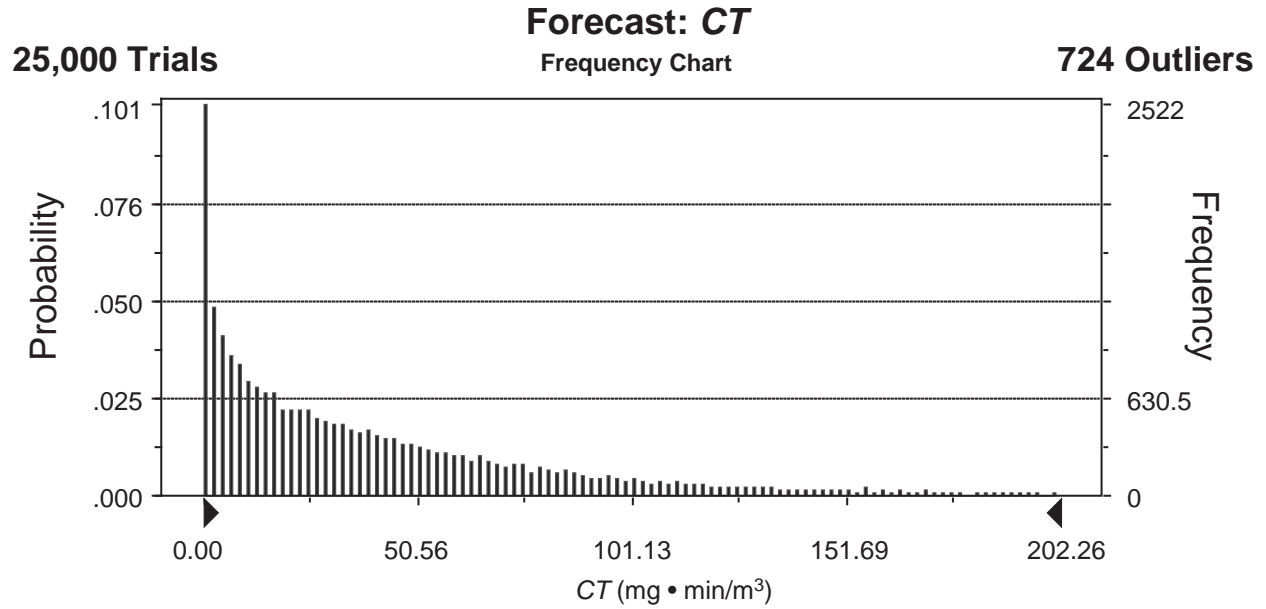


Figure 4. Monte Carlo forecast of total integrated exposure concentration (CT) of sarin when a triangular distribution represents the mass deposition (m_0). The time-integrated exposure concentration is the sum of exposure concentration as contaminated patients file past medical personnel. The contaminated body surface area is assumed to be 20%, which represents the potential exposure to healthcare workers when victims immediately disrobe.

APPENDIX: Hazard Assessment Modeling

In previous work, a reasonable maximum dose deliverable by terrorist devices was developed by Arnold and Lavonas [Arnold and Lavonas 2003]. Dissemination was modeled by SBCCOM [Fulco, et al. 2000; NIOSH 2001] to determine the maximum vapor concentration produced by typical devices. In addition, assumptions about battlefield chemical warfare agent exposure/dose delivery were reviewed and considered [Fulco, et al. 2000]. Agent exposures might occur through aerosol spray or vapor generation [US Army 1990; Winters and Chenoweth 2002], although condensation and evaporation may modify the dispersion of the airborne agents. An assumed reasonable upper bound of agent deposition on individuals is 100 g if the individual is in the direct line of dissemination. Table II provides the number of lethal doses for cutaneous toxicity [Grotte and Yang 1998] from 100 g of agent. In general, much lower exposure would be expected as most of the deposited agent will be on clothing [Jenkins, et al. 1992]. A practical limit also exists as victims who receive such high levels of lethal doses are not expected to survive. However, to ensure that the vapor hazard levels are reasonable maximum values, the influence of the agent on the individual victim is ignored. For sarin, which has a saturation concentration of over 20,000 mg/m³ at 25°C, a reasonable vapor concentration is 2,000 mg/m³ or less than one tenth of saturation [Mioduszewski, et al. 1998]. Therefore, the reasonable maximum concentration is not the absolute maximum that is physically possible, but rather a maximum that can be reasonably expected in a terrorist incident.

For the purpose of characterizing potential exposure to healthcare workers, an appropriate time period is assumed for transport to the medical facility. Given experiences in the release of sarin in the Tokyo subway [Ohbu, et al. 1997], discussions with emergency medical personnel, and

reviews of recent emergency planning for special events (e.g. major sporting events), ten minutes appears to be a realistic estimate and was selected as the average transport period.

Evaporation [Topp, et al. 1997] is assumed to begin after the conclusion of the dissemination and deposition processes and continues as victims travel to and arrive at the medical facility.

Evaporation prior to arrival and decontamination at the facility will limit hazards created by extremely volatile, quickly evaporating materials such as phosgene, chlorine, and hydrogen cyanide [Kukkonen, et al. 2001].

Agents will dissipate through both evaporation from free liquid surfaces [Topp, et al. 1997] and desorption [Hatch, et al. 1987; Karlsson and Huber 1996; Kukkonen, et al. 2001] from porous surfaces of clothing. Fedele, et al. [Fedele, et al. 2003] derived characteristic time constants for the evaporation of chemical warfare agents. The time constant, τ , is the time for approximately 63% of the current amount of material to leave the surface. In other words, the amount of material on the surface decreases by about 63%, every τ minutes, until the amount of material becomes negligible [Welty, et al. 1984]. This constant is defined in the following manner:

$$\tau = \frac{(m_0)}{C_{Vol} v_{evap}},$$

where m_0 is the amount of mass per unit area at which desorption begins to effect the evaporation rate, C_{Vol} is the volatility of the liquid, and v_{evap} is an empirically determined evaporation transfer rate.

Table II illustrates the range of τ values that apply to CWAs and some selected toxic industrial compounds. Compounds that are gaseous at standard conditions, such as phosgene, are expected

to evaporate from a liquid state in less than a minute. Water is expected to evaporate completely within hours, sulfur mustard within days, while VX would require years.

Agent that desorbs from a contaminated individual mixes into the passing air and is a secondary source to decontamination personnel standing near the victim. In order to estimate the vapor concentration downwind of the contaminated patient, additional parameters are taken into account. The evaporating agent is assumed to be uniformly mixed within a column of air that has a cross-sectional area (A_w) of about 1 m². An area, A_p , (also equal to about 1 m²) of the patient surface is assumed to be contaminated with the reasonable maximum amount of CWA from deposition (100 g). A low wind (or local air flow) speed (u_w) of 1 m/s is assumed.

Decontamination begins at a time t_s equal to the average transport period (i.e. ten minutes) and continues for six hours. The final expression for the integrated total exposure concentration [Fedele, et al. 2003] is then:

$$CT = \frac{m_0 A_p}{A_w u_w} \left(e^{-\frac{t_s}{\tau}} - e^{-\frac{t_s+360}{\tau}} \right).$$

The total concentration as a function of τ is shown in Figure 2. If τ is very small, the agent evaporates from the skin and clothing before the victim arrives at the medical facility and the potential exposure to medical personnel is limited. If τ is large, a small amount of agent will evaporate during transport to the medical facility. However, this expectation also implies a limited exposure to medical personnel as only a small amount of agent is expected to volatilize during the decontamination process. Agents with high toxicity and τ values similar to water can be expected to persist at the hospital site and thus would also represent potential hazards. Of the CWAs of concern, sarin, with its combination of toxicity and volatility, poses a realistic hazard after the estimated ten minute transport time. In this analysis of PPE requirements, the focus was

on the use of sarin as the worst-case scenario under the assumption that protection against this agent will protect against all others.

In the present modeling analysis, probability distributions were assigned to specific parameters to account for both uncertainty and variability. These simulations were then used to derive distributions of the potential exposure to decontamination staff. Initially, a bivariate Gaussian distribution served to describe the mass deposition on the victim population in a radially symmetric situation, where the greatest potential for contamination exists at the center. The standard deviation (σ) for the final distribution was chosen such that approximately 1 of every 4 or 5 (or 20-25%) victims is contaminated with a significant amount of agent. These probabilities were then used to generate a frequency distribution for mass deposition, as shown in Figure 3. This distribution was fit to a beta distribution which appropriately places the highest probability within the range of lower mass deposition of agent. As an alternative, a triangular distribution was also used to represent mass deposition, with a maximum value of 100 g of agent and a likeliest value of 10 g.

Evaporation, an important removal process, is controlled not only by molecular diffusion, but by macroscopic factors such as local air flows, temperature differences between the contaminated individual and the surrounding air, and proximity of other individuals [Bjorn and Nielsen 1996; Bjorn and Nielsen 2002; Brohus 1997; Chen and Xu 1998; Fan 1995; Yokoyama, et al. 2002]. These factors will increase the transfer rate of mass. Hence, simulations incorporated variability and uncertainty in transfer values by assigning a probability distribution to the evaporation rate with the value of 0.1 m/min as a lower bound.

Distributions were chosen for other parameters as well. Normal distributions described the exposed surface area of the patient (A_p) with a 1 m^2 mean [USEPA 1997] and wind (or air flow) velocity (u_w) where the mean is 60 m/min [Karayannis, et al. 1997]. The lag time from the initial dissemination of agent to the arrival time of the patient at the medical facility was represented with both a truncated normal and an exponential distribution (with mean value of 10 min) in the simulations [Ayyub and McCuen 2002; Larson and Odoni 1981; Zhu, et al. 1992].

Other factors in the analysis were held constant. The column of air into which the agent is mixed (A_w) was assumed to be a cross-sectional area of 1 m^2 . The volatility of sarin (C_{vol}) was also held constant. The 6-hour length of the decontamination process is based on the steps in the decontamination procedure and was held at this value as a conservative estimate [Brockman 1998; Cox 1994; Hurst 1997; Raber, et al. 2001]. Medical personnel were assumed to be wearing level C PPE, with a respiration protection factor of 1,000 and working for the entire six hour duration of the decontamination process.

A first set of Monte Carlo simulations was performed using the above defined parameters and assumptions with the maximum number of trials set to 25,000. According to the results obtained, in the absence of clothing removal, less than 2% of the trials resulted in a dose in excess of the NIOSH Chemical Biological, Radiological Nuclear and Explosive Materials (CBRNE) SCBA standard of $2.1\text{ mg}\cdot\text{min}/\text{m}^3$ [NIOSH 2001]. When more realistic distributions for evaporation transfer rate and lag time were incorporated, the percentage above the NIOSH CBRNE SCBA was reduced further.

As previously stated, the majority of the contamination resides on victims' clothing, which leads to the recommended decontamination process that requires disrobing as a first step in order to reduce the exposed surface area. Similar to the prior worst-case scenario, less than 2% of the Monte Carlo trials resulted in an exposure that required the use of an SCBA. When the contaminated clothing is immediately removed upon arrival at the health care facility, the level of sarin exposure to a healthcare worker is estimated to be negligible (see Figure 4).

Even if these exposures are doubled to account for "applied protection factors" or field performance, and to address the standard on "warm zone equipment", no overexposure is expected to occur that would require the use of an SCBA [NPPTL 2003].