4

Environmental and Exposure Pathways

Knowledge of environmental pathways is an important component of any strategy to protect the health of deployed forces. In the event of an overt attack with CB agents, inhalation, and to a lesser extent dermal, pathways are the obvious environmental pathways. However, when assessing lower level, longer term, episodic exposures to CB agents or TICs, persistent and indirect pathways must also be taken into account. In this chapter, some strategies are presented for developing a portfolio of and prioritizing a number of environmental pathways that could result in troop exposures.

Because assessing exposures at any given time to all CB agents is impossible, assessments must be based on priorities. The goal of a health-protective exposure assessment is to combine data on the concentrations of harmful agents with characterizations of troop activity to determine potential patterns of current and future exposures, as well as patterns of past exposures of individuals and/or groups. Meeting this goal requires (1) selecting the harmful agents to be monitored; (2) identifying potential environmental pathways; (3) detecting the presence of harmful agents along these pathways; (4) monitoring the agent concentrations; and (5) tracking the contact of troops with these agents at these concentrations.

ENVIRONMENTAL TRANSPORT, ENVIRONMENTAL PATHWAYS, AND EXPOSURE ROUTES

Exposure to CB agents is defined in terms of contact between the agent and the exterior surfaces of the body. Contact points include skin

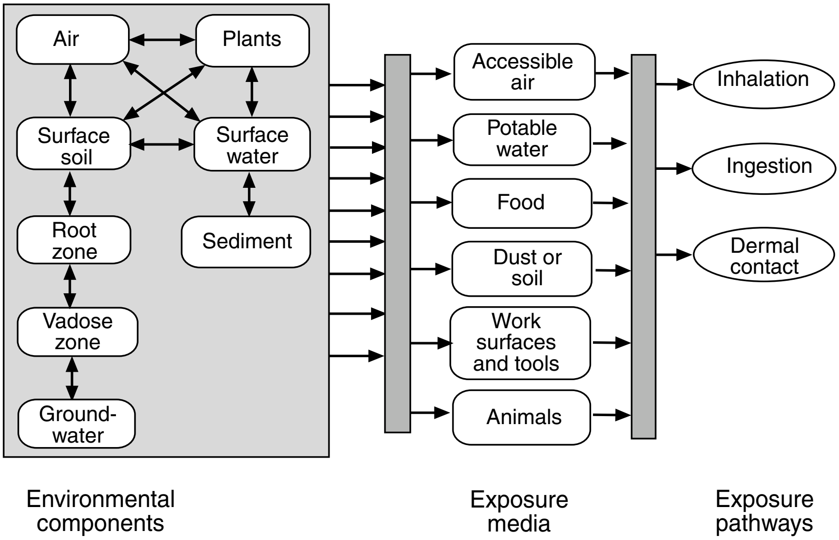

FIGURE 4-1 Links among environmental media, exposure media, and exposure routes. Source: Eisenberg and McKone, 1998.

and openings into the body, such as the mouth and nostrils. Exposure assessments often rely implicitly on the assumption that exposure can be linked, by simple parameters, to ambient concentrations in air, water, and soil. However, total exposure assessments also include time and activity patterns and microenvironmental data to provide a comprehensive view of exposure pathways and identify major sources of uncertainty. Figure 4-1 illustrates the links between ambient environmental media and exposure pathways that must be included in an exposure model.

For an exposure assessment, a harmful agent identified in one environmental medium must also be characterized in terms of its transport and transformation in that medium and its transport to other environmental media. The assessment should focus on areas with which deployed troops are most likely to have contact. For a meaningful characterization, the environment must be viewed as a series of interacting compartments. In this framework, one must then determine whether a substance will remain or accumulate in the local area of its origin; be physically, chemically, or biologically transformed in the compartment of its origin (e.g., by hydrolysis, oxidation, etc.); be transported to another compartment by cross-media transfer (e.g., volatilization, precipitation); and so forth.

An exposure assessment should focus first on contact media, which include the envelope of air surrounding a soldier; the water and food ingested; and the layer of soil, water, or other substances that contact the skin. The magnitude and relative contribution of each exposure route and pathway must be accounted for to assess total human exposure to a harmful agent and determine the best approach for characterizing the exposure. Consider, for example, exposures to a semivolatile hazardous air pollutant (e.g., an aromatic hydrocarbon) released to the ambient air. Once released, this chemical will partition between the vapor phase and the condensed phase (i.e., airborne particles). Both the vapors and the particles containing the pollutant can be transported to the indoor or outdoor air surrounding a person, who would then inhale the pollutant. The partitioning will ultimately affect the nature of the exposure.

The pollutant could also be transferred by deposition and runoff to surface water that provides drinking water. It could be transferred by deposition to vegetation that feeds humans or to vegetation that feeds the animals that supply meat and milk to troops. Each of these scenarios defines a pathway from the air emission to contact with a person, and each pathway has an associated route of contact. The true potential for exposure cannot be quantified until the pathways and routes that account for a substantial fraction of the intake and uptake for the receptor population have been identified. The likelihood of any pathway depends on the chemical properties of the substance released, where and how it is released, and environmental conditions. Sometimes the exposure increases along a pathway (e.g., bioaccumulation), but more often it decreases.

Defining and Ranking Required Information

Sources and emissions factors, transport and transformation processes, exposure scenarios and pathways, and routes of intake or uptake have all been identified as important components of an exposure assessment. The exposure characterization process can be short term (over a period of hours or days) or long term (over a period of months or years). The critical step is combining information on sources, emissions, transport, exposure media concentration, and activity tracking (locations and activities at different times). To facilitate this process, the factors that define an exposure event must be defined and ranked by their impact on health. Characterization should include the following factors (in descending order of importance):

1. agent physiochemical properties and concentration
2. exposure route

3. time/space scale of agent concentration
4. duration of exposure
5. time scale of potential health effects
6. contributing environmental media
7. exposure medium
8. demographic characteristics of the exposed individual (e.g., age, gender)

Exposure routes are the ways an agent can enter a person (e.g., by inhalation, ingestion, or dermal uptake). The route of exposure is very important in an exposure event. Inhalation is the most rapid route of uptake, followed by dermal contact and ingestion. The health effects may vary significantly among the exposure routes. The phase of the pollutant (vapor or condensed) is an additional factor that influences health effects from inhalation of an agent.

To construct a model to characterize an exposure event, the speed of movement and change in agent concentration of a CB agent cloud must be known. If a harmful agent cloud shows little change in agent concentration over a large sample area (even if the cloud is moving), this is an indication that the cloud is relatively remote from the source and is no longer expanding or rising rapidly. In this situation, a model of the plume can be constructed without detailed sampling over the large area.

If the concentration of an agent cloud does not vary significantly over time (even if it does vary over space), less time resolution would be necessary in modeling the cloud than if the concentration varies more quickly in time. However, the time of onset of health effects associated with an exposure also strongly affects the time resolution required to describe the effects of the exposure. For some warfare agents and many nonwarfare toxic chemicals, the number and duration of peak concentration must be estimated. To characterize the effects of hazardous agents with severe acute health effects, the aggregate effects of exposure over an hour or less must be estimated. For less toxic industrial chemicals, health effects may show up only after long-term cumulative intake.

To advance the science of exposure analysis in a way that will be useful to DoD, models and measurements must be integrated. Models provide a means of integrating and interpreting measurements, designing hypothesis-driven experiments, and predicting the effectiveness of risk management strategies. Measurements provide tests of models and "ground truth." Models are widely used and have been calibrated for limited situations for many exposure pathways. Nevertheless, because of uncertainties and inconsistent or incomplete data, these models are often not reliable enough for making predictions in a number of situations (NRC, 1991a, 1999c).

Sources and Emissions

Characterizing exposure pathways begins at the source of the agent release. In some situations, such as the intentional use of warfare agents, the source may be obvious and can be defined and characterized from air or soil concentrations. In many cases, such as contamination of water supplies and indoor exposures, sources and emissions may be multiple and poorly characterized. However, classification of a potential threat should, as much as possible, be based on the released volume, duration, and rate of emission, which can only be estimated by reconnaissance and observation.

Determining potential sources of CB agents must be based on established potential and detected actual use of these agents. This requires a combination of intelligence information on the potential use of the agents, rapid and accurate observation of delivery ordnance combined with visual observation of an aerosol cloud (if possible), and detection of agent concentrations in plumes or on surfaces.

Sources of environmental health hazards, such as endemic-disease organisms and industrial pollution in the theater of deployment, can be identified by several means. Information on disease patterns is typically available but must be given to the appropriate agency in order to begin monitoring. Industries, of course, are potential sources of contamination, and industrial production data by country and region are available in many areas of the world. The EPA has information on the types of chemicals used in many industries, as well as emission factors for these agents based on the production volume of the industry (Gratt, 1996). Geographical information systems and satellite images can be used to identify potential sources of pollution. These systems may also be able to locate hazardous waste dumps. Intelligence data can also be used to identify possible toxic sites. Chemical surveys are useful for confirming the existence and magnitude of many pollutant emissions. However, haphazard surveys that are not informed by other sources of information are not likely to find hot spots unless a large number of samples has been collected over a large region.

Stores of chemicals (e.g., above-ground storage tanks) provide targets of opportunity and potential sources of agents. Identifying such sources in a theater of deployment requires a prior inventory of facilities that have industrial stores of harmful substances, such as large chemical stores (e.g., chlorine) and/or biological agents used in research and production. CB weapons production facilities and storage facilities are obvious sources.

Throughout the world, soils are contaminated to some extent from local, regional, and global pollution sources of both natural and human origin (McKone and Maddalena, 1997). The large number of industrial chemicals and pesticides used by deployed forces as part of deployment operations are sources of exposure that are difficult to characterize and, therefore, are generally poorly characterized. In many cases, assessing the source of exposure to these agents requires either detailed personal sampling or a systematic effort to define their use and exposure source. Characterization requires information on when, where, how, and how much of the chemicals are used in different situations based on the deployment supply manifest and troop interviews.

Surveillance could substantially enhance the amount of quantifiable information about the relative magnitude and duration of sources and exposures. For example, combining individual dose data with information on chemical use could shed light on where or whether a trend is developing. DoD will have to evaluate the likelihood of liability claims if detailed information on the array of industrial chemicals and other materials (e.g., pesticides) deployed with its forces is collected.

Environmental Transport and Transformation

DoD has a continuing need for data on the magnitude, extent, and causes of troop exposures and concentrations of CB agents and TICs. Yet much of the data now collected on environmental contaminants cannot be synthesized into any understandable form because of the lack of a comprehensive framework for evaluating chemical transport, transformation, and interaction over multiple media. For a comprehensive framework, DoD would have to take the following steps:

- Document and monitor geographic and time trends in exposures to chemicals and biological substances through multiple media (air, water, soil), multiple pathways (indoor air, house dust, food, tap water, etc.), and multiple routes (inhalation, ingestion, dermal uptake).
- Identify and gather critical data for linking exposure, dose, and health information in ways that enhance epidemiological studies, improve environmental surveillance, improve predictive models, and enhance risk assessment and risk management.
- Assess contaminant transport consistently over a wide range of time scales, from hours to years, and a wide range of spatial scales, from local to global.
- Account for the interaction and coupling of all media.

To define a strategy for detecting and monitoring CB agent concentrations, the pathway an agent takes from its source to the point of contact must be defined. In situations where troops face potentially lethal concentrations of CB agents, the exposure pathway can be simple and obvious. For example, for an aerosol, dermal contact and inhalation are the pathways. However, for low-dose exposures to CB agents and TICs, the pathways from source to contact can be more complex and less obvious. For example, CB agents released to the air can be deposited on the soil where they can give rise to low-dose exposures by inhalation through volatilization and resuspension, exposures by dermal contact when dust comes into contact with troops passing through the area, and exposures by ingestion if rainfall washes the agents into a nearby water supply. For many substances, including CB agents and TICs, inherent properties of the soil, (e.g., pH, moisture content, oxidation potential, etc.) can significantly affect the fate and redistribution of chemicals deposited on the soil. For many TICs, exposures can also result from multiple environmental pathways.

Transport and Dispersion in Air

Aerosols and gases in outdoor (ambient) air are dispersed by atmospheric advection and diffusion. Meteorological parameters have an overwhelming influence on the behavior of contaminants in the lower atmosphere. Among them, wind parameters (direction, velocity, and turbulence) and thermal properties (stability) are the most important. Standard models for estimating the time and space distribution of CB agents to the atmosphere are Gaussian statistical solutions of the atmospheric diffusion equation (Hanna et al., 1982; Pasquill, 1961; Turner, 1970).

Numerous computer programs are available and many papers have been published describing algorithms for assessing the dispersion of point, line, and volume air pollution sources. These models are widely used and have been calibrated in a number of situations. Nevertheless, these models are often not reliable enough to make predictions in a number of situations, such as for complex terrain, for urban environments, for various meteorological conditions (e.g., plume mixing down to the surface as the height of convective cells increases because of surface heating), or for situations where the interaction of the dispersed agent with ground and vegetation surfaces is strong.

Modeling the transport of hazardous materials will require much more analysis, particularly for chemicals that partition among multiple environmental media (e.g., air, soil, water, vegetation, etc.). For example, one of the key lessons from the Khamisiyah event in the Gulf War was that the very limited meteorological data, especially upper-air wind data, made it very difficult to predict a downwind concentration with any degree of certainty. This example points out the necessity of more reliable air-transport modeling for the short-term and

BOX 4-1 U.S. Demolition Operations at the Khamisiyah Ammunition Storage Point

Immediately after Operation Desert Storm, U.S. Army units occupied the area known as the Khamisiyah Ammunition Supply Point, which covers 50 square kilometers and contained about 100 ammunition bunkers and several other types of storage facilities. To demolish the site, U.S. forces set off two very large explosions, one on March 4, 1991, and a second on March 10, 1991. They also set off a number of smaller explosions to destroy small caches of munitions and to test techniques for destroying bunkers. Demolition operations continued in the area through most of April 1991.

Source: DoD, 1997b.

long-term transport of chemical agents and the need for accurate meteorological data (see Box 4-1).

Transport and Dispersion in Water

Ground and surface waters receive contaminants from many different sources. In many countries, domestic wastes constitute one of the largest sources of contaminants in surface streams and groundwater (Layton et al., 1993). Point sources, such as discharges of liquid wastes from domestic or industrial wastewater treatment facilities occur at a specific location (outlet) along a surface body of water. Nonpoint sources of water contamination usually originate from runoff from large urban and agricultural areas and are harder to characterize because of their diffuse nature. The behavior of chemicals and biological agents in surface waters is determined by two factors, the rate of physical transport in the water system and chemical reactivity (Schnoor, 1985). Physical transport processes are dependent to a large extent on the type of body of water (e.g., ocean, sea, estuary, lake, river, or wetland).

Dispersion on Land, Including Soil and Vegetation

The relative mix of air, water, mineral, and organic components in soil determines, to a large extent, how a chemical or organism added to soil will be transported and/or transformed. Soils are characteristically heterogeneous. Contaminants in soil can affect human health and the environment through a complex web of interactions (McKone and Maddalena, 1997). A number of competing processes influence the fate of soil contaminants.

Vegetation generally has contact with two environmental media, air and soil. Plant interactions with these media are not understood well enough to define an accurate method of predicting CB agent uptake by vegetation (McLachlan, 1995).

Surfaces

Transport onto and from surfaces is a potentially important pathway for exposures in both outdoor and indoor environments. Contaminants can accumulate from air, water, soil, and clothing on exposed skin and then slowly be transmitted to the bloodstream. CB agents, as well as TICs, can accumulate through deposition on the soil surface where these agents can come into contact with troops. These same agents and chemicals can accumulate on the surface of equipment and uniforms. Transport from these surfaces to humans can be an important mechanism for contact. To date, however, these processes have been poorly characterized (Zartarian and Leckie, 1998). A better definition of CB agent uptake from surfaces will require information on the frequency of contact (e.g., hand-to-surface contacts per hour or per day) and the kinetics of uptake during each contact.

Indoor Environments and Microenvironments

Human beings spend most of their time in indoor environments. Although time-activity data is not readily available for deployed forces, much of their time will be spent outdoors, but, indoor environments will also be important as microenvironments for many troops. Microenvironments include spaces within buildings, spaces inside vehicles and other enclosed spaces where troops can come into contact with environmental contaminants.

The transport of outdoor contaminants to indoor environments, and the resulting changes in contaminant concentrations, must be determined to assess potential exposures. For example, the relationship between the indoor and outdoor concentrations generally depends on the ventilation rate and the rate of removal in the building. Because of the high surface-to-volume ratio of building interiors, both particles and vapors can be removed from air by deposition on surfaces where they can be destroyed by surface reaction, by homogeneous chemical reactions, or by ventilation. Vapors sorbed on indoor surface materials can also be re-emitted to varying degrees (i.e., out-gassing), depending on vapor pressures and chemical reactivity. Thus, the removal and re-emission processes must be accounted for in predictions of indoor air concentrations.

Indoor and microenvironments may (1) offer some protection against certain agents, (2) be relatively neutral for other agents, and (3) actually amplify exposures for still other agents. The nature of the effect depends on the physical and chemical properties of the agent in question. Indoor environments offer some protection from agents that are present in outdoor air as aerosols or as highly reactive gases. Larger aerosols do not penetrate the building envelope as fast as gases. For reactive gases, protection is provided by the relative rates of penetration and reaction. For these gases, surface removal is important. Indoor environments offer little protection from gases or vapors that are relatively inert.

When a structure is erected over a contaminated site or when an agent is actually introduced within a structure or vehicle, the building or vehicle confines the agent so that the indoor exposure is greater than the outdoor exposure at the same location. For certain agents, the heating, ventilation, and air-conditioning (HVAC) system of mechanically ventilated structures may become a convenient delivery system for CB agents or even for TICs and endemic biological agents. In many structures, outdoor air intakes are readily accessible. Typical HVAC filters offer only fractional protection from aerosols and virtually no protection from gases or vapors. Indoor environments can be greatly improved if high-efficiency particulate air (HEPA) filters are used in the system, either singly or in banked systems, which could substantially reduce the biohazard and, with a long enough bank, the chemical hazard. "Arrays" of filters have been and are currently used to protect people in occupational and residential environments.

Transformation Processes

The transformation of chemical and biological substances in indoor and outdoor environments can have a profound effect on their potential for dispersion, persistence, accumulation, and exposure. Chemical transformations, which may occur as a result of biotic or abiotic processes, can significantly reduce the concentration of a substance or alter its structure in such a way as to enhance or diminish its toxicity or change its toxic effect. For example, for many airborne organic compounds, transformation processes, such as photolytic decomposition and oxidation/reduction reactions, can result in conversion to other compounds. For organic chemicals, a compound's half-life for any given transformation process provides a very useful index of persistence in environmental media. (Photochemical half-lives can vary from day to night, if they are less than about a day.) Specific information on the rates and pathways of transformation for individual chemicals of concern must be obtained directly from experimental determinations or derived indirectly from information on chemicals that are structurally similar. Consequently, quantitative estimates are difficult to derive for classes of compounds for which empirical data are lacking.

The magnitude and variation of transformation processes for CB agents and TICs must be better understood, measured, and cataloged. Variations in the rate of transformation in different microenvironments should be characterized. Characterizations should include measurements of transformation in different environmental media under different seasonal conditions and in different climates (e.g., deserts, jungles, temperate zones, etc.).

Exposure Routes

The exposure route refers to the way an agent enters the person during an exposure event. Exposure routes include inhalation of gases and aerosols, ingestion of fluids and foods, dermal contact with water or soil, dermal applications of creams, and other substances, medical inoculations, inoculation by a vector (i.e., an insect or tick bite), and sexual contact. The route of potential uptake is considered a very important attribute of an exposure event. Health effects of an exposure may vary significantly, depending on the exposure route. For example, most chemical warfare agents have lethal or incapacitating effects at much lower concentrations for inhalation than for dermal contact. For CB agents, the exposure medium and the exposure activity tend to be strongly associated with the potential route of intake. For example, the inhalation rate varies significantly with activity and location. Water, food, and soil are associated with the ingestion route and with eating and hand-to-mouth activities.

Data currently available on breathing rates and the relation of breathing rates to various activities have been summarized in the *Exposure Factors Handbook* (EPA, 1996b). Most ingestion exposures involve the intake of food or beverages. Hence, dietary information for troops that are or could be exposed to harmful agents in food and water should be documented. Quantitative estimates of dermal uptake should be determined for contact with harmful agents in dusts, soils, clothing, dermal creams, and water used for bathing and/or recreation. Present estimates include a rather large uncertainty because the processes are complex and have not been well characterized.

In summary, estimates of inhalation exposures to contaminated particles and gases require information on particle size distribution, as well as breathing rates associated with different physical activities. Information on dietary and water intake for deployed forces are necessary for assessing ingestion intakes. And, more experimental data and better models will be necessary to assess the dermal uptake of both chemical warfare agents and TICs.

Exposure Scenarios and Environmental Pathways

An environmental pathway is the route of a CB agent from a source to a person. This pathway describes a unique mechanism by which an individual or population is exposed to CB agents originating from a defined location, microenvironment, or environmental medium. Exposure scenarios are used to define a plausible pathway for human contact. Health-protective strategies for limiting low-dose contact will require a comprehensive portfolio of environmental pathways and scenarios.

Direct Exposure Pathways

Exposures to CB agents at high doses or high dose rates are often associated with a single, relatively simple pathway. For example, the highest intake of chemical warfare agents released to air will be through direct inhalation or through eye contact. Other important exposure pathways would be the direct ingestion of contaminated water, transfer from ambient (outdoor) air to the indoor environment of buildings and vehicles, and transfer from ambient air to and through protective clothing.

Indirect Exposure Pathways

Exposures to CB agents at low doses and low dose rates are often associated with multiple, indirect, and complex pathways. For example, chemical warfare agents and TICs can be transferred from air to soil and then tracked into buildings and vehicles or deposited onto vegetation and transferred to food. The agents could also be deposited by direct deposition or by runoff from air to surface water and from there to water supplies.

Soil contaminants bound to soil particles can be resuspended and inhaled along with the fine particles to which they are attached. Inhalation of suspended particles can occur outdoors or indoors. In recent years, studies have shown that a significant fraction of the fine and coarse particles in the indoor environment originate from outdoor sources. Soil enters the indoor environment by processes such as resuspension, deposition, and soil tracking (i.e., the process by which soil particles are carried into the indoor environment by the shoes and clothing of human occupants).

Dermal exposure to contaminants in soil can occur during a variety of activities during a deployment. Adults who work outdoors can have rather high soil loading on their skin (McKone and Maddalena, 1997). Lipid-soluble chemicals have a strong tendency to move from a soil layer on the skin surface to the lipid-rich outer layer of human skin. However, the rate at which this transfer takes place is often very slow and could require hours or even days to reach equilibrium. Soil contaminants can be transferred to edible parts of vegetation from the root zone by root uptake and from the surface-soil layer by resuspension/deposition, rain splash, or volatilization followed by partitioning (McKone and Maddalena, 1997). Contaminants in vegetation can be transferred to food products.

The vapors of volatile contaminants can be transported through diffusion from the soil pore spaces into buildings. Defining the ratio of contaminant concentration in indoor air to observed contaminant concentration in soil gas requires three components: (1) the distance between the contaminant source and the building foundation; (2) the permeability of the soil; and (3) the area of cracks in the foundation relative to the total area of the foundation (Little et al., 1992).

POTENTIAL EXPOSURES, CLASSIFIED BY TIME SCALE AND PLAUSIBILITY

Exposures to drugs, chemical agents, biological agents, and combinations of agents have been suggested as possible causal factors of medical symptoms among Gulf War veterans (DoD, 1994). The number of harmful agents to which deployed forces can potentially be exposed is very large. To date, cumulative exposures experienced by military personnel during deployments have either not been characterized at all or have been poorly characterized. Medical surveillance has traditionally focused on infectious disease as the major cause of noncombat injuries and has paid little attention to the health effects of nonweapon CB exposures. In preparation for current and emerging exposure threats (both intentional and unintentional), a portfolio of exposure threats should be developed. Threats should be ranked by plausibility, temporal scale of contact, and health effects. Past experience can be valuable for developing and ranking threats. However, the portfolio should be expanded to include plausible threats that cannot be predicted from past events. This portfolio, which could be stored in a computer database, could be used by service schools, as well as for training, research, equipment development, and other purposes.

Past and Present Threats

Past experience has shown that defense personnel may be exposed to harmful agents as a result of number of events:

- intentional and unintentional actions of an enemy resulting in the release of TICs
- industrial or agricultural pollution "hot spots"
- actions by friendly forces
- actions by indigenous populations

Table 4-1 summarizes potential chemical exposures of deployed personnel according to three attributes: (1) the time scale of the exposure and health effects; (2) plausibility; and (3) whether the threat is intentional or unintentional. The plausibility of the scenarios in Table 4-1 is based on past experiences (GEO-CENTERS and Life Systems, 1997); combinations of scenarios in this table are plausible. For the purpose of strategies for exposure assessment, the scenarios are presented along a gradient of episodic (short-term) to long-term exposures. "CB agents used against U.S. forces" are in the same group as "accidents and mishaps" because both have the same episodic exposure assessment aspects. Mission-related exposures and common pollution of the local environment would be at the other (long-term) end of the spectrum.

All of the unintentional threat scenarios are likely to be experienced during any deployment. Unintentional threats are associated with any action by either the enemy or friendly forces that could cause unplanned exposures to harmful agents by either side. These actions could either cause the release of new agents to the environment or enhance the exposure to existing agents. For example, a combat action could rupture storage tanks at an industrial facility containing harmful chemical or biological substances.

Intentional threats are more likely to be associated with the overt use of CB weapons. These threats are likely to involve high-dose exposures and some precursor events to signal the use of these agents, such as the observation of a delivery system rocket or mortar and/or the observation of an unusual aerosol cloud (although CB aerosols are not directly observable once ejected from the source). Intentional threats are more likely to result in calls for detection and monitoring equipment.

Agents of Concern during the Persian Gulf War

Because a complex, although not unique, set of exposures was combined with psychological stress, the Persian Gulf tour was unique. Individuals were subject to severe psychological stresses upon entering the area because they had been given multiple vaccines and medications, were working long hours, and were living in crowded and often unsanitary conditions among flies, snakes, spiders, and scorpions (DoD, 1994). Chemical contaminants from oil fires, burning dumps (feces and trash), fuels, and solvents were ubiquitous. The climate was characterized by temperature extremes in a sand/dust environment, and the threat of CB warfare was always present.

Some of the chemical and biological exposures of concern involved Leishmaniasis, vaccines, desert sand, depleted uranium, paints and coatings, pesticides, petroleum vapors, and oil-well fires (NIH, 1994). Leish-

TABLE 4-1 Potential Exposures of Deployed Personnel

Scenario	Plausibility and/or Past Examples	Threat Category
Short-Term and/or Episodic Exposures		
CB agents used against U.S. forces: known agents and unknown synthesized agents.	Prevalence of CB agents and ease of synthesis and culture. Iran-Iraq War and Gulf War threat.	Intentional
Direct poisoning of resources (air, water, soil, or food) by enemy forces or terrorists.	Persian Gulf oil fires. Dumping of pesticides in water supplies. Ignition or pressurized release of fuels and industrial chemicals and munitions.	Intentional
Accidents and mishaps that release quantities of toxic substances or by-products into the environment.	Bhopal-type disasters. Transportation accidents. Spills and leaks from equipment or weapon systems (PEP hydraulic fluids, fuels, refrigerants, fire suppressants, etc.). Firefighting during damage control at industrial facilities.	Unintentional
Long-Term Exposures		
Collateral, intentional friendly forces emissions, discharges, etc., into the environment.	All intentional, unavoidable releases from all military operations during deployment.	Intentional
Mission- and job-related exposures during deployments and maintenance support activities by troops.	Hand-held or mobile weapons systems releasing chemical contaminants and by-products. Agent Orange exposures in Vietnam. Exposures to chemical agents in confined spaces (inside ships, submarines, tanks, aircraft, etc.).	Unintentional
Environmental exposures from nonmilitary activities causing pollution in an area of operations.	Air and water pollution. Hazardous waste sites. Contaminated soils and foods. Black market dumping of hazardous wastes.	Unintentional

maniasis is an infectious disease endemic to the Persian Gulf region. Desert sand and dust were dispersed into clouds by wind and mechanical disruption by vehicles resulting in ambient concentrations measured as high as a few milligrams per cubic meter. Depleted uranium in an aerosolized form, resulting from shell impacts and burning of the metal, provided a source of exposure for individuals in certain localized areas. Vehicles and equipment were painted with chemical-agent resistant coatings (CARCs), which contain toluene diisocyanate, either before being shipped to the Persian Gulf or at the port in Dammam/Dhahran. Pesticides and rodenticides were used to control vector-borne diseases. Records of the use of these agents were not kept, but their use was apparently unrestricted (NIH, 1994). Pyridostigmine was fielded as a "pretreatment" for nerve-agent poisoning in anticipation of chemical warfare. Troops were also vaccinated against expected infectious diseases, as well as against two biological warfare agents, anthrax and *Botulinum toxin.*

Exposures to petroleum vapors, solvents, and combustion products were common during the Gulf War deployment. Inhalation was evidently the dominant exposure route, but ingestion and dermal exposure were important in some circumstances. Diesel fuels and other petroleum products were used as sand/dust suppressants. Mobile armaments and transport vehicles used gasoline and diesel fuel. Kerosene, diesel fuels, and leaded gasoline were used for heating. Engine exhaust, the burning of petroleum, and the evaporation of petroleum products resulted in exposures to aromatic hydrocarbons, gaseous aliphatic and aldehyde compounds, and a great number of semivolatile organic compounds. Electric generators, which give off diesel exhaust, were often located near intakes for ventilation systems. In addition, oil-well fires produced soot composed of carbonaceous fine particles holding unburned hydrocarbons, PAHs from combustion, and metals. Oil-well fires produced dense clouds of soot, liquid aerosols, and gases.

Future Threats

Past experiences provide a general guide to future threats but not an accurate prediction of threats that can be expected in a given deployment. Anticipated CB agent threats, as well as industrial and environmental threats, must be continually monitored in potential theaters of combat through a combination of intelligence and research.

Ranking Potential Exposures Based on Dimensions of Harm

Allocating resources both in the field for reacting to potential threats and away from deployment areas for prioritizing R&D for new detection and monitoring technologies, requires classifying and prioritizing assessment capabilities. A useful approach to setting these priorities can be based on an index of hazard, such as the Dimensions of Harm Scale developed for the Deployment Toxicology Research and Development Master Plan (GEO-CENTERS and Life Systems, 1997). In this approach, the dimensions of harm are illustrated along three scales: (1) time to effect, (2) number at risk, and (3) severity of consequences. A potential exposure at the high end of the numbers at-risk and severity scales and at the low end of the time-to-effect scales should be given the highest priority both for detection in the field and for research to improve the detection.

MULTIPLE (CONCURRENT/SEQUENTIAL) EXPOSURES

In current and future deployments, troops are likely to confront some risk of exposure to CB agents. In addition, these operations will consume, produce, release, and dispose of multiple CB agents, giving rise to growing concerns about the hazards and risks of cumulative exposures to chemically and biologically toxic agents. Especially in the working environment, the health impact of long-term multiple-agent exposures has become an important issue of concern in academic research, as well as for workers and regulators. The important questions are whether and how these combined exposures interact. Measuring these interactions, which can be additive, synergistic, or antagonistic, will be an important aspect of monitoring the health of deployed forces and the key to understanding how to prevent and mitigate the effects of combined exposures.

Studies are likely to require the cooperation of agencies like CDC and the National Oceanic and Atmospheric Administration to construct models for predicting exposures. Because of the low levels of exposure and potential interactions, the extent to which epidemiological or toxicological studies can be used to identify and quantify interactions among two or more agents must be determined. In addition, the magnitude and variation of mixed-agent exposures in an actual population must be compared with the magnitude of exposures necessary to quantify different types of interactions.

In the past several years, efforts have been made to develop methodologies for risk assessments of chemical mixtures (e.g., EPA, 1986b). However, mixed exposures to biological agents and chemicals or CB agent exposures combined with exposures to intense noise and stress have not yet been addressed in any substantive way. Very little guidance has been provided on how to assess potential synergisms among these factors.

Monitoring and tracking exposures to multiple agents can easily become complex. If two agents interact synergistically, the characteristic time for the pharmacokinetics and pharmacodynamics of the two agents will first have to be defined. These times will be essential for defining the concentrations of the two agents in potential exposure media and for tracking the time/activity history of individuals who might be exposed to these agents concurrently and/or sequentially.

FINDINGS AND RECOMMENDATIONS

Finding. During a deployment, troops may be exposed to multiple harmful agents from multiple sources at various concentrations. Therefore, measurements and models must be designed to evaluate the factors that affect the multipathway intake of pollutants released from single or multiple sources. In preparing a detection and monitoring strategy for the large number of potentially harmful agents and the variety of pathways by which a person can come in contact with agents, priorities must be set on combinations of agents and pathways. Past experience can provide valuable information for ranking threats, but the list should also include plausible threats that have not been encountered in past deployments.

Recommendation. The Department of Defense should develop a portfolio of exposure threats that can be used to set priorities (based on the dimensions of harm), to distinguish between short-term and long-term hazards, and to establish plausibility. Developing this portfolio is likely to require the cooperation of other federal agencies, such as the Food and Drug Administration, the Environmental Protection Agency, the National Oceanographic and Atmospheric Administration, and the Centers for Disease Control and Prevention. The decision-making strategy should include probabilistic techniques to ensure that it is applicable to situations with many uncertainties and rapid changes.

Finding. Combined exposures to drugs, vaccines, chemical substances, and biological substances have been suggested as causal factors for the symptoms among Gulf War veterans, who had ample opportunities to be exposed to these substances in many different combinations. Interactions among these substances can be cumulative, synergistic, or antagonistic. The risk assessment community has done very little research to provide exposure assessments of the combined health impacts of even two interacting agents.

Recommendation. The Department of Defense (DoD) should begin scientific studies to measure interactions among chemical and/or biological agents and industrial chemicals. DoD's analysis of the effects of mixed-agent exposures should include toxicological studies on mixtures and epidemiological evidence of mixed-agent effects.