Environmental Health Risk Assessment Methodology for Overseas Military Deployment

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The Johns Hopkins University School of Hygiene and Public Health is developing a framework for evaluating environmental health risks that may affect the health of military personnel deployed overseas. Based on quantitative risk assessment, traditional public health evaluation, and risk prioritization methods, this framework was originally designed by The Johns Hopkins University to assess environmental health risks in urban environments. The methodology is a three-tiered approach: Tier One focuses on short-term (acute) catastrophic risks, and Tiers Two and Three focus on longer-term health risk issues. A detailed description of the Tier One approach and a demonstration using U.S. data are presented in this article. (Keywords: Public health, Risk assessment, Risk prioritization.)

BACKGROUND

With few exceptions, toxic industrial chemical operations are found in every country around the world. Consequently, deployment areas are likely to contain numerous sources of potentially hazardous substances.

Military personnel deployed overseas could be exposed to environmental contamination as a result of routine industrial operations or mishaps in industrial complexes. Unintentional release of chemicals resulting from careless operating procedures, improperly trained operators, inadequate preventive maintenance, and equipment degradation poses realistic dangers. Examples of mishaps include the 1970 gas explosion in Osaka, Japan, that killed 92 people, the 1976 incident in Seveso, Italy, that resulted in human exposure to dioxin, and the 1984 methylisocyanate leak in Bhopal, India, that caused 2,500 casualties and 10,000 injuries.

Direct, intentional contamination of resources by enemy forces, environmental warfare, or terrorism also poses threats to the health of military personnel deployed overseas. The oil well fires during the Gulf War, dumping of pesticides into water supplies, ignition of pressurized fuels and industrial chemicals in storage, and chemical by-products due to a direct hit of munitions exemplify the intentional release of chemicals.

The Johns Hopkins University School of Hygiene and Public Health entered into an agreement with the

Defense Intelligence Agency Environmental Health Branch at the Armed Forces Medical Intelligence Center in September 1996 to develop a framework for evaluating environmental health risks that may affect the health of military personnel deployed overseas. The overall goal of the framework is to assist analysts and decision makers in evaluating both short-term (acute) and long-term (chronic) health risks. The methodology will be developed with the Defense Advanced Research Projects Agency and APL. Once it is fully deployed, it will provide a supportive informational framework for development and application of battlefield sensors.

Chemical and biological warfare defense initiatives face a complex array of potentially harmful agents. Battlefield awareness of the potential signal-to-noise ratio of nonwarfare chemical hazards will greatly contribute to the removal of this threat in the planning and conduct of military operations.

APPROACH

The framework under development is based on a methodology for characterizing environmental health risks by identifying sources of exposure to contamination and evaluating potential health impacts in an urban environment. The presentation of multidimensional environmental data (e.g., air, water, and soil) and associated exposure and health risk information poses a difficult challenge in risk evaluation. The disparate data must be compiled in a format that is both understandable and useful to the scientific and technical community, to decision makers, and most importantly, to the public. A matrix that includes elements of quantitative risk assessment, health risk assessment, traditional public health evaluations, and qualitative risk ranking was developed to form a structure for collecting information and evaluating potential effects on human health.

Risk information, including source descriptions, environmental pathways, target populations, exposure estimates, health effects, and both qualitative and quantitative estimates of risks, are essential components of this matrix (Fig. 1). The three basic tenets of risk assessment, which are embedded in the matrix, are as follows: (1) identify potential hazardous sources, (2) describe the health implications of specific agents of concern, and (3) characterize the risks to potentially exposed personnel. While presenting multidimensional categorical information, the matrix maintains flexibility. It allows toxicological comparisons to be made among compounds and provides a structure for qualitative rankings of the overall risks posed by facilities and other sources of environmental hazards. The ranking of risks into categories of high, medium, and low is aimed at assisting decision makers in effectively developing and identifying strategies and approaches for reducing environmental health risks to the population. Because of the inherent scientific uncertainties in this process, an overall numerical ranking is not generated.

This matrix approach to characterizing and prioritizing industrial sources of environmental health risks in the urban environment is being applied to U.S. military personnel deployed overseas. The methodology has three tiers. Tiers One and Two focus on identifying potential sources of hazardous substances and characterizing likely scenarios where these substances may be of concern. Together they are designed to provide the basis for identifying information needs and supplying guidance for environmental sampling and exposure assessment strategies. While Tier One focuses on acute or catastrophic risks, Tier Two builds upon the findings of Tier One to develop a more comprehensive framework to assess both immediate (noncatastrophic) and chronic (delayed) risks. For Tier Three, the intent is to refine the information gained through the previous tiers, building upon exposure and risk estimates to develop approaches for understanding individual exposures and potential health impacts. The Tier Three method aims to assess the long-term health issues that include effects of cumulative exposures and exposures to mixtures, as well as risks from low-level exposures. The goal of Tier Three is to complement surveillance and epidemiological approaches to understanding and preventing health risks. This article focuses on the Tier One methodology.

Tier One Methodology

For each environment where military personnel are deployed, a catalog of potentially hazardous sources can be compiled by examining the following questions:

1. What do we know about the general environment, for example, about its demography, geography, and topography?
2. What is the industrial base of the region? What are the associated toxic chemical uses, and what hazardous waste disposal methods are in place? Are accidental releases anticipated?
3. Is there any information on the levels of chemicals in the environment, their industrial origin, and the corresponding human exposure?
4. Is there any surveillance information on industrial poisoning incidents, or are there case studies of illness caused by environmental and industrial contamination?
5. Where are the military and government installations, and what are some of the potential sources of hazardous substances?
6. What are the sources of energy: solids, liquids, gas, nuclear fuels?

Sources of Concern				
Substances of Concern				
Regulatory Concerns	Jurisdiction	Federal		
		State		
		Local		
	Compliance Status			
Types of Hazards	Aesthetic			
	Nuisance			
	Human Health			
		Health Guidelines	Acute Lethal	LD50[a]
				LC50[b]
				IDLH[c]
			Chronic	Q*[d]
				NOAEL[e]
				Rfd[f]
		Health Hazards	Acute	
			Chronic	Organ systems
		Exposure Potential	Amount Released	Pounds
				Gallons
			Contaminated Media	Air
				Surface water
				Groundwater
				Soil
			Environmental Persistence	Short term
				Persistent
				Bio-accumulative
			Pathway of Exposure	Air
				Drinking water
				Recreation
				Soil
			Exposure Routes	Inhalation
				Ingestion
				Dermal contact; absorption
			Nature of Exposure	Acute
				Chronic
		Human Receptor	Population	Size
				Age
				Gender
				Ethnicity
Rank of Concern		**High**		
		Medium		
		Low		

[a]LD50 = lethal dose 50
[b]LC50 = lethal concentration 50
[c]IDLH = levels immediately dangerous to life and health
[d]Q* = cancer potency factor
[e]NOAEL = no observable adverse effect level
[f]Rfd = reference dose

Figure 1. Environmental characterization matrix.

7. What are the potential agricultural hazards? Consider the following:
   - Inventory of types and amount of fertilizers used for the production of different crops (agricultural chemicals)
   - Inventory of different kinds of food processing plants and possible sources of hazards
8. What is the quality of the water supply?
9. What are the general waste disposal practices?
10. What are the demographic characteristics of the local and the deployed populations?
11. What are the leading causes of mortality and morbidity?

For most environments the list of potential sources is likely to be large. However, conducting a comprehensive health risk assessment for every potential hazardous source is neither feasible nor appropriate. It is essential that a risk screening approach be applied so that detailed assessments can be targeted for sources or sites presenting the greatest risk. Indeed, the Tier One methodology is an acute, or catastrophic, risk prioritization scheme.

Tier One has three components: (1) identify sources and substances, (2) evaluate the acute or catastrophic hazard potential of substances, and (3) link sources and substance toxicity/hazard and sources based on acute/catastrophic potential.

Component 1

Within the framework of Tier One, two levels of data are required: (1) types of industrial sources that may be present in the environment and (2) substances that may be associated with those sources. This information requirement could present an enormous challenge, particularly overseas where such information is not as readily available as it is in the United States owing to weaker environmental laws and limited reporting requirements. Although the first level of information needs to be gathered on a case-by-case, country-by-country basis, some information could probably be gleaned from the U.S. databases for the second level of data. For example, it is likely that chemicals found in a U.S. petroleum refinery will be encountered at non-U.S. refineries overseas.

To demonstrate how such a source and substance identification step should be carried out, the Tier One methodology accessed the Accidental Release Information Program (ARIP) 1996 data and the Standard Industrial Classification (SIC) system. ARIP is the U.S. national database that tracks accidental releases of hazardous chemicals at fixed operating facilities (i.e., stationary industrial plants as opposed to ship, rail, or pipeline). The ARIP database is collected and maintained by the U.S. Environmental Protection Agency (USEPA) as authorized by Public Law 101-584, under the Comprehensive Environmental Response, Compensation and Liability Act of 1980, and Public Law 101-144, the Superfund Amendments and Reauthorization Act of 1986.[1]

Using the 1996 ARIP database, a list of industrial sources that may pose acute or catastrophic threats was developed. These are sources that have reported at least one accidental off-site chemical release during the 10-year period from 1986 to 1996 (USEPA, personal communication, 22 September 1997). However, many of these sources have had multiple releases during that period. The rationale for using the ARIP data is that for an operation to have an accidental chemical release, it is likely (1) that the operation handles large quantities of the material, or (2) that the operation handles small quantities but at very high frequencies, or (3) that the operation is "sloppy." For any of these scenarios, a substance release can be viewed as a surrogate indicator of acute or catastrophic potential for the operation in question. From the ARIP database,[2] each source is tagged with the types and amount of chemicals that were accidentally released plus a 4-digit SIC code.

The SIC is the statistical classification standard established by the U.S. Office of Management and Budget, which assigns an industry number to businesses and business units by type of economic activity.[3] The industry number reflects a 1- to 4-digit classification scheme, depending on how the business unit is defined. The classification covers the entire field of economic activities and defines industries consistent with the composition and structure of the U.S. economy (e.g., agriculture, forestry, mining, manufacturing, transportation, and utilities). The International Standard Industrial Classification System, developed by the International Labor Bureau of Statistics, provides a similar international industrial classification scheme.[4] Using the SIC database, sources identified by the 4-digit SIC code from the ARIP data set were classified into generic types of industrial operations, for example, petroleum refiners (SIC 2911) and industrial inorganic chemical manufacturers (SIC 2819).

It must be understood that the sources identified through the ARIP data are extremely limited and do not capture the universe of industrial operations. Furthermore, substances identified through ARIP that are associated with one type of industry in the United States may not be associated with a similar operation outside the United States. Nonetheless, the sources and substances compiled from ARIP serve as a starting point when there is no country-specific information.

Component 2

To evaluate the substance's acute/catastrophic hazard potential, the Tier One methodology requires the profiling of toxicity and physical hazard information for each substance. On the basis of the chemical hazard

Table 1. Criteria for assignment of flammability code.

NFPA code	Boiling point (°F)	Flash point (°F)
4	<100	<73
3	>100	<73
2	Not applicable	100–200
1	Not applicable	>200
0	Not applicable	>1500

Source: Ref. 9.

Table 2. Toxicity weighting algorithm.

Hazard ranking system proportional weighting	Oral LD50 (mg/kg)	Inhalation LC50 (ppm)[a]
1000	<5	<20
100	5–50	20–200
10	50–500	200–2000
1	>500	>2000
0	Not available	Not available

[a]Gas or vapor.
Source: Ref. 7.

profile, toxicity and physical hazard weights are then assigned to each substance.

Since the focus of Tier One is acute hazards with catastrophic potential, the Tier One methodology relies on oral LD50 and inhalation LC50 of the most sensitive rodent to characterize a substance's catastrophic toxic potential. LD50 is the statistically derived single dose of a substance that can be expected to cause death in 50% of the animals tested. Similarly, LC50 is the concentration of vapor or gas that can be expected to cause death in 50% of the animals tested.[5] Rodent toxicity data were gathered from the National Institute of Occupational Safety and Health Registry of Toxic Effects of Chemical Substances[6,7] and the National Institutes of Health/National Library of Medicine Hazardous Substance Data Bank.[8] The methodology also uses the National Fire Protection Association[9] (NFPA) flammability and reactive ratings or NFPA criteria based on flash and boiling points (see Table 1) to profile substance physical hazard potential. The NFPA flammability/reactive ratings are 4, 3, 2, 1, and 0, with a rating of 4 representing an extremely flammable/reactive substance and a rating of 0 representing a nonflammable/nonreactive substance.[9]

Two quantitative options for weighting substance toxicity and physical hazards include ordinal and proportional ranking systems. The NFPA rating (i.e., 0, 1, 2, 3, 4) is an example of an ordinal system. Under the ordinal system, a rank of 3 to chemical A and 1 to chemical B does not mean chemical A has effects that are 3 times more severe than chemical B. The mathematical functions involving these two scores convey information only about the order of severity and not about proportional magnitude. The proportional weighting system uses order of magnitude weights (e.g., 1000, 100, 10, 1). This order of magnitude weighting system attempts to incorporate more information about the proportional differences between chemicals but does not imply accuracy where such accuracy does not exist. Defining the proportional categories of weights maximizes the use of available toxicity information. In addition, the order of magnitude rank is unlikely to change unless significant new and different toxicity data become available.[10] Therefore, the Tier One methodology uses a proportional weighting system to assign toxicity and physical hazard weights to substances.

For each substance, a proportional toxicity weight can be assigned using the weighting algorithm described in Table 2. This proportional weighting algorithm was derived from the USEPA's Hazard Ranking System for Superfund Sites.[11] For each substance that has a physical hazard profile, a comparable proportional physical hazard weight can be assigned using the weighting algorithm described in Table 3. The NFPA ratings of 0–4 are assigned proportional weights for consistency with the toxicity weights.

Component 3

The Tier One risk screening algorithm integrates information about sources, substances, amount released, and toxicity/physical hazard data. This algorithm assigns toxicity-volume and physical hazard-volume scores to all substances based on the following formulas:

$$\text{Toxicity-volume} = (\text{amount released}) \times (\text{toxicity weighting}) \quad (1)$$

and

$$\text{Physical hazard-volume} = (\text{amount released}) \times (\text{physical hazard weighting}). \quad (2)$$

For each industrial source, the substance-specific toxicity-volume and physical hazard-volume scores are then summed to develop the overall toxicity and physical-hazard scores, respectively. The algorithm used to

Table 3. Physical hazard weighting algorithm.

Hazard ranking system proportional weighting	NFPA code	Flammability criteria, boiling point (°F)		Flammability criteria, flash point (°F)	Reactivity criteria
1000	4	<100		<73	Readily explosive, highly reactive with water
100	3	>100 <100	OR	<73 >73	Explosive upon initiation with heat or pressure; highly reactive with water
10	2				Not generally unstable; reacts violently with water
1	1				Becomes unstable at high temperature or pressure; may react with water
0	0			1500°F for 5 min	Stable materials; not water reactive

Sources: Refs. 9 and 11.

derive the overall toxicity and physical-hazard scores for each source is summarized in Table 4.

On the basis of their overall toxicity and physical-hazard scores, industrial sources can be rank-ordered. Once rank-ordered, sources with the highest scores (hence, risks) can be identified. Sources can also be grouped into categories of acute/catastrophic risks—(1) very high, (2) high, (3) medium, and (4) low—using a distribution approach, such as

- Sources with scores in the upper 25th percentile as "very high" risk
- Sources with scores between the 50th and 75th percentiles as "high" risk
- Sources with scores between the 25th and 50th percentiles as "medium" risk
- Sources with scores in the lower 25th percentile as "low" risk

Demonstration

Following the Tier One process, toxicity and physical hazard information was profiled and toxicity and physical hazard weights were assigned to all substances found in the ARIP database. Subsequently, the Tier One risk-scoring algorithm was applied to generate two overall scores for each source in the ARIP database: (1) toxicity and (2) physical hazard. Table 5 provides an example of how these risk scores were derived for the wet corn milling type of industry (SIC 2046).

This approach was used to develop acute/catastrophic risk scores for all industrial sources in the ARIP database. Once scoring was completed, sources were rank-ordered on the basis of their scores. Ranking based on toxicity scores showed the following 10 types of industrial operations and their corresponding 4-digit SIC codes bearing the highest risk scores:

- Warehousing and storage of special products (SIC 4226)
- Petroleum refining (SIC 2911)
- Alkalies and chlorine manufacturing (SIC 2812)
- Liquified petroleum gas production and distribution (SIC 1321)
- Synthetic resins and plastics manufacturing (SIC 2821)
- Smelting (nonferrous metals) (SIC 3339)

Table 4. Scoring scheme for each industrial source.

Industrial source	Chemical substances	Pounds released[a]	Toxicity or physical hazard weight[b]	Toxicity or physical hazard score[c]
Source 1	$Subs_1$	X_1	Y_1	$X_1 \cdot Y_1 = S_1$
.	$Subs_2$	X_2	Y_2	$X_2 \cdot Y_2 = S_2$
.	$Subs_3$	X_3	Y_3	$X_3 \cdot Y_3 = S_3$
.	⋮	⋮	⋮	⋮
	$Subs_n$	X_n	Y_n	$X_n \cdot Y_n = S_n$
Source 1				
			Overall score	$\sum S_n$

[a]X_1 = pounds released for substance 1, and so on.
[b]Y_1 = toxicity or physical hazard weight for substance 1, and so on.
[c]S_1 = toxicity or physical hazard score for substance 1, and so on.

Table 5. Example of risk score derivation for wet corn milling (SIC 2046).

Substance	Pounds released	Toxicity weight	Toxicity-volume scores = (pounds released) × (toxicity weight)	Physical hazard weights	Physical hazard-volume scores = (pounds released) × (physical hazard weight)
Ethylene oxide	70	1000	70,000	1100	77,000
Propylene oxide	3,647	1000	3,647,000	1010	3,683,470
Sulfur dioxide	5,610,571	1000	5,610,571	0	0
Hydrochloric acid	288,850	1000	288,850,000	0	0
Sulfuric acid	28,110	1000	28,110,000	10	281,100
Sodium hypochlorite	10,170	1	10,170	0	0
Overall toxicity score			326,297,741		
Overall physical hazard score					4,041,570

- Wet corn milling (SIC 2046)
- Semiconductor manufacturing (SIC 3674)
- Industrial organic chemical manufacturing (SIC 2869)
- Industrial inorganic chemical manufacturing (SIC 2819)

These industries would be labeled as "very high" acute/catastrophic potential under the Tier One methodology. Among the chemicals that contribute these 10 industries' toxicity scores, the most common are ammonia, benzene, chlorine, chloroform, hydrochloric acid, hydrofluoric acid, hydrogen sulfide, and sulfuric acid. The wet corn milling industry was surprisingly ranked as "very high" because it has had large off-site releases of acute toxic chemicals such as sulfuric and hydrochloric acids during the 10-year period for which the ARIP data were analyzed. Table 6 provides a more detailed list of toxic substances associated with some of these industries.

When the ranking was based on physical hazard scores, the following industrial sources were identified as the top 10:

- Synthetic resins and plastics manufacturing (SIC 2821)
- Petroleum refining (SIC 2911)
- Aromatic chemicals, organic dyes, and pigments (SIC 2865)
- Wood preservation (SIC 2491)
- Petroleum product wholesalers (SIC 5172)
- Industrial organic chemical manufacturing (SIC 2869)
- Special products storage and warehousing (SIC 4226)
- Petroleum bulk stations and terminals (SIC 5171)
- Miscellaneous chemicals manufacturing (SIC 2899)
- Synthetic rubbers manufacturing (SIC 2822)

Substances such as butane, ethane, ethylene, hydrogen, methanol, and methyl chloride are common among the 10 industries with the highest physical hazard scores. The lists of substances with extreme physical hazards that determine the overall scores for several of these industries are provided in Table 7.

SUMMARY

Military operational environments, from humanitarian missions to combat, are becoming more dangerous simply because of the ubiquitous risks posed by environmental contamination. An increasingly important issue is the potential for exposure to chemical and physical hazards. Personnel deployed in support of missions ranging from war to peacekeeping may be exposed to harmful chemicals because of industrial accidents, sabotage, or the intentional or unintentional actions of enemy or friendly forces.

The environmental health risk assessment methodology described in this article provides a standardized and rational framework for the gathering of data, stepwise analysis, and aggregation of disparate information. The tiered approach is designed to capture both the near-term and long-term health risk issues. Particularly, the Tier One methodology requires (1) acquisition of source information and characterization of chemicals that may be associated with these sources, (2) evaluation of toxicity and physical hazards, and (3) aggregation of these data to prioritize sources into categories

Table 6. Substances of industries with highest overall toxicity scores.

Smelting (SIC 3339)	Wet corn milling (SIC 2046)	Petroleum refining (SIC 2911)	Alkalies and chlorine manufacturing (SIC 2812)	Synthetic resins and plastics manufacturing (SIC 2821)
Ammonia	Hydrochloric acid	Ammonia	Ammonia	Chloroform
Chlorine	Sulfuric acid	Benzene	Chlorine	Sulfuric acid
Nitric acid	Ethylene oxide	Chlorine	Chloroform	Acrylamide
Sulfuric acid	Propylene oxide	Hydrochloric acid	Hydrochloric acid	Acrylic acid
Calcium hypochlorite	Sodium hypochlorite	Toluene	Methylene chloride	Butyl acrylate
	Sulfur dioxide	Acetic acid	Sulfuric acid	Chlorotrifluoroethylene
Sulfur trioxide		Hydrazine	Ethyl chloride	Ethyl chloride
Trichlorosilane		Hydrofluoric acid	Ethylene dichloride	Formaldehyde
		Hydrogen sulfide	Biphenyl	Hydrochloric acid
		Naphthalene	Carbon tetrachloride	Methanol
		Phenol	Potassium hydroxide	Methyl methacrylate
		Sulfur dioxide	Sodium hydroxide	Vinyl chloride
		Chromic acid	Sodium hypochlorite	
		Butadiene		
		Cumene		
		Dimethyl sulfate		
		Dimethylbenzene		
		Ethanolamine		
		Furfural		
		Xylene		

Table 7. Substances of industries with highest overall physical hazard scores.

Petroleum refining (SIC 2911)	Aromatic chemicals, organic dyes, and pigments (SIC 2865)	Wood preservation (SIC 2491)	Special products storage and warehousing (SIC 4226)	Synthetic rubbers manufacturing (SIC 2822)
Dichloroethane	Ethylene	Butane	Methanol	Methyl chloride
Hydrogen	Naphtha	Creosote	Benzene	Ethylene oxide
Furfural	Creosote		Methylene chloride	Isoprene
Xylene	Acrylonitrile		Acrylonitrile	Styrene
Dimethylbenzene	Formaldehyde		Toluene	Butadiene
Toluene	Toluene		Sodium hydroxide	Acrylonitrile
Benzene	Cumene		Sulfuric acid	Chlorobenzene
Cumene	Chlorobenzene			Cyclohexane
Hydrogen sulfide	Maleic anhydride			
	Ethyl benzene			

of "very high," "high," "medium," or "low" catastrophic/acute risks. The progression from Tier One to Tier Two will allow potential longer-term health threats to be assessed. A key component of the Tier Two process is to provide guidance for "on the ground" environmental sampling and exposure surveillance strategies.

Ultimately, information from Tiers One and Two is refined in Tier Three to foster understanding of individual exposures to mixtures of low levels of contaminants (i.e., aggregate exposures) and health impacts (i.e., cumulative risks).

Overall, this methodology is a risk prioritization framework that aims to minimize diseases and illnesses to military personnel deployed overseas. It is a practical approach for identifying and prioritizing threats of hazardous chemicals, for evaluating the potential for exposure, and for characterizing risks, both quantitatively and qualitatively. We envision that exposure and risk information generated within this framework can be fed into a broader and more complex pre-deployment risk management process. In essence, this methodology can help facilitate the communication of risk information so that preventive medicine and operational planners can make informed choices that would promote mission success while minimizing adverse health outcomes.

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