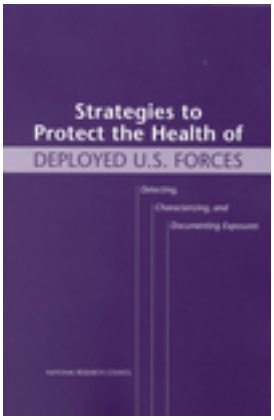

Strategies to Protect the Health of Deployed U.S. Forces: Detecting, Characterizing, and Documenting Exposures

Thomas E. McKone, Beverly M. Huey, Edward Downing, and Laura M. Duffy, Editors; Division of Military Science and Technology and Board on Environmental Studies and Toxicology, National Research Council

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and Laura M. Duffy, *Editors*

Strategies to Protect the Health of Deployed U.S. Forces:
Technology and Methods for Detection and Tracking of Exposures
to a Subset of Harmful Agents

Division of Military Science and Technology
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STRATEGIES TO PROTECT THE HEALTH OF DEPLOYED U.S. FORCES
Technology and Methods for Detection and Tracking of Exposures to a Subset of Harmful Agents

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Preface

Since Operation Desert Shield/Desert Storm, Gulf War veterans have expressed concerns about health effects that could be associated with their deployment and service during the war. Although similar concerns were raised after other military operations, the Gulf War deployment focused national attention on the potential, but uncertain, relationship between the presence of chemical and biological (CB) agents and other harmful agents in theater and health symptoms reported by military personnel.

A number of studies have addressed the issues of veterans' health and the potential health effects of their service, focused mostly on understanding the current health of veterans, ensuring that they are receiving appropriate evaluation and care, and determining the connections between veterans' current health status and service in, and specific exposures during, the Gulf War. As a result of these studies, the U.S. Department of Defense (DoD) has begun to focus more on better monitoring and control of exposures to multiple harmful agents.

Responding to this need, the DoD Office of the Special Assistant for Gulf War Illnesses, through the National Academies, sponsored Strategies to Protect the Health of Deployed U.S. Forces, a study that consists of four two-year studies followed by a consensus study. At the end of the second year (November 1999), the four study groups are issuing reports to DoD and the public on their findings and recommendations. These reports will then be used as a basis for a consensus study by a new National Academies committee in the third year of the project. The consensus committee's report will include the issues raised in the four

two-year studies, as well as overarching issues relevant to its broader charge.

This report, which is one of the four two-year studies, examines the detection and tracking of exposures of deployed personnel to multiple harmful agents. Unlike most National Academies studies, which are conducted by a committee led by a chair, this study was conducted by a principal investigator who was supported by a panel of technical advisors. As principal investigator, I worked with the National Research Council (NRC) staff to identify potential advisors, collect and synthesize data and information from relevant sources, and prepare this report, including its conclusions and recommendations. The members of the technical advisory panel participated in the report development process and the planning and management of workshops, the commissioning of papers, and gathering of information.

During this study, the panel, staff, and I received numerous briefings, visited facilities, consulted with experts, solicitated commissioned papers, attended symposia, and reviewed the open literature. Relevant sources of information used in this study include reports and databases from regulatory and research organizations, as well as information from experts in relevant disciplines. We visited and/or were briefed by individuals from numerous organizations, including the U.S. Army Soldier and Biological Chemical Command (SBCCOM), the U.S. Army Chemical School, the U.S. Army Center for Health Promotion and Preventive Medicine (CHPPM), the U.S. Army Center for Environmental Health Research (CEHR), and Brooks Air Force Base Crew Systems Division. Five meetings were held: one in March 1998 and one in August 1998, both at the NRC in Washington, D.C.; one at Woods Hole, Massachusetts, in September 1998; and two at the Beckman Center in Irvine, California, one in December 1998 and one in April 1999. A workshop was held in January 1999 at the NRC in Washington, D.C. At each meeting, the principal investigator, advisory panel members, and NRC staff attended presentations of technical information related to specific issues, were given briefings by DoD experts, and discussed key issues with invited participants.

The overall purpose of this study (discussed in Chapter 1) was to assess current and potential approaches to detecting and tracking exposures of deployed military personnel to a number of harmful agents. These agents include CB warfare agents, as well as environmental contaminants, such as hazardous air pollutants, soil contaminants, pesticides, particulate matter, fuels, metals, and microbial agents. This assessment also includes an evaluation of the efficacy and extent of implementation

of current military policies, doctrine, and training. Based on this evaluation, opportunities are identified for adjusting or augmenting strategies to improve the protection of military personnel in future deployments.

From the very beginning of this study, it became apparent that characterizing troop exposures requires many different types of information, as well as information collection and storage technologies. The focus of this study is on the overall practice of collecting, managing, and using information on potential exposures to deployed forces. The study addresses not only detection, monitoring, and tracking technologies, but also the framework in which these technologies are applied.

Understanding exposure requires knowing (1) which agents to look for; (2) whether, in what medium, and at what concentrations they were detected; (3) the space and time distribution of agent concentrations; and (4) the space and time distribution of the troops at risk. Tracking individuals and their exposures over time and space requires methods of determining and recording time-specific locations, detectors, and monitors, as well as methods of assessing harmful agent concentrations and environmental exposure pathways, including meteorological conditions over a wide area and, sometimes, groundwater-flow vectors. Detecting, monitoring, and tracking exposures of deployed forces to multiple agents requires making decisions with multiple, often competing, objectives. In response to a critical situation, the requirements for new equipment and monitoring must be defined and ranked according to the value of the information they will provide.

This study was completed with the full and timely cooperation of the DoD. Our requests for information were quickly and thoroughly answered. This made our work easier and our findings more credible. The members of the advisory panel and I were impressed with the level of research and development, training, and application that DoD is currently devoting to the issues addressed in this report. In fact, the rapid pace of change made it necessary for us to update and revise our findings continually, and many of the issues raised in this report may be resolved before the report has been widely circulated.

The report was refined and improved by reviewers both on the National Academies' staff and external to the Academies. Their thoughtful and constructive comments significantly enhanced the quality of the final report.

Finally, I gratefully acknowledge the work and support provided by NRC staff members: Beverly Huey, the NRC study director for this project, whose dedication, intelligence, and enthusiasm were invaluable; Jack

Downing, who spent long hours editing and revising initial drafts; Ray Wassel, who assisted in the development and preparation of this study; Norm Haller, who served as technical consultant; and Laura Duffy, who helped organize the multiple sources of information and was particularly adept at finding information resources on the Worldwide Web.

Thomas E. McKone
Principal Investigator
Strategies to Protect the Health of Deployed U.S. Forces: Technology and Methods for Detection and Tracking of Exposures to a Subset of Harmful Agents

Acknowledgments

We are appreciative of the cooperation we received from the many individuals and organizations who provided us with valuable information and guidance in the course of our work. First, we extend our sincere thanks to the members of the advisory panel who provided assistance and guidance during the information-gathering process, gave thought-provoking presentations in their respective areas of expertise, participated in briefings from various organizations, and provided thoughtful comments on the initial drafts of this report. We are deeply indebted to those individuals who prepared commissioned papers for our use and who gave presentations at the January workshop: COL Mike Brown, on predeployment operational decision making; Roy Reuter, on a situational framework for future deployments; Detlof von Winterfeldt, on dimensions of harm; Don Stedman and Murray Johnston, on the analysis of chemical detection technologies; Linda Stetzenbach, on the analysis of biological detection technologies; Peggy Jenkins, on strategies for tracking people; Michael Lebowitz, on tracking exposures; Keith McDonald, on GPS technologies; and Robert Spear, on GPS applications.

We are grateful for the guidance and support of others at the National Academies, including Joseph Cassells and Suzanne Woolsey, who assisted in the coordination of the four studies as they were being conducted simultaneously; Bruce Braun, who assisted in defining the scope of the study and provided ongoing oversight; and Douglas Bauer and Dennis Chamot, who adeptly dealt with stumbling blocks and provided

thoughtful insights. We also appreciate the work of Andre Morrow and Pamela Lewis, who provided administrative assistance in preparing this document for review and publication, and Carol Arenberg, who edited this document for technical content and clarity. Finally, we are indebted to numerous other National Research Council staff: Mike Clarke, associate division director; Margo Francesco, staff associate; Delphine Glaze, Tracie Holby, and Jacqueline Campbell-Johnson, senior project assistants; and Alvera Wilson, financial associate.

The extensive contributions and thought-provoking comments freely given by so many individuals throughout the course of this study enabled us to complete our task. We would like to acknowledge individuals who provided briefings, prepared commissioned papers, arranged site visits to their organizations, gave presentations at the workshop, supplied invaluable information and reports critical to our charge, answered our searching questions honestly, and assisted us in contacting other sources who could provide additional information and documentation. No doubt the list is incomplete, and we apologize for any oversights (see Appendix F).

This report has also been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the National Research Council in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

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While all of the advisors and the reviewers listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring principal investigator and the National Research Council.

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Box, Tables, and Figures

BOX

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Abbreviations and Acronyms

AC	hydrogen cyanide (blood chemical agent)
AEL	allowable exposure limit
ATOFMS	aerosol time-of-flight mass spectrometry
B(a)P	benzo(a)pyrene
CARC	chemical-agent resistant coatings
CATI	computer-assisted telephone interview system
CB	chemical and/or biological
CDC	Centers for Disease Control and Prevention
CEHR	Center for Environmental Health Research
CG	phosgene (chemical choking agent)
CHPPM	Center for Health Promotion and Preventive Medicine
COT	Committee on Toxicology
CX	phosgene oxime (urticant chemical agent)
DEHP	di-2-ethylhexylphthalate
DNA	deoxyribonucleic acid
DoD	U.S. Department of Defense

EC_{50}	the airborne concentration of a chemical agent sufficient to produce severe effects in 50 percent of those exposed for 30 minutes
ED_{50}	the amount of liquid agent on the skin sufficient to produce severe effects in 50 percent of the exposed population
ELISA	enzyme-linked immunoassay
EPA	Environmental Protection Agency
FTIR	Fourier transform infrared
GA	tabun
GAO	General Accounting Office
GB	sarin
GD	soman
GPS	global positioning system
H	Levinstein mustard
HAP	hazardous air pollutant
HCB	hexachlorobenzene
HCH	hexachlorocyclohexane
HD	distilled mustard
HEPA	high-efficiency particulate air filters
HL	mustard-lewisite mixture
HN	nitrogen mustard
HVAC	heating, ventilation, and air-conditioning
H_2S	hydrogen sulfide
ICt_{50}	the incapacitating effect of a vapor or aerosol agent, which is the product of the concentration and exposure time, sufficient to disable 50 percent of a group of exposed and unprotected personnel at an assumed breathing rate (active or resting)
ID_{50}	the dose in mg or mg/kg of liquid agent expected to incapacitate 50 percent of a group of exposed unprotected personnel
IDLH	immediately dangerous to life and health
IMS	ion mobility spectrometry
IPT	Integrated Product Team
JCS	Joint Chiefs of Staff
JSMG	Joint Service Materiel Group
JWARN	Joint Warning and Reporting Network

L	lewisite
LCt_{50}	a measure of vapor or aerosol agent lethality, which is the product of the concentration and exposure time that is lethal to 50 percent of a group of exposed and unprotected personnel at an assumed breathing rate (active or resting)
LD_{50}	a measure of liquid agent lethality; the dose in milligrams (mg) of liquid agent or mg of agent delivered per kilogram (kg) of body weight expected to kill 50 percent of a group of exposed, unprotected personnel
MICAD	multipurpose integrated chemical agent alarm
MIST	Man-in-Simulant Test Program
NBC	nuclear, biological, chemical
NHEXAS	National Human Exposure Assessment Studies
NO_x	nitrogen oxides
NRC	National Research Council
OSHA	Occupational Safety and Health Administration
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyls
PCD	phosphorous chemiluminescence detector
PCE	Tetrachloroethylene
PCR	polymerase chain reaction
PD, ED, MD	double chlorinated arsines
P-DCB	1,4-dichlorobenzene
PEP	propellants, explosives, and pyrotechnics
PIC	personal information carrier
PIDS	photo-ionization detectors
PIRS	photoacoustic infrared spectroscopy
PVC	polyvinylchloride
R&D	research and development
RfC	chronic reference safe concentration
RfD	chronic reference safe dose
RNA	ribonucleic acid
SAW	surface acoustic wave
SBCCOM	Soldier and Biological Chemical Command

TEAM	total exposure assessment methodology
TIC	toxic industrial chemicals
TIME	total isolated by microenvironment exposure (monitor)
TCDD	2,3,7,8 tetetrachloro-dibenzo-p-dioxin
TCE	trichloroethylene
TWA	time-weighted average
VX	nerve agent
VX2	binary form of nerve agent VX
Vx	volatile nerve agent similar to VX
VOC	volatile organic compound
VOI	value of information

Strategies to Protect the Health of Deployed U.S. Forces

Executive Summary

BACKGROUND

Since Operation Desert Shield/Desert Storm, Gulf War veterans have expressed concerns about the health effects associated with possible hazardous exposures during their service. In response, several expert bodies have conducted extensive studies and recommended improvements in U.S. Department of Defense (DoD) policies, procedures, and technologies for protecting military personnel during deployments. Recently, the National Academies was also asked to conduct an independent, external, unbiased evaluation of DoD's efforts to protect deployed forces and to provide advice on a long-term strategy for protecting the health of deployed U.S. military personnel.

The complete evaluation involves four areas: risk assessments; technologies for detecting and tracking exposures (the present study); physical protection and decontamination; and medical surveillance, record keeping, and risk reduction. These four preliminary studies will provide a basis for a synthesis report by a subsequent National Academies committee.

Task of This Study

The objectives of this study are listed below:

- Assess current and potential future approaches used by DoD for detecting and tracking exposures of military personnel to

potentially harmful agents, including chemical and/or biological (CB)[1] warfare agents and other harmful agents.

- Evaluate the efficacy and implementation of current policies, doctrine, and training and identify opportunities for adjusting or augmenting strategies to provide better protection in future deployments.
- Review and evaluate tools and methods for tracking and characterizing inventories of CB agents in the deployed theater; for tracking and characterizing the locations and time-activity patterns of deployed military personnel; for detecting and monitoring concentrations of potentially harmful agents; for estimating exposure concentrations and patterns of exposure for individuals or groups; and for implementation (e.g., documenting exposures).[2]

Conduct of the Study

The principal investigator, an expert in exposure assessment, conducted the study with the help of National Research Council (NRC) staff, who collected data, and an advisory panel that reviewed the report while it was being developed and furnished additional information. Other sources of information included reports and databases of regulatory and research organizations, experts in relevant disciplines, meetings with DoD representatives, and reviews of relevant documents (e.g., field manuals) and literature.

Study Approach

This study focuses on technologies for detecting and monitoring concentrations of agents and for tracking exposures of troops to those agents. The study also includes a review of the overall framework in which these technologies could be used. No attempt was made to assess the budgetary impact on DoD of adopting some or all of the recommendations in this report. The study excludes the many computing, information processing, data storage, and communications technologies being developed, mostly in the private sector. DoD's use of these technologies has been investigated in many other reports; and it is widely agreed that future military

[1] In this report, the acronym CB refers to chemical and/or biological agents that can be used as weapons.

[2] In this study, the terms *detecting*, *monitoring*, and *tracking* are differentiated as follows. *Detecting* is the process of determining the presence of agents. *Monitoring* is the process of collecting data to develop space and time profiles of agent concentrations. *Tracking* provides information on both the geographic locations of troops and on their activities at those locations (e.g., marching, operating inside a vehicle, sleeping in a tent, or eating).

systems for command, control, communications, intelligence, surveillance, and reconnaissance will require new technologies to meet the growing demand for sensor integration, high-speed data transport, additional data storage, and data distribution and analysis to achieve full, real-time, situational awareness on the battlefield and meaningful postdeployment assessments. If the recommendations in this study are implemented, they could add significantly to DoD's existing needs for improving computers, information processing and storage, and communications technologies.

This report is intended to assist DoD in coping with issues raised by exposures before, during, and after future deployments. Because data documenting past experiences are limited and variable, this report recommends a prospective strategy for handling exposure-related issues in future deployments.

Military Doctrine and Training

For many years the military has adhered to a doctrine of contamination avoidance, which involves four steps: (1) implementing passive defensive measures (e.g., camouflage, dispersion) to reduce the probability of exposures to CB agents; (2) warning and reporting attacks with CB agents to protect others who might be affected; (3) locating, identifying, tracking, and predicting CB hazards to enable commanders to decide whether to operate in spite of them or to avoid them; and (4) limiting exposures of personnel if operation in a contaminated area is deemed necessary. According to military guidance documents, avoiding CB hazards completely is the best course of action; but this is not always possible. Thus, military personnel are trained in the use of protective gear (e.g., masks and suits). Although operating effectively in a CB environment is extremely difficult, the military believes that well trained troops can survive and fight on a contaminated battlefield.

Although the military offers substantial guidance for protecting personnel against chemical attacks, it also acknowledges that its detection capabilities (especially for biological agents) are limited and is working to improve its equipment. As recently as 1996, troops were told to treat any future suspected biological attack like a chemical attack and to rely on protective masks, although then-current detector systems would not react to biological agents. Although contamination avoidance is still the guiding principle of CB doctrine, the military is also developing concepts for CB defense. The focus of CB defense will certainly change as technologies and threats evolve and as troops are deployed to areas where toxic industrial hazards are known to be present. Training goals for the future include virtual, live, and simulated training exercises, modeling and simulations (e.g., of agent dispersion), and specialized training in protecting troops against military and industrial toxic agents.

CHARACTERIZING EXPOSURES

Characterizing the effects of exposures to harmful agents is vital for defining the level of protection necessary for operations in contaminated areas and for providing postexposure medical treatment. Characterizing exposures requires detecting the presence of agents, assessing and monitoring agent concentrations, tracking time-specific locations of troops relative to these concentrations, and determining exposure pathways. Although all of these information sets are treated in this report, no single information set can provide sufficient information for characterizing exposures in real time or for completely characterizing potential or past exposures. As discussed below, information sets must be combined to be useful for decision makers.

Monitoring agent concentrations requires a system that can detect and record both concentrations and environmental factors, such as wind, that can affect the spread and concentration of agents. Perhaps the best way to monitor the movement of an agent is with a combination of a monitoring network and dispersion simulations. However, even detailed information on space and time distributions of concentrations is not sufficient to characterize troop exposures; the location of the troops in relation to the concentration, the rate and direction of their movements, and their degree of protection must also be known. Ideally, every individual should be tracked in real time, but this may not be practical in the near future. Modeling and war games can be used to help determine the feasibility of eventually tracking every individual. For now and in the near future, however, units could be tracked by tracking a representative sample of individuals in that unit.

DoD is aware that it must be able to anticipate significant exposures to CB agents and other harmful agents in future deployments. Therefore, DoD is currently devoting significant resources to improving its capabilities of anticipating health-threatening exposures. DoD is also aware of the need to collect and store information on low-level exposures to CB agents and other harmful substances. The low-level issue involves not only improved technology and equipment, but also interpreting trends from measurements collected near the detection limits of equipment and using exposure data for a representative fraction of the exposed population. [3]

[3] If tracking and exposure information on individuals could be temporarily stored and retrieved at a later date for historical purposes, this would alleviate the near-term problems of data overload and provide an option for determining later the effects on individuals of low-level exposures to CB agents. A high-capacity version of the Personal Information Carrier now under development by the Army might provide these capabilities.

Finding. To date, exposure assessments for both civilian and military populations have focused primarily on exposures to contaminants in a specific medium (e.g., air, water, soil, food) or on exposures to specific environmental pollutants. DoD's current plans for monitoring CB agents would also be limited to a specific medium and would not be time-space specific, would not include time-activity records, and would not account for both short-term and long-term exposures. These factors would only be included in settings where deployed personnel were active (in garrisons or in the field).

Most of the sampling protocols included in CB agent reconnaissance operations are designed to provide comprehensive area coverage, rather than statistical sampling or stratification. DoD has not systematically evaluated how modeling, simulations, and decision analysis could be used in real time to anticipate acute exposures (especially imminent threats). DoD's current capabilities and strategies have not been structured for making optimum use of these tools.

Recommendation. The Department of Defense (DoD) should devote more resources to designing and employing both statistical sampling and sample stratification methods. Two useful examples of probability-based statistical sampling are the National Human Exposure Assessment Studies (NHEXAS) and Total Exposure Assessment Methodology (TEAM) studies. DoD should modify these sampling techniques to meet its needs and should evaluate how modeling, simulations, and decision analysis could be used in real time to anticipate acute exposures.

Finding. Personal passive monitoring of atomic radiation, in the form of dosimeters and radiation badges, has been successfully used for many decades. In some limited situations, small passive monitors have also been used to detect chemicals. However, current technology limits personal monitoring of many toxic gases and particulate matter to the use of active monitoring, which is a complex process.

Recommendation. The Department of Defense should explore and evaluate the use of personal monitors for detecting chemical and biological agents, toxic industrial chemicals, and other harmful agents at low levels. If all personnel were equipped with monitors, probabilistic sampling could be used to select a subset of data for short-term, immediate use (e.g., to define the contaminated parts of the deployment area). The full data set could be used for long-term purposes (e.g., recording an individual's exposure to low-level toxic agents). Stratification of the subsets should be decided on the basis of exposure attributes, such as location, unit assignment, and work assignment. If the logistics problems

can be solved, every deployed person could ultimately wear a personal monitor.

Finding. DoD is currently devoting significant resources to improving its capabilities of monitoring life-threatening exposures but not of significant exposures to other harmful agents. At this time, DoD also recognizes the value of, but has taken little action, to collect and store information on low-level exposures to CB agents, toxic industrial chemicals (TICs), environmental and occupational contaminants, and endemic biological organisms. Different capabilities will be required for detecting life-threatening exposures, monitoring low-level exposures to CB and industrial agents, monitoring potential exposures to harmful microorganisms, and maintaining complete exposure records for all military personnel.

Recommendation. The Department of Defense (DOD) should rank the threat levels of all known harmful agents and exposure pathways based on the dimensions of harm (e.g., health consequences, the number of personnel affected, the time to consequences). When assessing the need for and applications of new equipment, increased surveillance, and improved documentation, DoD should include these data, and, if applicable, use decision analysis methods, such as probabilistic decision trees, to make decisions and prepare operations orders.

THRESHOLDS OF HEALTH EFFECTS

Measures of safe and unsafe doses have been established for high-level exposures to both CB agents and TICs. Information on dose responses for low dose rates and long-term exposures to chemical agents is still sparse. In addition, exposures to biological agents have been much more difficult to detect and measure than exposures to chemical agents. For chemical agents, a low-level exposure is one that does not result in acute effects. However, over the long term, low-level exposure may increase the likelihood of chronic illness. In contrast to high-level exposures, for which clear evidence of health effects exists, as low-level chemical exposures increase, it is postulated that the probability of disease increases. Risks from chemical agents have been assessed, but risks from biological agents have not. Therefore, it is difficult to define a low-level exposure to biological agents. Although an acute threshold concentration for chemical agents can be characterized and a safety factor establishing a low-level exposure can be applied, this information is rarely available for biological agents.

Finding. Because little information is currently available to relate long-term health effects to low-dose or low-dose-rate exposures to chemical agents, it is extremely difficult to set performance criteria for detecting and monitoring concentrations of these agents to assess long-term health effects. As a starting point for a working definition of low-level concentration, DoD could use the low-dose data currently available and the capability of available detection equipment.

Recommendation. The Department of Defense (DoD) should increase its efforts to collect and evaluate individual and group dose-response data for a broad set of chemical warfare agents. Studies could include standard animal toxicity testing protocols for long-term effects, as well as retrospective epidemiological studies on individuals exposed to these substances in their occupations. DoD should use the detection capability of available equipment as its working definition of low-level concentration.

Finding. In addition to chemical warfare agents, thousands of TICs are in or are brought into the theater of deployment. These chemicals include pesticides, fuels, paints, and lubricants. Under combat conditions, existing controls and safety precautions may not be practical. Storage tanks, production facilities, pipelines, and other equipment may be damaged, for example, and the TICs dispersed. Exposure under these conditions may be uncontrolled, unreported, unrecorded, and extremely dangerous. Exposures could have long-term health effects that cannot be easily distinguished from the long-term health effects of low-level exposures to chemical warfare agents.

Detecting and monitoring exposures continually to the full set of toxic chemicals, would be extremely difficult, if not impossible. Toxicity data for a number of TICs being developed by some government agencies, such as the Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA), are being reviewed by independent groups, such as the NRC Committee on Toxicology. The data thus far show large variations in toxicity.

Recommendation. The Department of Defense should review its current efforts to catalog and prioritize toxic industrial chemicals. This information should be used to anticipate the types of chemicals that may be encountered during a deployment and to prioritize them.

Finding. Very little information is currently available to relate long-term health effects to low-level exposures to biological agents. Almost no information is available on how combined or sequential exposures to low

levels of CB agents can affect the short-term or long-term health of troops. Until DoD can accumulate and analyze information on low-level exposure or dose response, as well as on long-term chronic effects, it will be very difficult to set performance criteria for detecting and monitoring concentrations of CB agents for assessments of long-term health effects. Potential interactions among agents add to the difficulty. Interactions can be cumulative, synergistic, or antagonistic. For example, chemical interactions may, in fact, abate, or even destroy, a biological agent. In fact, at one time, DoD research focused on using a chemical agent to counter a biological agent cloud.

Recommendation. The Department of Defense should increase its efforts to collect and evaluate low-level dose-response data for a broad set of biological agents. The data should include information on the infectivity of a range of both warfare and endemic biological agents. At the same time, studies should be undertaken to determine whether and which combined chemical and/or biological agent exposures should be investigated. This information should be used for defining a strategy for monitoring exposures to multiple agents.

Finding. Current criteria for detecting CB agent concentrations are designed to prevent exposures to lethal and incapacitating levels. Often the only way to determine if individuals have been affected by exposures to harmful agents is if they have immediate symptoms. Thus, data are not provided in a form that can be used to establish or verify retrospectively the health effects of CB agents over the long term.

Recommendation. The Department of Defense should establish a plan to collect data for all types of potential agent exposures to identify potential or emerging medical problems quickly. If possible, these medical problems should then be evaluated in terms of any prior exposures to chemical and/or biological warfare agents that have been associated with that health outcome. This plan should include guidelines for who should get the information and when they should receive it.

ENVIRONMENTAL AND EXPOSURE PATHWAYS

Potential environmental exposure pathways are important considerations of a strategy to protect the health of deployed forces. In an overt attack with CB agents, the inhalation path, and to a lesser extent, the dermal path, are obvious exposure pathways. However, when assessing low-level, long-term, or episodic exposures to either CB agents or TICs, persistent and indirect pathways must also be investigated.

Total exposure assessments must take into account ambient concentrations of harmful agents in multiple environmental media (e.g., air, water, solid surfaces), as well as the time and activity patterns and microenvironments of individuals. Exposure can only be quantified when pathways and routes that account for a substantial fraction of the intake have been identified.

Unfortunately, much of the current data on environmental contaminants cannot be synthesized into an understandable form because no comprehensive framework has been developed for evaluating chemical transport, transformation, and interactions in multiple media. Another important aspect of a credible exposure assessment is the possibility of concurrent or sequential exposures. Tracking these exposures can be a complex undertaking, especially if the agents interact synergistically or antagonistically.

Finding. During 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. Gulf War veterans had ample opportunities to be exposed to these substances in many different combinations, and interactions 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.

DETECTING AND MONITORING HARMFUL AGENT CONCENTRATIONS

CB agents can be detected and monitored in several ways: (1) point and area sampling; (2) local, stand-off, and remote detection; and (3) real-time and delayed analysis. In assessing technologies and detection and monitoring equipment, it is important to consider whether they can provide information on both long-term and short-term (e.g., acute effects that could immediately affect a unit's ability to fight) health effects. Until recently, the focus has been only on short-term affects.

Technologies and equipment are evaluated for accuracy, reliability, sensitivity, selectivity, speed, portability, and cost. Two very different kinds of information are essential during a deployment: (1) real-time detection of harmful agents; and (2) monitoring and archiving of low levels of agent concentrations for postdeployment assessments.

Many harmful agents are dispersed as aerosols or attached to aerosols. Detecting them requires either collecting and analyzing the aerosol particles or using particle spectrometry. Currently, mass spectrometry is used to characterize atmospheric aerosols in an attempt to provide online, real-time analysis of individual aerosol particles. However, results of current systems are questionable. Current detection methods involve isolating particles on filters and subsequent analysis performed in the laboratory. The isolation processes often disturb the aerosol, which renders the data questionable because the chemicals on particles can evaporate or react before analysis. To overcome these difficulties, technologies such as aerosol time-of-flight mass spectrometry (ATOFMS) have been developed to eliminate the need for filters and chemical collection.

Current mass spectrometers weigh a few hundred pounds and are, therefore, not easily portable. Ion-mobility spectrometers (now under development) may weigh only 10 pounds. Other developments could also improve spectrometers. In addition to basic mass spectrometry, DoD is investigating surface acoustic wave (SAW) and light detection and ranging (lidar) technologies to detect CB agent aerosols. The information

provided by this equipment will require data evaluation systems to sort and assess the large amount of information.

Current and planned detection equipment is primarily designed to detect nerve and blister chemical agents. TICs have not been given as high a priority. Most technologies that can detect chemical agents in air, water, and food, however, can be adapted to detect TICs and other harmful chemicals likely to be found in the deployment environment. The SAW detector, for example, would have a limited capability of detecting TICs and other harmful chemicals.

Although the current capability to detect biological agents is limited, developing that capability has recently been given a high priority. Emerging technologies for detecting and identifying microorganisms include polymerase chain-reaction amplification, microchips, molecular beacons, electrochemiluminescence, biosensors, mass spectrometry, and flow cytometry.

Finding. Overall, the technologies and equipment either in use or under development are severely limited in their ability to measure concentrations associated with long-term health risks. A significant reason for this problem is that no formal requirements have been established for detecting and monitoring low-level, long-term exposures. Until acceptable low-dose exposures are specified, performance goals for low-dose detection technology cannot be established. Specifications would provide designers, developers, and operators of detection and monitoring equipment with goals for their research.

Recommendation. The Department of Defense should establish criteria for detecting and monitoring low-level exposures to chemical and biological warfare agents and toxic industrial chemicals. These criteria should specify three detection levels: (1) immediate, dangerous, and life-threatening hazards; (2) short-term hazards; and (3) long-term health risks.

Finding. Because different technologies have different strengths and weaknesses, no single technology should be relied on for detection. By using complementary and redundant technologies and sensor fusion techniques, which are commonly used in other areas of the military (e.g., air defense and antisubmarine warfare), the risk of false alarms could be reduced, and agents could be detected at lower limits.

Recommendation. At least two different but complementary technologies should be used, along with sensor fusion techniques, for the detection of a given type of agent. This combination could significantly reduce the number of false positives and false negatives.

Finding. Most of the equipment currently available, as well as most of the equipment under development, for sensing CB agents is designed for detection and warning only. Detection devices typically give off audible or visible signals when the concentration is above the sensitivity level of the device or above a preset value. These devices are valuable for protecting troops from immediate harm but do not provide the kind of monitoring needed to assess less-than-debilitating exposures or to assess exposures that might lead to delayed health impacts.

Not enough attention has been given to archiving the measurements from different detectors. In some cases, archiving is not possible because of the nature of the device. Devices operated for "warning-only" cannot be used in combination with systems like the multipurpose integrated chemical alarm and Joint Warning and Reporting Network (JWARN) to determine the spatial and temporal trends in agent concentrations—essential information for determining the evolution of a threat or for confirming the absence of an agent.

Recommendation. The Department of Defense should develop a comprehensive plan for collecting and archiving data and samples based on a matrix of short-term threats and long-term health risks for situations before, during, and after deployment. This matrix could be used to prioritize types of information.

TRACKING DEPLOYED MILITARY PERSONNEL

A full characterization of an individual's exposure requires knowing where that person is and what (s)he is doing. General-population, time-activity data cannot be used for estimating exposures of deployed troops; only data specific to deployed personnel can yield accurate estimates of exposures. These data can be provided by the global positioning system (GPS), the total isolated microenvironment exposure (TIME) monitor, and various motion sensors and data loggers, which have been recently introduced.

The GPS will help greatly with the location of units and even of individual soldiers. Miniaturized instruments would have to be developed for use in the field. A wristwatch style GPS, for example, combined with a miniaturized data logger, would provide activity and location information that could be used to prevent acute exposures, as well as to estimate long-term exposure. The most promising automated approach for obtaining data for estimating long-term exposures appears to be a modified TIME device or similar data logger combined with GPS.

Finding. GPS is a critical component of an effective system for predicting and preventing exposures to CB agents, including accidental agent releases. Currently, only one individual per unit or squad carries a GPS receiver. Once GPS devices have been miniaturized and militarized, each individual could carry one. The location of each individual and the individual's proximity to identified or suspected releases of CB agents could then be identified, and orders for preventive actions could be directed to the individuals at greatest risk.

Recommendation. The Department of Defense should continue to support the development of miniature (e.g., wristwatch style) military global positioning system (GPS) receivers. Given current technology, receivers could be fielded within five years. The actual decision to equip every deployed unit or individual with a GPS-based receiver should be based on the results of trade-off analyses.

Finding. A miniaturized, multifunctional device that can detect CB agents and TICs, determine location and time, and record the data would be extremely valuable both for protecting deployed troops and for analyzing past exposures. These devices could detect threats from harmful substances, locate the wearer in time and space, and store the data until it could be downloaded. There are, of course, many technical challenges (e.g., size, weight, power requirements) to achieving this capability. Very small devices already exist, however, that could partly meet these goals. The Army's Man-in-Simulant Test (MIST) Program, for example, uses a passive sampler no thicker than a common adhesive bandage and less than one inch square. Establishment of a goal to develop these devices would offer, at a minimum, a valuable target for researchers and developers.

Recommendation. The Department of Defense should support the goal of developing a miniaturized, multifunctional device for detecting agents, determining location, and storing data.

Finding. Individuals may have performed jobs prior to or during their deployment that involved higher-than-average or longer-than-average exposures to toxic pollutants. Predeployment information could be used to identify individuals whose prior exposures put them at higher risk from additional exposures during deployment, as well as to identify possible prior exposures to harmful agents that otherwise might be believed to have occurred during deployment. The postdeployment information would provide a concise record of major duties performed and the use of, or proximity to, possible or confirmed sources of pollutants.

Recommendation. The Department of Defense should implement measures to identify individuals whose predeployment exposures might put them at higher risk of harm from additional exposures during deployment. The information should include major duties performed and the use of, or proximity to, possible or confirmed sources of pollutants during deployment.

STRATEGY

DoD should modify its overall strategy in two ways: (1) by increasing the emphasis on detecting and monitoring concentrations of biological agents during troop deployments; and (2) by addressing the detection and monitoring of a broader range of CB and TIC concentrations and tracking low-level exposures to them in an integrated, systematic way. These two changes will require that DoD take the following steps:

- Develop and procure the technical means of assessing potential and actual exposures (e.g., real-time, field-usable devices for detecting biological agents and improved devices for detecting chemical agents).
- Develop doctrine and training protocols based on improved knowledge of CB exposures for conducting military operations.
- Collect information on the postdeployment health of troops, whether or not they remain in the military.

Defining Needs

Recommendation. The Department of Defense should formulate an integrated approach to assessing the threats of chemical and/or biological agents. The approach should include: (1) a near-term and long-term perspective; (2) data collection; (3) estimates of the relative importance of various threats (e.g., biological threats, chemical threats, and chemical toxins derived from organisms) in a variety of overseas theaters; and (4) data on the effects of low-level doses of a broad range of agents.

Determining Exposure

Recommendation. The Department of Defense (DoD) should proceed with a robust program to develop chemical detectors and biological detectors that can detect and measure low-level as well as high-level concentrations. The first priority should be the development of improved passive sampling devices based on existing technologies that could be

fielded quickly. The DoD should also develop a support structure for using the devices and for archiving the data.

Recommendation. The Department of Defense should expeditiously develop the capability of identifying and archiving continuous data on the operational location of each small unit—and, if practical, each individual—as well as the unit or individual's proximity to actual or suspected releases of potentially harmful agents. Technical assessments and cost-benefit analyses should be used to determine the best ways to accomplish these functions in the near term (e.g., the best way of supplementing the miniature global positioning system receiver to achieve the desired result).

Recommendation. The Department of Defense should establish a long-term goal to develop very small devices that could be deployed with each individual to measure and record automatically exposures to one or more of the most threatening agents, the location of the individual, the activity of the individual, the microenvironment, and the time.

Recommendation. The Department of Defense should develop and field improved meteorological measuring and archiving systems to provide finer data grids of wind, temperature, and atmospheric stability in the theater of operations. These data will be necessary for improved transport modeling and for after-action analyses of data on the movements of chemical and biological "clouds."

Recommendation. The Department of Defense should support research to clarify how chemical and biological processes affect the rate of transformation of agents in different environmental media under a variety of conditions.

Handling Data

Recommendation. The Department of Defense should develop a representative activity-location database for different types of units, major military duty categories, and high-risk subpopulations of personnel likely to be deployed. This database, along with models and simulations, should be used to provide insights about potential exposures associated with specific deployments.

Recommendation. The Department of Defense should develop its data-handling capability to track the locations of all individuals (or, at least,

the smallest units) during future deployments and compare them to the locations of actual or potential agent concentrations at the same point in time. The data-storage capacity should be increased simultaneously so that these locations can be recalled and analyzed after each deployment (e.g., data could be recalled from a high-capacity personal information carrier).

Recommendation. In the future, the Department of Defense should characterize the variations in exposures of members of groups believed to have been exposed during their deployment. To help accomplish this, location data and agent-concentration data that pertain to individuals or small units should be analyzed thoroughly, using statistical methods where applicable.

Recommendation. The Department of Defense should study the ramifications of establishing a national chemical and biological hazardous agent data center.

Doctrine, Training, and Administration

Recommendation. Doctrine and training for taking protective action should be reviewed to ensure a proper balance between military necessities and the risks of harmful exposures. The Department of Defense should reevaluate its doctrine and training for handling and reporting alarm activations and false alarms and revise them, if necessary.

Recommendation. Doctrine and training should take account of predeployment exposures that might put some individuals at greater risk during deployment. This information, along with data gathered on actual or suspected exposures or on the locations of individuals or units and the locations of concentrations of agents, should be used to assess the risk to individuals.

Recommendation. The Department of Defense should review its doctrine and training protocols governing the interactions of offensive operations and protective measures. If an offensive operation may cause exposure to troops nearby, this information should be factored into the decision.

1

Introduction

Since Operation Desert Shield/Desert Storm, Gulf War veterans have expressed concerns about the health effects of possible hazardous exposures during their deployment. The Defense Science Board Task Force on Persian Gulf War Health Effects (DoD, 1994), the National Institutes of Health Technology Assessment Workshop, the Institute of Medicine Committee to Review the Health Consequences of Service during the Persian Gulf War, the Presidential Advisory Committee on Gulf War Veterans' Illnesses, and others (e.g., Lebowitz, 1998) have all conducted extensive reviews and published reports on the health of veterans. The focus of most of these reports has been on the current health of veterans, appropriate evaluation and care of veterans, and the connections between veterans' health status and their service in and specific exposures during the Gulf War. These expert bodies have also recommended improvements in Department of Defense (DoD) policies, procedures, and technologies for protecting the health of military personnel during deployments.

Two types of health concerns are related to hazardous exposures. First, exposures to chemical and/or biological (CB)[1] warfare agents and other harmful agents can degrade troop performance and interfere with the fulfillment of their mission. Second, low-level exposures to multiple toxic agents could have long-term health effects. Thus, there has been a

[1] In this report, the acronym CB refers to chemical and/or biological agents that can be used as weapons.

growing demand for both the collection and management of information on potential exposures (at all levels) to a large number of harmful agents and for better monitoring and control of exposures.

In public statements, the Special Assistant to the Deputy Secretary of Defense for Gulf War Illnesses has stressed the need for a better understanding of exposures that occurred during the Gulf War to facilitate the treatment of illnesses affecting Gulf War veterans and other deployed troops and support personnel (DoD, 1998a; Rostker, 1997a, 1997b, 1999); the same information will be necessary for future deployments. Moreover, the chronic health effects must be understood in the context of lifelong exposures to harmful agents in military and nonmilitary situations.

CHARGE

DoD requested that the National Academies conduct an independent, unbiased evaluation of its current and planned efforts to protect deployed forces and recommend a long-term strategy for protecting the health of military personnel deployed to unfamiliar environments. The evaluation is focused on four areas: (1) risk assessments; (2) technologies and methods for detecting and tracking exposures to harmful agents; (3) physical protection and decontamination; and (4) medical protection, health consequences and treatment, and medical record keeping.

Scope of This Study

This study, which is one component of the overall evaluation, addresses the second area, DoD's approaches to detecting and tracking exposures of deployed military personnel to potentially harmful agents, including CB agents, toxic industrial chemicals (TICs), environmental and occupational contaminants, and endemic, disease-causing organisms. This study also includes an evaluation of current policies, doctrine, and training and identifies opportunities for modifying strategies to provide better protection in future deployments. The study evaluates the following:

- methods of monitoring and characterizing CB agents present in, or released or dispersed into, the deployed theater
- use of the global positioning system (GPS) and other technologies to track troops and characterize locations and time-activity patterns of deployed military personnel, including high-risk subpopulations
- fixed-site and mobile methods of detecting and monitoring concentrations of potentially harmful agents
- computational methods and biological markers for estimating

exposure concentrations and patterns of exposure for individuals or groups
- implementation procedures, including tactical and administrative processes, for detecting, monitoring, and documenting exposures

Definitions of Terms

CB agents and other harmful agents is assumed to include all chemical agents (those that may be used as warfare agents, as well as TICs and environmental and occupational contaminants) and all biological agents (those that may be used as warfare agents as well as those that cause endemic disease). Traditionally, the agents of concern were primarily agents that could be weaponized and used against U.S. deployed forces (referred to by DoD as CB warfare agents); TICs, environmental and occupational contaminants, and agents of endemic disease were considered lesser concerns. Since the Gulf War, DoD has attempted to redress this gap. Although this study includes agents other than the traditional weaponizable warfare agents, a distinction between CB agents and other harmful agents is made to be consistent with the terminologies used by DoD and the other three concurrent studies.

Potentially harmful agents, a subcategory of chemical agents, includes TICs and environmental and occupational contaminants. *Inventories* refers to a category, class, or type of CB agent and its concentration in the local environment. The term does not refer to the amount or numbers of agents stored in stockpiles.

Detection and monitoring of agents refers to the detection and monitoring of CB and other agents that may be harmful to U.S. troops. Detecting and monitoring an agent, toxic cloud, or contaminated area includes discovering its presence and noting its location, identifying the agent, determining the size and boundaries of the cloud or contaminated area, measuring the concentration, and predicting its future path.

Tracking refers to identifying and monitoring troop locations. In the near term, tracking includes locating and following troops and keeping track of their contacts with harmful agents. Near-term tracking can be done at the unit or organizational level. Tracking also means following where individual service members are at particular times and determining whether or not they have been or could have been exposed to agents in a given location. For the purposes of this report, tracking includes gathering information on the levels and times of contact with the agents.

Detecting, *monitoring*, and *tracking* are defined as follows. *Detecting* is the process of finding the presence of agent(s). *Monitoring* is the process of collecting data for space and time profiles of agent concentrations. *Tracking* provides information on both the geographic locations of troops and

their specific activities at those locations (e.g., marching, operating inside a vehicle, sleeping in a tent, eating, wearing normal uniforms, or wearing protective clothing).

APPROACH OF THE STUDY

The National Academies Board on Army Science and Technology in the Commission on Engineering and Technical Systems, in collaboration with the Board on Environmental Studies and Toxicology in the Commission on Life Sciences, contracted a principal investigator, Thomas E. McKone, an expert in exposure assessment, to conduct this study. As part of the study, the principal investigator and National Research Council (NRC) staff assembled an advisory panel to provide supplementary information, review the report during development, and participate in planning and conducting workshops and commissioning papers.

The principal investigator worked with the NRC staff to collect and synthesize the data and information. Sources of information included reports and databases at DoD and regulatory and research organizations, as well as information provided by experts in relevant disciplines. Data was gathered at a series of meetings with DoD representatives, who made presentations on various topics related to the study. Individuals from the Soldier and Biological Chemical Command (SBCCOM) Edgewood Chemical Biological Center, SBCCOM Soldier Systems Center, the U.S. Army Chemical School, U.S. Army Medical Research Institute for Chemical Defense, the Joint Service Materiel Group (JSMG), and the JSMG Contamination Avoidance Commodity Area presented briefings at open meetings. Lessons from previous deployments, DoD field manuals, and other documents were also reviewed to provide a broad context for evaluating current and planned military doctrine and training.

Much of the DoD reference material cited in this report has been prepared by or for the Army. This is because the Army assumed the *de facto* role of executive agent for CB research and development (R&D) by virtue of its large and long-term investment in the development of chemical equipment and its extensive experience with chemical exposure on the battlefield. The Army controlled the production of chemicals, the development and production of defensive equipment, training, testing, basic research, and a chemical warfare unit. The Army, thus, has historically invested more resources than the other services in the area of contamination avoidance.

As operations became more and more integrated and cooperative (joint operations), both Congress and the military departments recognized the need for joint R&D programs and integrated procedures to improve joint operations and decrease logistical support burdens. This

resulted, in 1994, with passage of Public Law (P.L. 103-160), the National Defense Authorization Act for Fiscal Year 1994 (Title XVII) (U.S. Congress, 1994), which officially assigned the Army the role of executive agent for coordination and integration of the CB defense program. DoD reorganized its CB programs across the services, and each service was given responsibility for coordinating the R&D acitivities across all services in specific areas of the CB defense program. The Army was given lead responsibility for the contamination avoidance commodity area. Current and future work in this area will, therefore, continue to have much Army input and emphasis. Although the Army is the lead, there has been and continues to be related, ongoing activities in the other services (e.g., U.S. Air Force, 1999; U.S. Navy, 1999a, 1999b, 1999c).

ISSUES

This study is focused on technologies for detecting and monitoring concentrations of agents and for tracking the exposures of troops to those agents. The study also addresses the overall framework in which these technologies could be used. Because a comprehensive understanding of troop exposures requires many types of information, the study also focuses on DoD's procedures for collecting, managing, and using information. However, this study did not evaluate the many computing, information processing and storage, and communications technologies that would be associated with any large-scale attempt to detect and monitor many different harmful agent concentrations during deployments and to monitor, over an extended period of time, actual or potential exposures of deployed troops, as well as individual predeployment and postdeployment exposures. Computing, information processing, and communications technologies are being developed mostly by the private sector, and DoD's use of these commercial, off-the-shelf technologies has been evaluated in many other reports (e.g., National Defense Panel, 1997; NRC, 1995, 1997a).[2]

[2] It is widely agreed that future military systems for command, control, communications, intelligence, surveillance, and reconnaissance will require new technologies to meet the growing demand for sensor integration, high-speed data transport, more data storage, and distribution and analysis of data to achieve full, real-time, situational awareness on the battlefield and meaningful postdeployment assessments. If the recommendations of this study are implemented, they could add significantly to DoD's existing needs for improving computers, information processing and storage, and communications technologies.

No attempt was made to assess the budgetary impact on DoD of adopting some or all of the recommendations developed in this report. This report assesses techniques for detecting and monitoring agents, tracking troop activities, and characterizing exposures, as well as DoD's implementation of these techniques, according to the following criteria:

- applicability of the technology to the CB agents of concern
- technical feasibility of using the technology in theaters of deployment
- value of the technology for assessing physical protection, health risks, or medical follow-up
- usefulness of the technology for setting priorities for detecting and monitoring agents and tracking troops
- contribution of the technology to an understanding of the full range of exposures, including low-level and high-level exposures
- cost effectiveness of the technology

The utility of the information in DoD's decision making (i.e., whether the information is likely to make a difference) was an important consideration. The types and extent of exposure information needed during a deployment depend largely on the military mission, the deployment environment, and how the information will be used. Although DoD is putting forth a great deal of effort to develop technologies for detecting CB agents and for tracking military personnel during deployments, it is not yet clear how these technologies and the information they provide will be used to assess potential exposures to harmful agents or to make operational decisions. Decision analysis would be one method of identifying the most useful exposure information and the best ways of collecting it and preventing data overload. For example, a taxonomy of exposure information could be developed to prioritize various kinds of information. Appendix A contains a more detailed discussion of the decision framework and the elements of decision analysis.

MILITARY DOCTRINE AND TRAINING

This study should be seen in the context of doctrine and training related to CB attacks. For many years, the U.S. military has adhered to the doctrine of contamination avoidance, which involves four steps: (1) implementing passive defense measures (e.g., camouflage, dispersion) to reduce the probability of a CB attack; (2) warning and reporting a CB attack to protect others who might be affected; (3) locating, identifying, tracking, and predicting CB hazards so commanders can decide whether to operate in or around them; and (4) limiting the exposure of personnel if operation

in a contaminated area is necessary (U.S. Army, 1992). Military doctrine states, "If the mission permits, avoiding CB hazards completely is the best course of action. This is not always possible" (U.S. Army, 1992, p. vi). Since contamination may not always be avoided, military personnel are trained to use protective gear (e.g., masks and suits). Although operating in a CB environment is extremely difficult, the military believes that well trained troops can survive and fight on a contaminated battlefield.

DoD recognizes that its current detection equipment has many limitations. The basic manual of the Army Chemical Corps and the Marine Corps, which describes the principles of operating in a contaminated environment, reiterates the importance of avoiding contamination (U.S. Army and U.S. Marine Corps, 1996). If a unit is contaminated or must enter a contaminated area, protection becomes very important. The manual, which offers substantial guidelines for protection against chemical attacks, includes the following statement on protection against biological attacks: "Personnel should treat a suspected biological attack just as a chemical attack. *The protective mask provides protection against all known biological and military chemical agents. However, current detector systems will not react to biological agents*" [emphasis added] (U.S. Army and U.S. Marine Corps, 1996, p. 4-7). In the *Annual Report to Congress on Nuclear/Biological/Chemical (NBC) Defense* (DoD, 1999a), DoD identified nine projects under way, managed by the Joint Program Office for Biological Defense, to improve its detection technology.

The Army's training program emphasizes contamination avoidance but also includes protocols for training troops to conduct effective combat operations in a CB environment with protective equipment (U.S. Army, 1993). One objective of the program is "to ensure that all soldiers, leaders, and units achieve and maintain proficiency in combat operations under NBC conditions" (p. 20). Monitoring for CB hazards is designated as a unit responsibility, and the planning and control of chemical surveys and biological sampling are assigned to the battalion or squadron and higher levels.

However, some evidence indicates that actual training does not always meet these goals. In 1998, the DoD Office of the Inspector General conducted an audit of unit CB readiness training. The audit results are summarized in the following paragraph.

> Except for Navy surface ships, at 187 of 232 units reviewed, unit commanders generally were not fully integrating chemical and biological defense into unit mission training. As a result, commanders could not adequately assess unit readiness to successfully complete wartime missions under chemical and biological conditions (DoD, 1998b, p. i).

The Annual Report to Congress included an extensive discussion of training for CB operations by all of the military services, as well as an

assessment of training and readiness (DoD, 1999a). The assessment identified the following three unresolved issues (solutions suggested by DoD are summarized in parentheses):

- "DoD lacks a mechanism to provide adequate information on the current status of training, equipment, and readiness" (p. 5-34). (Solution: assign higher priority to defense against NBC attacks; provide adequate resources to joint service organizations.)
- "There are limited chemical and biological features in wargames and planning models" (p. 5-34). (Solution: add CB warfare defense to joint simulations in funding for fiscal year 1999 and beyond.)
- "Joint NBC defense doctrine needs to be continually developed to include joint service tactics, techniques, and procedures" (p. 5-34). (Solution: continue interaction and cooperation by military services to produce next-generation doctrine.)

The Army is exploring concepts for CB defense for its army of the next decade, known as Force XXI (U.S. Army, 1998). The Army argues that Force XXI must have the capability (1) to sense the battle space (i.e., identify hazards in air, water, or land to personnel, equipment, or facility by means of surveillance, detection, identification, monitoring, and reconnaissance); (2) to shape the battle space (i.e., provide visualization so the commander can clearly understand the current and predicted situation); (3) to shield the force (i.e., prevent casualties by reducing the threat, contamination avoidance, protection); and (4) to sustain the force (i.e., medical intervention and decontamination).

Although contamination avoidance remains the guiding principle, the Army states that chemical doctrine will change "to include considerations of evolving technology, chemical force structure, and threats . . . in support of other services . . . for operational concerns across the spectrum of conflict." The Army concept also delineates the following training goals for the future: (1) virtual, live, and synthetic theater of war training exercises; (2) modeling and simulations; and (3) specialized training in toxic and industrial hazards (U.S. Army, 1998, p. 16).

OVERVIEW OF THE REPORT

The purpose of this report is to evaluate DoD's ability to cope with the range of exposures faced during a deployment, including exposures to CB agents, to other harmful agents, to vaccines, and to drug interactions. The recommendations are made with the knowledge that data on past deployments are limited and variable and that DoD will have to

develop a prospective strategy for handling exposure issues in future deployments.

This report lays out a sequence for planning and information-gathering activities that could be followed in exposure characterizations. Chapter 2 describes approaches for estimating exposure concentrations and patterns of exposure for individuals or groups by a combination of computational methods and biological markers. The chapter also describes tactical and administrative procedures for detecting, monitoring, and documenting exposures. A technical annex discusses exposure assessment.

In Chapter 3, detecting and monitoring a range of agents, as well as characterizing exposures, are discussed. Once detection and monitoring properties of agents have been identified, their exposure pathways must be determined. Chapter 4 addresses the processes that transport and transform agents along possible pathways from their sources to points of contact with deployed troops. An understanding of these processes will be essential for tracking and characterizing inventories of agents that exist in or are released or dispersed into the deployment theater.

Characterizing potential exposures requires information on how agent concentrations vary, both geographically and in time. Chapter 5 addresses techniques for detecting and monitoring concentrations of potentially harmful agents by both fixed-site and mobile methods. Because characterizing exposures requires an understanding of how and where troops might come into contact with agents, their geographic locations—using technologies such as GPS—and their specific activities at those locations must be identified. Chapter 6 addresses the challenge of tracking and characterizing locations and time-activity patterns of deployed military personnel. The chapter also includes a discussion of subpopulations that might be at higher risk, such as individuals or units that have been subjected to previous exposures. In closing, chapter 7 recommends strategies to meet the challenges of detecting and tracking exposures of deployed military personnel to potentially harmful agents.

2

Characterizing Exposures

Characterizing the potential or actual exposures of deployed troops to harmful agents is vital for determining the health risk of contamination, defining a level of protection if operation in contaminated areas is required, and providing medical treatment, if necessary. Characterizing exposures involves several processes: (1) detecting agents; (2) assessing and monitoring concentrations; (3) tracking time-specific locations of troops relative to these concentrations; and (4) understanding exposure pathways. Subsequent chapters treat these elements individually. However, none of these elements alone provides sufficient information for characterizing exposures in real time or for characterizing potential future exposures or past exposures. Moreover, the information must be linked in a way that provides useful input for decision makers.

Various methods have been developed for combining detection and monitoring data on agent concentrations with troop tracking data. These methods can be divided into two groups: (1) sampling strategies to detect an imminent threat (i.e., high-level exposures); and (2) sampling strategies to collect information on low-level exposures to single or multiple agents but not immediate/short-term life-threatening levels of toxic agents.

The following topics are addressed in the sections below: the need for exposure characterization; strategies for assessing exposure to harmful agents; the collection of environmental samples; the use of modeling, simulation, and decision trees; and needs, capabilities, and opportunities for the future. The final section contains key findings and recommendations for characterizing exposures.

NEED FOR EXPOSURE CHARACTERIZATION

Characterizations of exposure provide three different types of information:

- estimates of potential exposures—harmful agents likely to be present, weather patterns, and troop activities likely to bring troops in contact with agents
- estimates of actual exposures, or of exposures avoided, during deployment—monitoring of harmful agent concentrations in the deployment area, the number of troops threatened, and the implications of spatial and temporal changes of concentrations and troop locations
- assessments of exposure[1]—a basis for understanding or predicting postdeployment health effects

Monitoring requires a network of instruments to detect and record concentrations, as well as to gather information on environmental factors, such as wind, that can affect the dispersion and concentration of the agent. Perhaps the best way to monitor the movement of an agent is with a combination of a monitoring network and dispersion simulations. But detailed information on space and time distributions of concentrations is not sufficient to characterize troop exposures. The location of the troops and the rate and direction of their movements with respect to the concentrations must also be known.

Although tracking every individual would be desirable, it may not be practical in the near future. Individuals could be tracked with GPS, but the amount of data could overload the data fusion process and equipment. Modeling and war games could be used to determine the feasibility of tracking every individual. DoD's current strategy is to track units by tracking representative samples of the individuals in that unit. If the unit has a high probability of being exposed, all members of the unit would be assumed to be at risk. If tracking and exposure information on individuals could be temporarily stored and then, at a later date, retrieved for historical purposes, this could alleviate the near-term problem of data overload and enable DoD to analyze the effects of low-level exposures to CB agents and other toxic agents on a given individual.

[1] The components of an exposure assessment are discussed in detail in the Technical Annex at the end of this chapter.

Exposure Information

The information required to characterize exposures includes data gained from monitoring (e.g., the nature, size, and location of the agent concentration); the tracking information on the location and previous exposures of troops; and time-activity data during the exposure.

Combining these for tracking purposes will be different for short-term exposures that could pose an imminent threat, than for low-level exposures that could have long-term chronic health effects. Record keeping must start at the predeployment stage, with determinations of past and current exposures, health factors indicating susceptibility, and job-activity classifications. Different combinations of these data will be necessary to characterize exposure for individuals and groups.

Strategies for Characterizing Exposures

Strategies for characterizing exposures can be defined in terms of time scales—real-time, prospective, or retrospective. Real-time sampling strategies are used for determining exposures of deployed personnel (in various settings) to protect them against imminent threats. Sampling may be used in future analyses to determine the probability of an exposure that may have occurred in a recent, well defined setting, as well as to evaluate factors that can explain observed levels of exposure. Prospective monitoring refers to sampling taken before the appearance of health effects. For example, consider exposure to benzene. Prospective sampling would be sampling to identify who has been exposed to benzene prior to the appearance of health effects. Typically, the sampled population is then tracked to determine if an increase in the incidence of any disease correlates with the level of sampled benzene concentration. Retrospective sampling takes place after an exposure has occurred and is based on records or proxy indicators, which are used to determine the magnitude of the exposure. In the example just described, for instance, retrospective sampling would be used to sample a group of people who already have a disease, such as leukemia, to determine which of them was exposed to benzene and at what levels.

The spatial scales in exposure characterization depend on whether one is tracking dispersed agents (e.g., in air or water) or nondispersed agents (e.g., in soil or food). Stand-off sampling is better suited for real-time assessments of potential threats, but stand-off sampling is often time consuming and not always reliable. Therefore, proximate samples are often collected at, or near, the point of contact.

Characterizing exposures that have chronic and latent adverse health effects from low-level (single or multiple) exposures presents

many problems for strategists, policy makers, and health-care systems. These exposures add a new dimension to the requirements for operational planning and research. A study by the General Accounting Office indicated that DoD does not have a strategy for characterizing low-level exposures and that risk assessment standards need to be improved, including the standards for assessing multiple exposures (GAO, 1998).

Uncertainty, Variability, and Reliability

Current estimates of potential troop exposures to harmful agents are based on large amounts of data collected by different instruments and individuals. The data are so complex that in some cases models and simulations must be used to interpret the results. Because these data and models must be used to characterize many things (e.g., individual and group behaviors, engineered system performance, contaminant transport, human contact, and skin absorption) in a variety of geographical locations, often under less than ideal conditions, uncertainties and variabilities are "facts of life."

An *uncertainty* refers to an error, bias, or lack of information that results in an inherent uncertainty in measured exposure factors (e.g., concentrations, locations, activities). Characterizations of exposures are bound to include large uncertainties (e.g., errors, incomplete data) associated with the information collected and ultimately provided to the decision makers. Uncertainties in exposure tracking information are the results of high detection thresholds, false alarms, improper sampling, improper documentation, lost or incomplete records, miscalculations, and subjective interpretations of results. *Variability* refers to natural variations or heterogeneities in human populations and natural systems. *Reliability* refers to the overall precision and accuracy of an assessment and is related to both the uncertainties and variabilities in the components of the assessment.

The greater the uncertainties and variabilities in the exposure information, the lower the reliability. Although many factors can be quantified based on variance propagation techniques, uncertainties that are difficult to characterize cannot be reduced. Thus, exposure information should not be provided as single values but should be accompanied by some measure of reliability. In some cases, some uncertainties and variabilities can be resolved using decision trees and event trees (see Appendix A).

STRATEGIES FOR ASSESSING EXPOSURES DURING DEPLOYMENTS

The first priority in the DoD strategy for assessing exposures to CB and other harmful agents is to detect, monitor, and avoid life-threatening

situations, particularly from CB agents. However, DoD recognizes that low-level exposures and multiple exposures to other hazards (e.g., TICs) during deployments must also be assessed. These assessments will require that DoD continue to modify its strategies for collecting exposure information.

A growing body of evidence in the public health field indicates that determining total exposure would greatly facilitate the identification, assessment, and management of health risks. To date, exposure assessments (see the Technical Annex to this chapter) have focused primarily on exposures to contaminants in specific media or occupational exposures to specific environmental pollutants (Krzyzanowski et al., 1990; Krzyzanowski, 1998; NRC, 1981a, 1991a; RIVM, 1989; U.S. Army, 1991; WHO, 1982a, 1983, 1989). But DoD now recognizes the need for a strategy of "total exposure assessment" (i.e., the cumulative effects of multiple contacts with harmful agents in multiple media) (GEO-CENTERS and Life Systems, 1997).

Detection and Monitoring Strategies

Chemical agent concentrations can be monitored either by fixed-site monitors, portable monitors, or personal monitors. Fixed-site monitors involve measuring chemical concentrations at specific fixed locations. Portable monitors track chemical concentrations at various locations as troops move around or use a sampling strategy. Personal monitors track exposure concentrations by individuals. Current DoD practice relies primarily on fixed-site monitoring by point or stand-off detection.

Fixed-Site Monitoring

Sampling strategies for monitoring civilian air pollution rely on a few stationary monitors for each area of interest (usually population centers near major point sources). Monitoring strategies have been generally limited to identifying common TICs, including particulate matter, lead and lead compounds, ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide (EPA, 1982, 1986a, 1992a, 1993, 1996a; WHO, 1982a). Military fixed-site monitoring networks are similar to their civilian counterparts (U.S. Army, 1991). During the Gulf War in 1991, an attempt was made to set up a monitoring network, essentially a garrison-based system for monitoring air, water, and soil; however, little monitoring was actually accomplished (Heller, 1998; U.S. Senate, 1992).

Limited monitoring of hazardous air pollutants (HAPs) and CB agents in the Persian Gulf area (U.S. Army, 1991) was conducted, as well as some other scattered monitoring (U.S. Senate, 1998). No source-specific

monitoring was done of TICs, such as petroleum products, lubricants, cleansing solvents (including degreasers), off-gases from weapons discharges, outdoor and indoor nonoperational (combustion and other) sources, toxic waste dumping, stored toxic substances, or transported toxic substances. Although the military has CB defense plans and reconnaissance operations for field situations, as well as some emerging strategies (i.e., predeployment environmental sampling) for toxic agents, they were not used extensively prior to the Gulf War. Even during the Gulf War, they were used inconsistently and sporadically.

Multimedia Monitoring

Environmental media that can be monitored include air, water, food, and soil. A multimedia monitoring strategy is designed to assess the cumulative effect of exposures of a single individual to a single agent from multiple media. In general, DoD does only limited multimedia monitoring. For example, the military conducted some water and soil monitoring in the Persian Gulf area in connection with its air monitoring (Knechtges, 1998).

A few studies have been done on a few biological aerosols (pollen, bacterial endotoxins, and mold), but only research studies and specialized indoor environments (e.g., hospitals) monitor for infectious agents. Indigenous sources of nonwarfare biological agents during previous deployments have not been monitored because it was not required and funding was not provided.

Using Statistics

Environmental monitoring protocols can be an essential component of research studies on health effects or exposure trends. These studies typically include statistical sampling methods, and in some cases, monitoring is stratified using probabilistic sampling methods (the type of stratification depends on the objectives of the study). DoD's CB agent reconnaissance operations also include sampling protocols designed to provide comprehensive area coverage. However, at this point, DoD uses few, if any, statistical sampling or stratification methods, which could facilitate the characterization of variations in exposures within a population.

At present, two probability-based statistical sampling protocols have been used in the U.S. Environmental Protection Agency's (EPA's) National Human Exposure Assessment Studies (NHEXAS) (Lebowitz, 1995; Pellizzari et al., 1995; Sexton et al., 1995a, 1995b) and the Total Exposure Assessment Methodology (TEAM) studies (Wallace, 1987a, 1987b, 1992). These studies were carefully designed to assess the relative magnitude

and variation of exposures to commonly found TICs, such as benzene, lead, and pesticides. The NHEXAS studies include multimedia exposure assessments.

Using Monitoring Data with Exposure Models

Tracking exposures requires integrating monitoring data and time-activity data in a structured, time-dependent fashion. Computer models provide an automated process for combining, storing, and assessing the types of information that must be merged to characterize exposures. Modeling is particularly useful for interpreting environmental samples for low-dose assessments. Exposure characterization can also be improved by dispersion models (as is widely recognized by the military), models of chemical infiltrations of indoor environments, or models of indoor/outdoor ratios. An essential component of these models is accurate activity data for tracking individuals.

Simulations

Currently, DoD makes limited use of simulations or intelligent systems to interpret environmental samples (Knechtges, 1998). DoD is working with and developing a number of systems to simulate exposure patterns, but most of these systems are not currently available. Among these systems are the Army's Automated Nuclear, Biological and Chemical Information System (ANBACIS), the emerging Joint Warning and Reporting Network (JWARN) system, the Navy's Vapor, Liquid and Solid Tracking (VLSTRACK) model, the BIO 911 Advanced Concept Technology Demonstration (ACTD) simulation model for biological organisms, and the Joint Biological Remote Early Warning System (JBREWS) ACTD. A version of ANBACIS was used to reconstruct chemical exposures in the Gulf War (DoD, 1999b). To date, the military has not used these systems for prospective or real-time assessments, but that is the explicit goal of systems such as JWARN, which is being designed to integrate information from several detectors, monitors, and soldier-tracking devices with simulation models. Little information on how this will be done is available. Moreover, systems such as JWARN will only be used as tactical systems to monitor immediate threats. Currently there are no plans to apply them for documenting long-term health hazards (U.S. Army, 1994).

COLLECTION OF SAMPLES

Much more detailed sampling will be necessary for deployments abroad than for troops stationed in the United States, where emissions

data for occupational and environmental settings are well characterized. In contrast, for most deployments abroad (with the exception of standard overseas locations where sources of harmful agents are already known and well characterized), harmful agents will have to be identified in real time and analyzed for their potential effects. Few or no industrial and/or agricultural emissions data are likely to be available for most deployments.

When environmental samples are used to characterize exposure, the accuracy of the characterization depends on the types of samples collected. No monitoring strategy can completely eliminate uncertainties about agent concentrations and provide a sufficient number of samples to characterize precise exposure variabilities among deployed troops. In many situations, only surrogate or remote samples are available. In other situations, proximate samples may be available but may not be representative of the groups or individuals for which exposure data are needed. Personal sampling and biomarkers have the potential to characterize the range of exposures experienced by individuals, but these methods also have inherent limitations.

Surrogate Samples

Surrogate exposure information is obtained by linking characteristics of each individual's environment, residence, and workplace, to historical or actual knowledge of concentrations in those locations or in similar or typical locations (Lebowitz et al., 1989). Assessments based on surrogate samples are likely to be more reliable than assessments based simply on general categories. Surrogate samples require careful calibration and are often more useful for retrospective analyses than for prospective assessments. Although surrogate samples would seem to be feasible, they have not been thoroughly tested in actual deployment settings. If surrogates are available, DoD would benefit from investigating their use for assessing CB and other harmful agents.

Stand-off Sampling

Stand-off sampling is frequently used in the environmental health field, sometimes in conjunction with dispersion modeling. As noted in Appendix D, stand-off sampling has been used for sampling both CB agents and industrial chemicals, mainly to monitor air pollution. However, measurements taken at a "safe" distance from the source of contamination are often unreliable as measures of personal or group exposures because they cannot directly measure microenvironmental contamination.

Proximate Sampling

Proximate sampling involves measuring concentrations from a location near (proximate to), but often different from, the location of the person. For example, indoor and outdoor exposures could be estimated from a single indoor monitor. Proximate sampling is very useful for evaluating total exposures in a logical way (Colome et al., 1982, 1992; EPA, 1996b; Krazyzanowski, 1998; Letz and Spengler, 1984; NRC, 1981b, 1985a; Quackenboss et al., 1991; Spengler et al., 1981; WHO, 1982a, 1982b). Personal gaseous monitors (discussed below) also can be used as proximate instruments. Monitoring (with data loggers) in locations where individuals and/or small groups are present provides information on exposures during the time periods that are monitored and can be used to model exposures, and help calibrate models, to estimate exposures in these locations at other times. The method depends both on the level of information required and on the feasibility of collecting detailed individual data and making microenvironmental and personal exposure measurements (Colome et al., 1982, 1992; Krzyzanowski, 1998; Lebowitz et al., 1989; NRC, 1981b; Quackenboss et al., 1991; Spengler et al., 1981). Temporal measurements can also be made for evaluations.

Proximate continuous monitoring (with data loggers) of various airborne pollutants can be done in the field (in garrisons and for support personnel), aboard ships, and in aircraft cockpits; the National Aeronautics and Space Administration uses some cockpit monitors (e.g., NRC, 1988, 1992). Some CB monitoring capabilities exist, and more are being developed. However, proximate chemical agent monitors did not seem to work well during the Gulf War. The problems were attributable as much to operational factors, however, as to the devices themselves (DOE, 1998; Knechtges, 1998).

Proximate (active or passive) monitors could have been used in some of the tents where kerosene space heaters, which emit excess amounts of particulate matter, nitrous oxide, sulfur dioxide, carbon monoxide, and hydrocarbons, were used during the Persian Gulf deployment. Instead, postdeployment studies with simulants were conducted (U.S. Senate, 1998).

Personal Sampling

The most direct approach to characterizing human exposures is personal exposure monitoring. Passive monitoring of atomic radiation has been used successfully for many decades in limited situations. However, active monitoring of toxic gases and particulate matter requires a good deal of effort (especially if a pump is involved) and is usually only

practical for a limited number of subjects for short periods of time. Gaseous passive integrated monitors (such as the volatile organic compound [VOC] badges and the Palmes tubes for monitoring nitrous oxide) have been developed and appear to be more promising for widespread use in situations where the threat is not imminent. Personal exposure monitoring works well for VOCs, which can be generated indoors or diffuse in from outdoors (EPA, 1993; Lioy et al., 1991; Moschandreas and Gordon, 1991; Perry and Gee, 1993; Wallace et al., 1989; Wallace, 1992, 1993). Participants in the SBCCOM Man-in Simulant Test (MIST) Program use the passive Natick Sampler to detect simulant vapors. The sampler is as thick as a common adhesive bandage and less than an inch square (NRC 1997b). Continuous time-location monitors with data loggers have also been available for some time (Ott, 1995). GPS with data loggers (see Chapter 6) is another promising technology for linking data from field locations.

Biological Markers

Biomarkers are biological samples that can be used to assess current and past exposures and health effects of CB agents and other harmful agents. Biomarkers can be obtained from samples of blood, urine, or hair. The analyses of biomarkers for the agent of concern, its metabolites, enzymes induced, and/or adducts formed in endogenous proteins and/or deoxyribonucleic acid (DNA) can indicate the presence of agent or its metabolites in the body (Lippman, in press). To date, biological markers have not been useful for low-level exposures. Improved methods are increasing the number and sensitivity of useful biological markers, although they have been limited to higher exposures usually in occupational settings. Biomarkers are used for measuring lead, and the Centers for Disease Control and Prevention (CDC) is currently investigating their use for measuring classes of organophosphate pesticides. If successful, biomarkers could also be used for measuring other organophosphate chemicals, such as nerve agents.

Emerging sampling strategies are relying more on biomarkers; and less invasive biomarkers, such as urine, saliva, or hair, might eventually be used for monitoring exposures to a large number of harmful chemicals. Urinary biomarkers have worked very well for measuring the presence of metals, tobacco smoke, and some other pollutants. In the future, DoD may be able to evaluate more DNA adducts, possibly even after the exposure of embedded personal DNA worn by individuals as a monitor (Lebowitz, 1999).

Limited studies of biological samples were performed on U.S. troops in the Persian Gulf. Among these were two separate CDC studies of VOCs

in the blood of Persian Gulf troops (U.S. Senate, 1998). Only tetrachloroethylene (PCE) was found to be higher than usual in a few individuals, and this was related to their degreasing activities. Also, the USAEHA-KRAT program studied biomarkers in some troops before, during, and after their deployment from Germany to Kuwait (U.S. Army, 1991). Generally, metals were found to either remain the same (e.g., nickel, vanadium) or were not detected (e.g., arsenic, mercury). Only lead increased in troops deployed in Kuwait (although the levels were still within normal limits). No substantial changes in VOCs were found, and most were within the range found by the National Center for Environmental Health in studies in the United States. Five VOCs were significantly lower in Kuwait (ethylbenzene, two xylenes, styrene, toluene); PCE was higher (U.S. Senate, 1998), as was acetone; benzene increased; chlorobenzene decreased; chloroform fluctuated, but increased only slightly. Polycyclic aromatic hydrocarbon (PAH) DNA adducts were higher in predeployment samples, implying that there were reduced exposures in Kuwait. A study of nine U.S. firefighters before deployment and within three weeks of their return from a six-week deployment showed levels of DNA adducts within the range reported by their laboratory for nonexposed groups.

MODELING, SIMULATIONS, AND DECISION ANALYSES

Modeling, simulations, and decision analysis can greatly improve interpretations of information obtained from CB detection equipment by providing a systematic and iterative process for assessing the value of improved or new information. To date, only limited modeling has been used to interpret chemical agent detection, and it is unclear how much DoD intends to use modeling, simulations, and decision analysis methods in deployment settings to identify and interpret information obtained from CB detection equipment. Although DoD acknowledges that these methods will be necessary for exposure and health hazard assessments (Heller, 1998), no systematic evaluation has been made of how they could be used in real time to anticipate acute exposures (especially imminent threats).

Exposure Modeling

Exposure models are being used to evaluate activities that would bring troops in contact with a contaminated medium in a specified microenvironment at a given location. To construct an exposure model, an individual or a population group is linked with a series of time-

specific activities and with the geographic locations and microenvironments associated with those activities. In addition, a combination of detection and monitoring data and process models are used to define contaminant concentrations (and sometimes contact time) in each combination of location and microenvironment. An exposure model must represent peak exposure concentration, average exposure concentration, the number of times the concentration exceeds specified levels, and the cumulative intake or uptake during a series of exposures.

Exposure prediction models can take various forms. One commonly used approach is to estimate the average exposure at each location (for an individual or group) using the time budget (as collected or even predetermined by job) and integrated samplers in that location. Differences between the integrated average exposure estimate in a location and the actual exposure measured for an individual or group may be due to the uneven spatial distribution of the pollutant in the compartment, room, building, or geographic area. Differences can also result when the pollutant concentration is associated with the presence of the individual or group (e.g., the use of a stove or space heater, resuspension of particles on floors or soil, or cigarette smoking).

Follow-up questionnaires, as well as time-activity data, are used to evaluate reasons for variations to facilitate assessments of the time relationship between the presence of the sampled individual or group and the source. Based on the time spent in each sampled location, the average exposure received by the individual or group at a given location can be calculated directly. The ratio of this partial exposure component to the cumulative exposure calculated for that individual or group can then be compared with the estimates based on the integrated samplers to assess the magnitude of error. If these data are supplemented by portable, proximate, continuous sampling, the estimates are much more accurate.

Although continuous monitoring is required for acute, especially imminent, threat situations in the field, continuous monitoring on the ground will only be possible using reconnaissance vehicles, in an aircraft, on board a ship, or in a garrison situation. For long-term effects we must rely on integrated averages.

Time-weighted averages (TWAs) of personal or group exposures are typically based on the time and location information derived from the time-activity data, as well as on monitoring data. The TWA contains a discrete sequence of time periods, j, that are spent in a limited number of locations; each period has a unique duration, t_j. For each time period, a concentration, c_j, can be estimated from a passive or active integrated sampler or from continuous data (if available) for that location and time period. The TWA is calculated as follows:

$$TWA = \sum(t_j\, c_j)/\sum t_j$$

for $j = 1, \ldots,$ number of time periods.

The calculated TWA can be compared with the integrated personal exposure measurement using an analysis of covariance procedure to assess the agreement between the estimated and measured exposure and to estimate the average pollutant concentrations in nonmeasured locations and their importance from the value and relative significance of the regression coefficients (Quackenboss et al., 1986; Spengler et al., 1985).

Models of Daily Intake

An alternative to exposure modeling frequently used for chemicals with long-term cumulative health effects (e.g., carcinogens) is a model of daily intake. A general EPA model states that the potential average daily intake dose, ADD_{pot}, over an averaging time (A), is given by:

$$ADD_{pot} = C_i/C_k * (IU_i/BW) * (EF * ED)/AT * C_k$$

where C_i is the contaminant concentration in the exposure media i; C_k is the concentration in environmental media k; IU_i is the intake/uptake factor (per body weight [BW]) for exposure media i; EF is the exposure frequency (days/year) for this population; ED is the exposure duration (years); and AT is the averaging time for population exposure (days).

Models of daily intake link sources to exposure pathways. Establishing human activity patterns associated with exposures are, thus, critical to these models.

Simulations

Simulations of CB and other toxic chemical releases and of their subsequent atmospheric dispersion are still being developed. Most current simulations deal primarily with air dispersion (Heller, 1998; U.S. Senate, 1998). Simulations for personal and group exposures must use monitoring data linked to time-location-activity data and the results of exposure modeling of different scenarios. These results could then be used to determine preventive measures, as well as to assess other scenarios, such as acute short-term vs. long-term exposures. In turn, these results could be stored for long-term retrospective health evaluations, as well as for determining short-term medical response.

NEEDS, CAPABILITIES, AND OPPORTUNITIES

DoD is currently devoting significant resources to improving its capabilities to anticipate life-threatening exposures. But DoD will also have to collect and store information on low-dose exposures to CB agents, TICs, environmental and occupational contaminants, and endemic biological organisms.

Different capabilities will be required to (1) anticipate life-threatening exposures, (2) monitor low-dose CB and other agent exposures, (3) monitor potential exposures to harmful microorganisms, and (4) maintain complete exposure records for all military personnel. Allocation of resources for these different capabilities should be based on the following factors:

- priorities among harmful agents and among multiple exposure pathways based on the dimensions of harm (e.g., severity of impacts, number of people affected, persistence of the harm) (See the Technical Annex to this chapter.)
- strategies for dealing with uncertainties, including incomplete information, proxy indicators of exposure, reliability problems with equipment, and lack of real-time information
- the relative value of new equipment, increasing surveillance, and improving documentation

Tracking Strategies and Emerging Needs

For determining health effects, assessments of total exposures in microenvironments are much more meaningful than assessments based on stationary monitoring alone (Bertollini et al., 1995; Lebowitz, 1995; Pellizzari, 1991; Wallace, 1992). Total exposure assessments includes measurements, or estimates, of contact with contaminants of concern through inhalation, ingestion, and dermal contact. The estimates of total exposure for deployed forces from this combination of data will probably be much higher than estimates based on either occupational or ambient pollutant concentrations (Bertollini et al., 1995; Corn, 1971; Moschandreas, 1981; NRC, 1981b, 1985a, 1985b, 1991b; Ott, 1995; Pirkle et al., 1995; Quackenboss et al., 1991; Sexton et al., 1992, 1995a, 1995b; Sexton and Ryan, 1988; Spengler et al., 1981, 1985; Wallace, 1992; WHO, 1982a, 1982b, 1983, 1989).

Real-Time Monitoring Strategies

Detecting imminent CB threats requires real-time monitoring strategies (e.g., Heller, 1998; JSMG, 1998; U.S. Army and U.S. Marine Corps, 1993). Determining CB agent concentrations before they reach troops is

important for minimizing immediate casualties. A chemical stand-off system, with alarm, has been developed for the Fox reconnaissance vehicle. Also, stand-off monitoring may be simulated by models based on likely emissions from remote "imminent threat" sources (Resta, 1998).

The issue of low-level exposures must still be addressed. Because there are so many agents troops may be exposed to at low levels and so many troops that could be exposed, the low-level issue involves more than just technology and equipment. It also involves strategies for interpreting trends from measurements collected near the detection limit of the equipment and methods for using exposure data for only a fraction of the exposed population.

Continuous monitoring (with data loggers) of CB agents and other airborne toxicants can theoretically be performed in the field by reconnaissance units (also in field garrisons and by support personnel), on board ships, and inside aircraft. Although sampling strategies did not seem to work well in the Gulf War, the sampling strategies were mostly haphazard, and no apparent effort was made to select the most likely sample locations or to sample media for future applications. In the future, an effort should be made to use data loggers with continuous time-location monitors and, if possible, GPS receivers.

Prospective Monitoring Strategies

Prospective monitoring strategies for acute high- and low-level surveillance monitoring for TICs have been defined, and strategies for the long-term investigation and surveillance of TICs are being developed. These strategies could be adapted for low-level monitoring of CB agents (as they are for TICs), since they are needed for deployed personnel, but the capabilities are currently even more limited than for higher levels (see Chapter 4).

Volatile Chemicals

Passive monitoring badges worn by a small number of individuals for 24- to 72-hour periods during days in the field can be used to monitor hazardous volatile chemicals (Coutant and Scott, 1982). Because of the burden associated with wearing and collecting these badges, only a small sample of deployed troops should be required to wear them. The badges could be similar to the Natick Sampler, which has been used in the MIST program to detect simulant. The permeable membrane in the Natick Sampler has also been tested successfully with a number of chemicals (NRC, 1997b). Badges could also be used as proximate monitors and as monitors for subgroups known to be sensitive to these toxic chemicals. New badges could be developed or the current badges used for monitoring chemical

agents in the parts-per-million and even parts-per-billion range—a level of sensitivity adequate for many but not all chemical vapors (e.g., GB and VX). Inferential statistics could be used to test the impact of several exposure variables on personal exposures to airborne toxic agents. For instance, one could compare the personal exposure sampling results with exposure estimates based on the indirect method of combining area sampling with personal time budgets.

Aerosol and Particulate Matter

Potential health impacts of exposure to particulate matter are related to particle size. Small particles (less than 2.5 microns) are deposited deep in the lung and are potentially more damaging per unit mass than large particles. Monitoring for particulate matter is currently done with real-time (one hour), 24-hour integrated personal, indoor, and ambient sampling techniques. The samples are then analyzed for total mass chemical speciation (e.g., trace metals) and selected anions and cations to determine the emission sources, topography, meteorology and climate, and relationships between coarse and fine particulate distributions. Diaries or recorders for time-location and activity levels are used to index individuals (and groups) and to provide the results and individual calculations of particulate-matter dosimetry. Continuous monitors with data loggers could be placed on key individuals within a deployed group (e.g., a platoon) for a convenient (e.g., 3- to 14-day) sampling period to compile a real-time (one- or two-hour intervals, as well as cumulative) exposure file of daily time and activity data.

Summary

Prospective sampling could be used to evaluate acute and semiacute exposures of individuals and groups, either with data loggers or by electronic transfer of laboratory analyzed data. The monitoring could be done with real-time or integrated samplers worn by individuals of concern or designated individuals within a platoon (or smaller unit), along with miniaturized GPS (with data loggers) and time-activity data loggers. The latter and any real-time monitoring on the loggers could be downloaded when convenient. Like epidemiological and occupational studies, these samples would be supplemented by predeployment and postdeployment questionnaires (for past and current exposure information) and biological samples and the results entered into the electronic databases. Prospective sampling techniques are readily available for all standard chemical agents. Sampling techniques for biological agents are being developed (Ali et al., 1997; Lioy, 1999; U.S. Army SBCCOM, 1998).

Retrospective Monitoring Strategies

Estimates of prior exposures can be based on current monitoring, historical monitoring, and questionnaires. Retrospective sampling is more difficult to carry out than prospective sampling. Predeployment questionnaires, and all questionnaires asking about past exposures are, by their very nature, retrospective and uncertain. The availability of modeling and simulation for retrospective exposure assessments is very limited. Some biomarkers could be used for short-term retrospective estimates.

Data Storage, Management, and Analyses

Agent monitoring data will have to be stored, managed, and analyzed. For this, the capacity and batteries of data recorders and loggers will have to be improved. Near-term downloading could be performed by the larger units; real-time acquisition, storage, and analyses could only be done in real-time, acute situations. DoD should begin working to meet the enormous challenges of collecting and storing large amounts of data. One way to reduce the demand for data acquisition and storage would be to rely more on statistical sampling schemes, simulations, and modeling, as long as the decrease in reliability associated with statistical sampling can be accounted for.

Use of Scenarios, Training, and Exercises

All aspects of the exposure characterization process must be integrated into the deployment plan and included in soldier training. Exercises that incorporate this information gathering would benefit both mission planners and troops. The first step for developing exercises would be to consider the range of exposure scenarios likely to be encountered. The scenarios should then be designed to capture the taxonomy of probable exposure situations (see Appendix A), including exposures to CB agents, TICs, and environmental and occupational contaminants.

The training exercises and/or scenario evaluation should be designed to help commanders and troops, as well as system developers (R&D groups), medical support groups, policy makers, and operations groups to clarify the issues related to the mission (see Table 2-1).

Making Exposure Assessment Operational

Exposure tracking will be useful only if it is integrated into all aspects of military operations. This means that policies must be linked to field activities at all levels of command. Specified individuals must be

TABLE 2-1 Questions To Be Answered by a CB Training Exercise

Specific Group	Questions that Should Be Answered by a CB Training Exercise
Commanders	What to do?
Troops	How to do it?
R&D Groups and Policy makers	What types of emerging detector and tracking technologies are available to assess exposure to the harmful agents and what impact will these technologies have on policy and training?
Medical support and Policy makers	What types of exposure information are needed? That is: exposure concentrations, exposure media (indoor air, ambient air, water, soil, food, etc.), duration, location, activity, etc.
R&D groups and Policy makers	How much information is needed? That is: which individuals (all, selected subgroups), which locations, what time intervals (days, hours, or minutes) should be represented.
R&D groups and Operations groups	How is the information collected and by whom, including the equipment used, the protocol for monitoring, data entry, quality control/assurance, limits of detection? How and to whom is the information transferred?
R&D groups	How is the information assessed before action is taken to prevent or limit exposure, including the use of simulation models to enhance measurements, issues of uncertainty and variability, likelihood and cost of false positives and false negatives? How, how much of, and where is the information stored?

responsible for setting up detection and monitoring equipment, tracking troops, and assessing information collected from monitors and data storage systems. Even under low threat conditions, data collection should remain a priority up and down the chain-of-command.

FINDINGS AND RECOMMENDATIONS

Finding. To date, exposure assessments for both civilian and military populations have focused primarily on exposures to contaminants in a specific medium (e.g., air, water, soil, food) or on exposures to specific environmental pollutants. DoD's current plans for monitoring CB agents would also be limited to a specific medium and would not be time-space specific, would not include time-activity records, and would not account for both short-term and long-term exposures. These factors would only be

included in settings where deployed personnel were active (in garrisons or in the field).

Most of the sampling protocols included in CB agent reconnaissance operations are designed to provide comprehensive area coverage, rather than statistical sampling or stratification. Neither has DoD systematically evaluated how modeling, simulations, and decision analysis could be used in real time to anticipate acute exposures (especially imminent threats). DoD's current capabilities and strategies have not been structured for making optimum use of these tools.

Recommendation. The Department of Defense (DoD) should devote more resources to designing and employing both statistical sampling and sample stratification methods. Two useful examples of probability-based statistical sampling are the National Human Exposure Assessment Studies (NHEXAS) and Total Exposure Assessment Methodology (TEAM) studies. DoD should modify these sampling techniques to meet its needs and should evaluate how modeling, simulations, and decision analysis could be used in real time to anticipate acute exposures.

Finding. Personal passive monitoring of atomic radiation, in the form of dosimeters and radiation badges, has been successfully used for many decades. In some limited situations, small passive monitors have been used to detect chemicals. However, current technology limits personal monitoring of many toxic gases and particulate matter to the use of active monitoring, which is a complex process.

Recommendation. The Department of Defense should explore and evaluate the use of personal monitors for detecting chemical and biological agents, toxic industrial chemicals, and other harmful agents at low levels. If all personnel were equipped with monitors, probabilistic sampling could be used to select a subset of data for short-term, immediate use (e.g., to define the contaminated parts of the deployment area). The full data set could be used for long-term purposes (e.g., recording an individual's exposure to low-level toxic agents). Stratification of the subsets should be decided based on exposure attributes, such as location, unit assignment, and work assignment. If the logistics problems can be solved, every deployed person could ultimately wear a personal monitor.

Finding. DoD is currently devoting significant resources to improving its capabilities of monitoring life-threatening exposures, but not significant exposures to other harmful agents. At this time, DoD also recognizes the value of, but has taken little action, collecting and storing information on low-level exposures to CB agents, TICs, environmental and occupational

contaminants, and endemic biological organisms. Different capabilities will be required for detecting life-threatening exposures, monitoring low-level exposures to CB and industrial agents, monitoring potential exposures to harmful microorganisms, and maintaining complete exposure records for all military personnel.

Recommendation. The Department of Defense should rank the threat levels of all known harmful agents and exposure pathways based on the dimensions of harm (e.g., health consequences, the number of personnel affected, the time to consequences). When assessing the need for and applications of new equipment, increased surveillance, and improved documentation, DoD should include these data, and, if applicable, use decision analysis methods (e.g., probabilistic decision trees) to make decisions and prepare operations orders.

Technical Annex

Exposure assessment is a key step in analyzing the links between contaminant sources and human health risks and, ultimately, in developing effective risk-management strategies. This annex describes the components of an exposure assessment and a "dimensions of harm scale," an approach to setting priorities among exposure assessment capabilities.

COMPONENTS OF AN EXPOSURE ASSESSMENT

The science of exposure assessment is related to toxicology and risk assessment, but in the last decade it has emerged as an independent discipline (EPA, 1992b; Lioy and Pellizzari, 1996; McKone and Daniels, 1991; NRC, 1991a, 1991b; Zartarian et al., 1997). *Exposure* is defined as the contact over a specified period of time of a chemical, physical, or biological substance with the visible exterior of the person, including the skin and openings into the body, such as the mouth and nostrils.

In the past, exposure assessments often relied implicitly on the assumption that exposures could be linked by simple parameters to observed concentrations in the air, water, or soil proximate to the exposed population. However, this is rarely the case. Total exposure assessments that include time and activity patterns and microenvironmental data have revealed that an exposure assessment is most valuable when it provides a comprehensive view of exposure pathways and identifies major sources of variability and uncertainty.

To assess human exposure exhaustively, investigators would have to measure or estimate the time spent by each person in the presence of each concentration of each contaminant in each exposure medium. However,

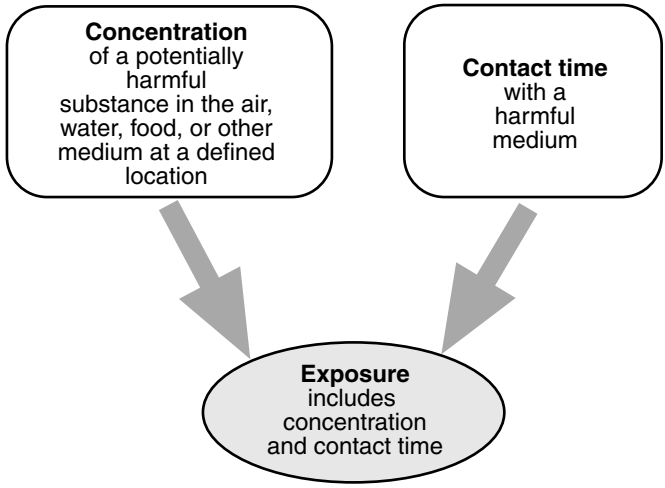

FIGURE 2-1 Links between concentration data and time-activity data.

in most cases, this is neither technically feasible nor even desirable. Even with precise exposure data, a determination of harm must be based both on exposure data and knowledge of an unsafe dose, which is typically available only at a population scale, not for individuals. For a specified contaminant, the most general way to define exposure is in terms of a concentration in a specified medium and the time that the person is in contact with that concentration. This concept is illustrated in Figure 2-1, which shows that an exposure characterization is based on both concentration information and time histories of the exposed population.

The standard approach to assessing exposure is to use the model equations proposed by Duan (1982). In this model, exposure is equal to the product of the concentration of the agent and the time of exposure. The sum of all exposures divided by the total time of exposure is the average exposure. This is shown in the following equation:

$$\xi_i = \sum_{j=1}^{J} t_{ij} c_j \; / \; (\sum_{j=1}^{J} t_{ij})$$

where ξ_i is the average exposure of person i; c_j is the concentration that person i encounters in microenvironment j; and t_{ij} is the time spent by person i in microenvironment j. J is the total number of microenvironments visited over the total time person i is exposed to CB agents. The

successive times, t_{ij}, person i spends in various microenvironments is referred to as the person's "activity budget."

When assessing human exposure, it is useful to focus on contact media, which include the envelope of air surrounding a human receptor; the water and food ingested; and the layer of soil, water, or other substances that contacts the skin surface, including inoculations. The magnitude and relative contribution of each exposure route and environmental pathway must be considered in an assessment of total human exposure to a potentially harmful agent to determine the best approach for reducing exposure.

Exposure assessments of deployed forces would require that the following steps be taken:

- Establish and target potentially harmful agents based on the dimensions of harm (discussed below) and on issues addressed in other studies (IOM, 1999a; NRC, 1999a, 1999b).
- Document and monitor geographic and temporal trends in exposures to the deployment population from CB agents through multiple media (e.g., air, water, soil), multiple pathways (e.g., indoor air, dust, food, water), and multiple routes (e.g., 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 (NRC, 1994a).
- Assess contaminant transport in a consistent manner over a wide range of spatial and time scales, from minutes and hours to weeks and months, on local and regional scales.
- Account for interactions and coupling of media through detailed measurements and/or models.

DIMENSIONS OF HARM

Exposure assessment is a prerequisite for both risk assessment and risk management. Not every exposure necessarily causes harm or has a health effect. Controlling the exposure of human populations to CB contaminants using a risk-based approach requires both an accurate metric for the effects of contaminants on human health and a defensible process for determining which exposures will be measured and controlled (NRC, 1994a).

Assessment capabilities for exposures to harmful agents should be classified and prioritized before resources are allocated for reacting to potential threats and R&D projects are prioritized for new detection and monitoring technologies. A useful approach to setting these priorities

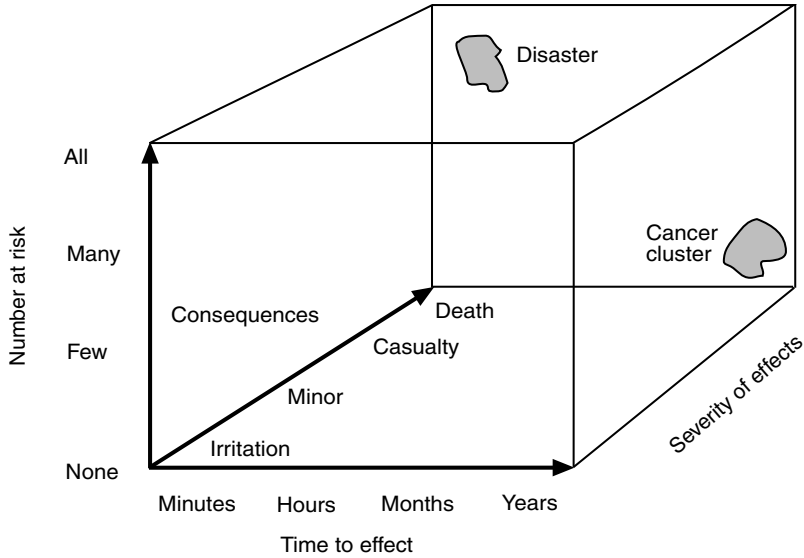

FIGURE 2-2 The dimensions-of-harm scale.

could be based on an index of hazard, such as the dimensions of harm developed for the Deployment Toxicology Research and Development Master Plan (Figure 2-2) (GEO-CENTERS and Life Systems, 1997). The dimensions of harm are measured along three scales—time to effect, number at risk, and severity of the consequences. Along the "Number at Risk" and "Consequences" axes, greater is a measure of importance. However, on the "Time to Consequences" axis, shorter (minutes) is generally more important than longer. For example, the effects of some agents, such as phosgene and mustard, are delayed, which may cause a delay in assuming a protective posture and thereby lead to increased morbidity and mortality.

3

Thresholds of Health Effects for Chemical and Biological Agents

In evaluating potential exposures to CB agents, DoD must consider how to detect and monitor health-relevant exposures to a broad set of CB agents, which will require knowing the dose-responses for these agents. In evaluating the potential use of CB agents, DoD must consider the nature of future deployments and the increasing capabilities of other countries to use CB agents as weapons.

Low-level exposure to chemical agents is unlikely to result in acute effects. However, over the long term, low-level exposure may increase the likelihood of chronic illness. In contrast to high-level exposures for which the severity of effect tends to increase as the level of exposure increases, it is postulated that as low-level chemical exposures increase, the probability of disease increases. These concepts are commonly used to assess risks from exposure to chemical agents but have not been tested for biological agents. Although it is possible to characterize an acute threshold concentration for chemical agents and apply a safety factor that establishes an acceptable low-level exposure, it is difficult to define an acceptable low-level exposure for biological agents.

Characterizing the effects of troop exposures to CB agents will require that research and field data on the effects be immediately available. However, no DoD plan for collecting, storing, and making these data available was described or even referred to during this study. These data must be kept current and made accessible to reseachers, medical personnel, decision makers, planners, and others responsible for protecting deployed troops.

CHEMICAL AGENTS

Deployed personnel face potential exposures to chemical warfare agents at concentrations that can be incapacitating or life threatening; however, they may also be exposed to chemical warfare agents at low levels that are currently not detectable or well monitored. As chemical warfare agents proliferate, the likelihood of in-theater and, possibly domestic, exposure to intentional releases of these agents increases.

In addition to exposure to chemical agents, troops may be exposed to a number of other potentially harmful agents during military deployments. Among these nonwarfare agents are volatile components and combustion products from propellants, explosives, and pyrotechnics (PEP) and a growing number of TICs, including chemicals associated with military materiel, such as pesticides, fuels, lubricants, cleaning agents, solvents, combustion products, chlorine, and other reactive compounds (from chemical storage depots), depleted uranium, and other toxic metals.

Important properties of chemical agents include the physical state at ambient conditions, toxicity, volatility, stability, and transport characteristics (i.e., how rapidly an agent travels or spreads in air, water, or soil). For liquid agents, ingestion, dermal contact, and eye contact are the most likely routes of intake and uptake. For airborne chemicals, uptake is usually respiratory (through inhalation), ocular (absorption by the eyes), or percutaneous (absorption through the skin) (Boyle, 1998a; U.S. Army et al., 1990). For airborne chemical agents, three factors determine the dose received: (1) the concentration of the chemical in the air and the characteristics of any aerosol-phase concentration (particle size distribution and chemistry); (2) the length of time an unprotected individual breathes the contaminated air; and (3) the individual's breathing rate, which is affected by his or her activity level.

The relative toxicity of a chemical agent is expressed either in terms of the lethal dose (*LD*) for a liquid agent or lethal exposure (*LCt*) for a vapor or aerosol agent; or incapacitating dose (*ID*) for a liquid agent or incapacitating exposure (*ICt*) for a vapor or aerosol. These expressions of toxicity are commonly described as median doses:

- LD_{50} is a measure of liquid agent lethality; the dose in milligrams (mg) of liquid agent or mg of agent delivered per kilogram (kg) of body weight expected to kill 50 percent of a group of exposed, unprotected personnel (U.S. Army et al., 1990).
- ID_{50} is the dose in mg or mg/kg of liquid agent expected to incapacitate 50 percent of a group of exposed, unprotected personnel (U.S. Army et al., 1990). In some cases, an ED_{50} is used instead of

the ID_{50}. The ED_{50} is the amount of liquid agent on the skin sufficient to produce severe effects in 50 percent of the exposed population (NRC, 1997c).

- LCt_{50} is a measure of vapor or aerosol agent lethality, which is the product of the concentration and exposure time that is lethal to 50 percent of a group of exposed, unprotected personnel at an assumed breathing rate (active or resting) (U.S. Army et al., 1990). The units commonly used to express the LCt_{50} are mg-min/m^3. If the exposed forces are very active and breathing rapidly, the LCt_{50} would be lower because of the higher breathing rate. The LCt_{50} is based on an assumption of a relatively short exposure time—typically less than an hour—but can often be applied for longer times. The LCt_{50} also varies with the degree of protection provided by masks and clothing, although the standard is based on unprotected personnel. The NRC Committee on Toxicology uses the term EC_{50} instead of LCt_{50}. EC_{50} is the airborne concentration of a chemical agent sufficient to produce the effects of interest in 50 percent of those exposed for 30 minutes (NRC, 1997c). EC_{50} is similar to, but higher than, the immediately dangerous to life and health (IDLH) concept used by the EPA as the maximum concentration of a contaminant to which a person could be exposed for 30 minutes without experiencing any escape-impairing or irreversible health effects.
- ICt_{50} is the incapacitating effect of a vapor or aerosol agent, which is the product of the concentration and exposure time sufficient to disable 50 percent of a group of exposed, unprotected personnel at an assumed breathing rate (active or resting) (U.S. Army et al., 1990). ICt_{50} also decreases as the rate of breathing increases and increases as the level of protection (e.g., clothing, masks) increases.

The allowable exposure level (AEL) is the chemical concentration in air that is safe for continuous exposure during an 8-hour work day/40-hour work week (ERDEC, 1996). The AEL is a general term indicating a level of exposure that is unlikely to result in adverse health effects. The Occupational Safety and Health Administration's (OSHA's) rules call for the use of maximum personal protection until concentrations can be shown to be less than 50 times the AEL.

These measures of effect are useful for defining the types and sensitivity of exposure information to protect against short-term or long-term health effects. In the past, DoD generally focused only on the lethal or incapacitating dose of chemical agents. However, given the concerns of Gulf War veterans about health symptoms and given recent congressional directives that DoD (1) modify its policies and doctrine to protect

personnel from low levels of agents in combination with other exposures, and (2) focus a research program on the effects of low-level exposures, DoD has become concerned about the potential health effects of exposures at lower levels (U.S. Congress, 1994).

Chemical Warfare Agents

Chemical warfare agents are chemical compounds used in military operations that are intended to kill, seriously injure, or incapacitate troops through their physiological effects (U.S. Army and U.S. Marine Corps, 1996). (A summary description of chemical agents of concern to DoD is provided in Appendix B.) A person becomes a casualty of a chemical warfare agent when s/he is affected to a point that prevents or degrades that individual's ability to carry out his/her duties.

Chemical warfare agents are classified as lethal, blister, or incapacitating agents. Lethal nerve agents include choking agents, blood agents, and nerve agents. Blister agents may be lethal, but their primary effect is skin damage. Incapacitating agents (lacrimators, sternutators, and psychochemical agents) cause psychological or mental effects that lead to temporary disability. However, in sufficiently high exposures and doses, incapacitating agents can also be lethal (U.S. Army et al., 1990). As chemical warfare agents proliferate, the likelihood of theater and even domestic exposure to intentional releases of these agents also increases.

Toxic Industrial Chemicals

In addition to traditional chemical warfare agents, deployed troops can be exposed to many other harmful chemicals, from environmental and occupational chemicals to TICs. These harmful chemicals may be a source of low-level exposures; they may even produce a chemical cloud that can degrade mission performance as much as some warfare agents. Toxic chemicals that are commonly used in modern and emerging industrial economies are also commonly used in military operations, and low to intermediate levels of exposure are plausible during a deployment. In addition to having an immediate impact on performance, exposures are believed to contribute to the risk of developing cancer and other serious diseases later in life (EPA, 1986b; Howard, 1989; WHO, 1979, 1982c, 1983, 1993).

The number and likelihood of exposures of U.S. forces to occupational and environmental chemicals are both increasing (GEO-CENTERS and Life Systems, 1997). The literature on the identification, evaluation, and control of human exposures to harmful industrial/commercial chemicals in both occupational and nonoccupational settings is extensive. In

areas where U.S. forces are likely to be deployed, the likelihood of exposures to multiple environmental chemicals is high. Although many industrialized nations have strict controls on the release of industrial chemicals, less-developed nations may not have the political or institutional infrastructure to provide protection from exposures to harmful substances. During military deployments, these exposures could be even higher as a result of the breakdown of local governments, damage to industrial facilities, or the use of operational areas as dumping grounds for hazardous industrial waste.

Detecting and monitoring chemical substances can be very difficult in a deployment setting. In the United States, harmful agents are typically identified for both occupational and environmental assessments. During deployments, these substances must first be identified, which could be difficult because the sources are not likely to be known or well characterized. Thus, a detailed sampling strategy is required to assess environmental levels. In contrast to well characterized emissions data for U.S. occupational and environmental settings, emissions data are sparse during deployment. Appendix B, provides some examples of the types of chemical substances associated with these source categories and gives examples of their sources and emission levels.

Defense personnel may be exposed to large chemical releases from industrial accidents at home or abroad, from deliberate acts of enemy forces or terrorists, from unintentional operational releases, and from natural disasters. Chlorine gas, for example, is used and stored by a large number of industrial-process facilities, especially water treatment facilities, and is also widely used as a reagent in the manufacture of chlorinated organic materials and inorganic chlorides and chlorates. Thus, chlorine storage tanks are likely to be present in an urban or industrial environment. Chlorine is a powerful irritant, both in the upper and the lower respiratory tract. The median lethal exposure for chlorine gas is 19,000 mg-min/m, and the median incapacitating exposure is 1,800 mg-min/m (U.S. Army et al., 1990). In many parts of the world, other potentially dangerous chemicals are also stored in large above-ground tanks.

Railroad tank cars and tanker trucks also carry a variety of highly toxic chemical agents and reactive intermediate agents for chemical synthesis. These cars and trucks are moving targets of opportunity. The potential release of toxic chemical intermediates from moving or stationary sources continues to be a cause for concern in many parts of the world. The disastrous release of methyl isocyanate near the city of Bhopal, India, in 1984 remains an icon for potential releases from chemical plants that store or use toxic intermediates.

Another source of contamination during deployment might be through U.S. or allied attacks on enemy CB manufacturing or storage

sites. Great care must be taken to identify these locations and assess the potential damage from the release of CB agents. One report stated that NATO briefers showed little regard for the danger of chemical releases during the recent bombings in Serbia. This danger was highlighted by both the Association of Greek Chemists and the Serbian Chemical Society (Heylin, 1999).

Exposures during deployments include not only exposures to agents, but also exposures to chemicals used with military materiel and exposures during off-duty hours. Operational exposures are associated with on-duty performance and may include exposures to chemicals, such as petroleum, oils, and lubricants; cleaning solvents; weapons discharge offgases; smokes and obscurants; and chemicals from nonoperational sources. Off-duty exposures are from ambient and indoor environments away from operational areas. Exposures to pesticides and dust-suppression agents can occur on or off duty. Damaged or nonoperational infrastructures can also be a source of harmful exposures.

Another source of toxic chemicals is the transformation of common industrial chemicals into more toxic species by environmental processes. For example, under certain conditions, parathion, an organophosphate pesticide, can be transformed to paroxon, a much more toxic compound. Many fieldworkers have been poisoned as a consequence of such transformations (Spear et al., 1977). Chemicals can also interact upon exposure to produce toxic effects. For example, reactive air pollutants, such as hydroxyl radicals (commonly found in the atmosphere of most U.S. urban areas), can interact with VOCs and convert them to other chemical compounds. Examples of common transformations can be found in a paper prepared by Yang (in press) for the risk assessment framework component of this study (NRC, 1999a). Unfortunately, given the wide variety of chemicals encountered during deployments, it is difficult to anticipate these interactions. One approach to this problem is to develop a matrix that links VOCs to the products of their transformation.

A common goal of several agencies, such as EPA, the World Health Organization, and OSHA, is to clarify the links between chemical exposures and health effects to protect both occupational and nonoccupational populations. These organizations consider a broad range of health effects, including cancer, reproductive effects, inheritable genetic defects, immunological effects, neurological effects, chromosome aberrations, and respiratory effects, many of which may be the results of cumulative exposures (i.e., from multiple exposure pathways and different chemicals with the same target tissue). For other substances, peak exposures are needed to determine the likelihood of health effects.

During deployments, the military should undertake surveillance of the local use of chemicals, evaluate the effects on military operations, and

keep records of this information. For chemicals commonly used by the military, a great deal of information has already been compiled, similar to the reports prepared by the NRC Committee on Toxicology (COT) on the potential health effects of exposures to fuel vapors (NRC, 1996) and to military smokes and obscurants (NRC, 1997d).

BIOLOGICAL AGENTS

Deployed personnel face potential exposures to harmful biological organisms, both as warfare agents and as endemic organisms, and toxins that can be transferred from air, water, soil, plants, animals, and other people in the theater of deployment. Potential exposures to biological agents have traditionally been much more difficult to detect and monitor than exposures to chemical agents. Often symptoms and patterns of disease can only be assessed *ex post-facto*.

Biological Warfare Agents

Biological warfare agents include both organisms and biological toxins derived from organisms. Organisms that could be used as biological agents include viruses, bacteria, rickettsia, and genetically altered organisms. Biological warfare agents can be disseminated as aerosols, liquids, or powders or can be introduced directly into food or water.

Current biological agents of concern to DoD include viruses, such as eastern equine encephalitis, western equine encephalitis, Venezuelan equine encephalitis, ebola, marburg, rick-borne encephalitis, smallpox, Congo Crimean hemorrhagic fever, junin, lassa, machupo, monkeypox, Rift Valley fever, and yellow fever; bacteria, such as *Bacillus anthracis, Brucella abortus, Brucella melitensis, Brucella suis, Burkholderia mallei, Burkholderia pseudomallei, Francisella tularensis, Yersinia pestis*; and rickettsii, such as *Coxiella burnetti*, *Rickettsia prowazeki*, and *Rickettsia ricketsii*. Table 3-1 provides a summary of diseases, likely pathways of transmission, lethality, and infectivity (i.e., the number of organisms required to cause disease in a healthy adult) associated with selected biological agents. Appendix C describes the characteristics of a number of biological agents.

Biological toxins are harmful chemical compounds produced by living organisms. They come from bacteria, dinoflagellates, algae, molds and fungi, plants, and animals. Some biological agents are highly toxic. Others, such as mycotoxin, poison ivy, and poison oak, attack the skin but are not lethal unless a break in the skin occurs. Biological toxins are often quite stable; are easily taken up on the skin, in the lungs, or in the gut; and produce symptoms that require extensive and rapid medical intervention. Table 3-2 provides summary information on characteristics of a number

of toxins that could be used as warfare agents. The table includes the sources and names of toxins, the LD_{50} based on the route of contact, the concentration corresponding to lethal effects, rates of action, and other relevant factors. The concentration corresponding to lethal effects is derived from the LD_{50} for a 70-kg adult breathing at a rate of 0.016 m/min for 30 minutes or ingesting three liters of water or three kg of food.

A comparison of data shows that the lethal doses for biological toxins are much lower than those for chemical agents. In other words, low concentrations of biological toxins can be much more dangerous to troops than chemical agents. AELs have not been established for biological toxins but are likely to be more than an order of magnitude below lethal chemical levels.

So far, little attempt has been made to set performance goals for detecting biological toxins even though some toxins, such as *Botulinium*, are many times more toxic than chemical agents, even lethal chemicals. Because of their lethality at relatively low doses, biological toxins could pose a threat comparable to the threat of many chemical agents. Detecting and monitoring exposures to life-threatening toxins requires a much more sensitive detection system than detecting and monitoring systems for most chemical agents.

Apparently, DoD has largely discounted the likelihood that toxins will be used against deployed forces. DoD's decisions for developing new detection technologies, however, should be based not only on the likelihood of use but also on lethality. If no strong justification is found for assigning toxins a low priority, then an appropriate level of research should be devoted to methods for detecting and monitoring biological toxins.

Endemic Biological Organisms

Endemic biological microbial organisms exist naturally in the deployment area to which deployed forces would not be immune. These organisms could include airborne microbes and fungi, waterborne microbes and fungi, biological agents in food, and disease organisms transmitted by human contact (Rose, in press).

RELATIONSHIP BETWEEN EXPOSURE AND TOXICITY FOR CHEMICAL AND BIOLOGICAL AGENTS

The prescribed safe doses for chemical agents vary greatly, as do the time-history of concentration and health effects. For some agents, the peak exposure concentration is most important; for others, the number of times the concentration exceeds specified concentration levels or the average exposure concentration exceeds a specified level is the key factor;

TABLE 3-1 Exposure Factors for Selected Biological Warfare Agents

Agent	Disease	Transmission
Bacteria		
Bacillus anthracis	Anthrax	Spores in aerosol
Vibrio cholera	Cholera	Food and water Aerosol
Yersinia pestis	Pneumonic plague	Aerosol inhalation
Franciscella tularensis	Tularemia (rabbit fever)	Aerosol inhalation
Shigelladysenteriae	Dysentery	Inhalation and ingestion
Rickettsia		
Coxiella burnetti	Q fever	Aerosol inhalation Food
Rickettsia rickettsii	Rocky Mountain spotted fever	Vectors
Viruses		
Ebola virus	Ebola	Direct contact Aerosol
Venezuelan Equine Encephalitis (VEE) virus	Encephalitis	Vectors
Yellow fever virus	Yellow fever	Vector/tick
Rift Valley fever virus	Rift Valley fever	Vector/mosquito
Variola virus	Smallpox	Aerosol
Hanta virus	Hanta	Aerosol
Dengue fever	Dengue fever	Aedes mosquito

[a] These numbers were calculated by dividing the infectivity level by 2 m^3 (the amount of air assumed to be breathed in two hours by an active adult) or by 2 L, the amount of water consumed during a day.
Source: Boyle, 1998b.

for still others, the cumulative intake or uptake during a series of exposures is the critical parameter. Dose-response information for chemical agents at low doses and low dose rates is still insufficient for determining safe doses (NRC, 1997c; GAO, 1998).

Because different levels of exposure and concentrations lead to health impacts for different agents, both the frequency and sensitivity with which chemical concentrations must be measured must be carefully defined, especially for low-level exposures. Figure 3-1 shows the variation in the median lethal air exposure, LCt_{50}, and median incapacitating air exposure, ICt_{50}, for a number of chemical warfare agents. This type of toxicity information can provide a basis for setting the performance goals of detection equipment. Protecting against incapacitating effects requires 2 to 10 times more sensitivity than protecting against lethal exposures. Most detection equipment measures concentrations. Unfortunately, there

Lethality	Infectivity	Required Detection Capability[a]
High ~ 100%	10,000 organisms	5,000 org/m^3 air
Low with treatment	1 million organisms	500,000 org/L water
High unless treated	< 100 organisms	50 org/m^3 air
Moderate	1 to 50 organisms	< 25 org/m^3 air
Moderate	10 to 100 organisms	25 org/m^3 air 25 org/L water
Very low	10 organisms	5 org/m^3 air < 5 org/kg food
Low	N/A	N/A
High for Zaire strain	N/A	
Low	N/A	
Low	N/A	
Low	N/A	
High to moderate	N/A	
43% in U.S.	N/A	N/A
Low to moderate	N/A	

is so little reliable information about the threshold effect for biological agents, that determining concentrations can be very risky. Figure 3-2 illustrates the range of sensitivity required for detection/monitoring equipment to protect against a range of health effects. This figure shows how the EC_{50}, the 30-minute average air concentration that would result in the LCt_{50}, compares to the estimated safe dose and to the Surgeon General's AEL. Defining a safe dose, or AEL, requires significantly more sensitivity than defining a lethal or incapacitating dose—in many cases, orders of magnitude more sensitivity.[1]

[1] The AEL, which is designed for controllable conditions, however, may be very different from the safe-dose level on the battlefield.

TABLE 3-2 Characteristics of Selected Biological Toxins

Source	Toxin	LD_{50} (μG/kg)	Required Detection Capability[a]	Notes
Bacteria				
Clostridium botulinium	Botulinium A, B, C, D, E	~ 0.02 (inhalation)	0.1 mg/m^3	Among the most potent toxins known.
		1 (oral)	0.02 mg/L (water or food)	Delayed lethality. Persists in food and water. Breaks down within 12 hours in air.
Clostridium perfringens	Gangrene-causing enzyme	0.1 to 5	0.3 mg/m^3	Delayed action. Low mortality, but very debilitating.
Clostridium tetani	Tetanus toxin	~ 3	N/A	Delayed action. Relatively unstable and heat sensitive.
Cornyebacterium diptheria	Diptheria toxin	0.03	N/A	Lethal. Rapid acting.
Staphylococcus aureus	Staphylococcus enterotoxin A, B, C, D, E (Toxicity is for type B)	0.4 (aerosol ED_{50}) 20 (aerosol LD_{50}) 0.3 (oral ED_{50})	0.058 mg/m^3	Rapid acting. Symptoms persist for 24 to 48 hours.
				Severely incapacitating.
			3 mg/m^3	Can be lethal. Large-scale production feasible.
			0.007 mg/L	Very stable.
Dinoflagellates				
Gonyaulax tamerensis, Gonyaulax catanella, and related species	Saxitoxin (shellfish poison)	1 (aerosol inhalation) 7 (oral)	0.01 mg/m^3 (air) 0.2 mg/L	Lethal. Rapid acting. Soluble in water. Relatively persistent.
Takifugu poecilonotuss	Tetrodotoxin	1.5 to 3 (inhalation) 30 (oral)	0.3 mg/m^3 (air)	Lethal. Rapid acting.

Algae				
Anacystis species, Anabanea flos-aquae	Anatoxin A (VFDF)	170 to 250 (IP)[b] 5,000 (oral) 2,100 (dermal)	100 mg/L(kg) (water or food)	Very fast death factor. Very rapid acting.
Microcystis aeruginosa, Microcystis, cyanea	Microcystin (FDF)	25 to 100 (IP)[b]	~10 mg/m^3 (air) ~2 mg/L (water)	Lethal, rapid acting. Fast death factor.
Fungi				
Fusarium species	Trichothecene mycotoxins ("yellow rain")	25 to 500 (inhalation) 1,600 (oral)	40 mg/m^3 (air) 40 mg/L	Nonlethal, delayed effects. Inhalation, ingestion, dermal. Very stable. Small repeated doses are cumulative.
Plants				
Ricinus communis	Ricin	1,000	150 mg/m^3 (air) 20 mg/L (water)	Lethal, delayed action. Easily produced. Persistent
Animals				
Palythoa (soft corals)	Palytoxin	0.08 to 0.4	0.035 mg/m^3 (air) 0.006 mg/L (water)	Lethal and rapid acting. Stable
Conus geographus; Conus magnus (fish-hunting cone snails)	Conotoxins	3 to 6	~0.6 mg/m^3 (air) ~0.1 mg/L (water)	Water soluble. Highly stable. Can be used as aerosols. Easily synthesized.
Phyllobates aurotaenia and Phyllobates terribilis (Columbian frog)	Batrachotoxin	0.1 to 0.2	0.015 mg/m^3 (air)	Rapid acting and lethal. Very stable. Can be synthesized.

[a] Assumes 70-kg adult breathing at a rate of 0.016 m^3/min for 30 minutes for air or the ingestion of 3 L water or 3 kg food by a 70-kg adult.
[b] IP refers to intraperitoneal injection dose to mice.

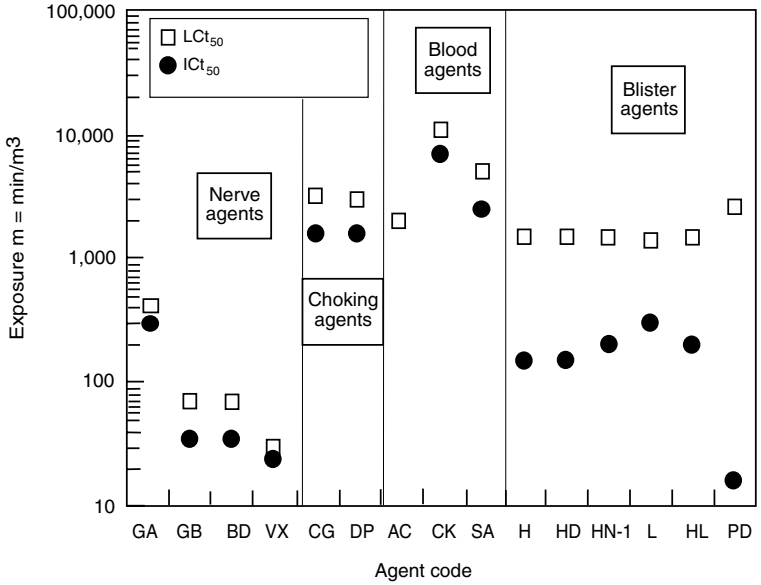

FIGURE 3-1 Variations in the median lethal air exposure, LCt_{50}, and median incapacitating air exposure, ICt_{50}, for some chemical warfare agents.

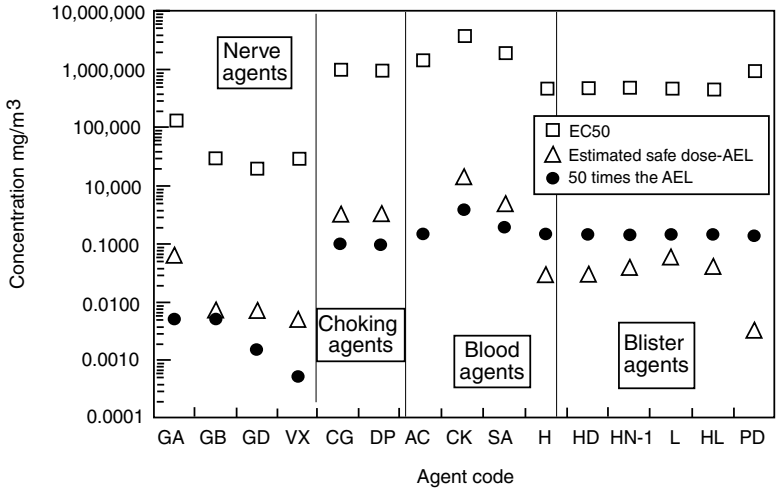

FIGURE 3-2 The EC_{50} (the 30-minute average air concentration that would result in the LCt_{50}) compared to the estimated safe dose and the Surgeon General's AELs.

Sources: Boyle, 1998a; ERDEC, 1996; NRC, 1997c; U.S. Army et al., 1990.

Assessing low-level exposures to a large number of chemicals will require detection and monitoring equipment with a high level of sensitivity and specificity over a broad range of chemical categories. Figures 3-3 and 3-4 show EPA estimated safe air and safe water concentrations for selected TICs. (The derivations of these are discussed in Appendix B.) These numbers are NOT meant to be used as standards by DoD but only to illustrate the level of sensitivity necessary for identifying low-level exposures to TICs.

In fiscal year 1996, DoD dedicated $5 million to evaluating the chronic effects of low-dose exposures to chemical agents (DoD, 1999a). In 1997, studies were initiated to develop highly specific and sensitive assays, preferably forward deployable, to detect and quantify low-level exposures to chemical agents. According to the *Persian Gulf Veterans Coordinating*

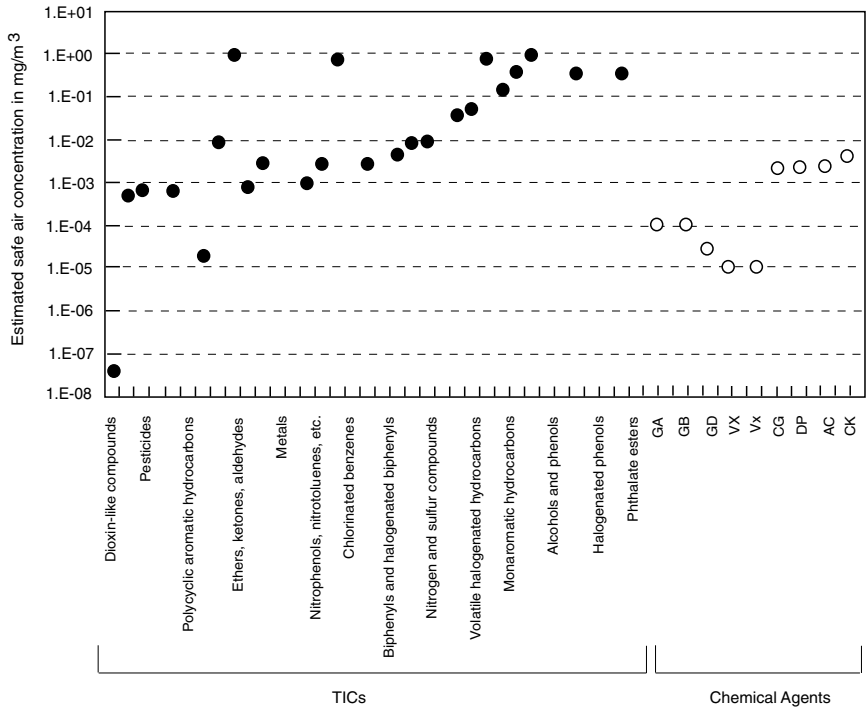

FIGURE 3-3 Estimated safe air concentrations for some TICs regulated by the EPA and some chemical agents. The numbers illustrate the level of sensitivity necessary to identify low-level exposures and should not be used as standards by DoD.

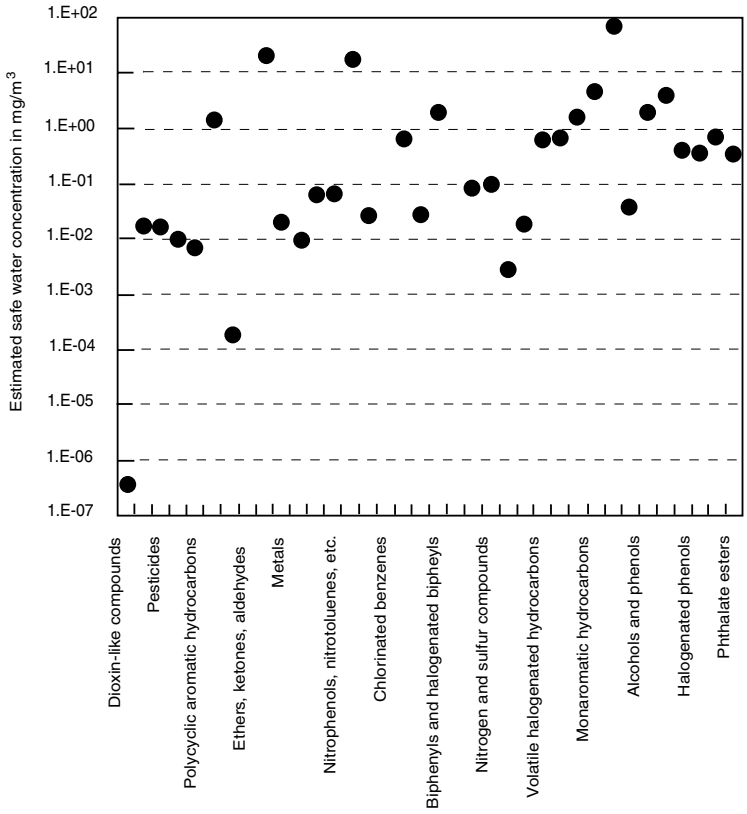

FIGURE 3-4 Estimated safe water concentrations for some TICs regulated by EPA.

Board Action Plan with Respect to the Findings and Recommendations of the Presidential Advisory Committee on Gulf War Veteran's Illnesses (1997, p. 2-3),

> Federal research requests for proposals include the possible long-term health effects of chemical and other hazards (including subclinical exposure to chemical warfare nerve agents) . . . development of a strategic plan [is under way] for research into the potential health consequences of exposure to chemical or other hazards, including low levels of chemical agents.

However these studies will take several years, and improvements can and should be made before then. A starting point for the working definition of low-level concentration could be the low-dose data currently available and the emerging capability of detection equipment.

The U.S. Army Center for Health Promotion and Preventive Medicine (CHPPM) has published Technical Guide 230A, *Short Term Chemical Exposure Guidelines for Deployed Military Personnel*, which can be used to address the potential health risks that may be experienced by deployed military personnel following temporary or short-term exposure to a number of toxic chemicals. The report gives Military Air Guidelines-Short Term and Military Water Guidelines-Short Term for chemical warfare agents, military smokes and obscurants, riot control agents, and TICs. The TICs are ranked according to high, medium, and low priority (U.S. Army CHPPM, 1999). A second technical guidance document (TG 230B) under development will address the risks associated with long-term exposures (i.e., from 14 days to one year).

For biological warfare agents, current DoD estimates of the detection level to protect against infection can be found in the last column of Table 3-1. Ideally, however, much greater detection sensitivity would provide a margin of safety before an area is declared free of biological agents. A first step toward more sensitive assessments and models of dose-response relationships would be to determine their feasibility. Methods developed by epidemiologists, toxicologists, and biostatisticians for chemicals would be a logical starting point.

FINDINGS AND RECOMMENDATIONS

Finding. Because little information is currently available relating long-term health effects to low-dose or low-dose-rate exposures to chemical agents, it is extremely difficult to set performance criteria for detecting and monitoring concentrations of these agents. As a starting point for a working definition of low-level concentration, DoD could use the low-dose data currently available and the capability of available detection equipment.

Recommendation. The Department of Defense (DoD) should increase its efforts to collect and evaluate individual and group dose-response data for a broad set of chemical warfare agents. Studies could include standard animal toxicity testing protocols for long-term effects, as well as retrospective epidemiological studies on individuals exposed to these substances in their occupations. DoD should use the detection capability of available equipment as its working definition of low-level concentration.

Finding. In addition to chemical warfare agents, thousands of TICs are in or are brought into the theater of deployment. These chemicals include pesticides, fuels, paints, and lubricants. Under combat conditions,

existing controls and safety precautions may not be practical. Storage tanks, production facilities, pipelines, and other equipment may be damaged, for example, and the TICs dispersed. Exposure under these conditions may be uncontrolled, unreported, unrecorded, and extremely dangerous. Exposures could have long-term health effects that cannot be easily distinguished from the long-term health effects of low-level exposures to chemical warfare agents.

Detecting and monitoring exposures continually to the full set of toxic chemicals would be extremely difficult, if not impossible. Toxicity data for a number of TICs being developed by some government agencies, such as the EPA and OSHA, are being reviewed by independent groups, such as the NRC COT. The data, thus far, show large variations in toxicity.

Recommendation. The Department of Defense should review its current efforts to catalog and prioritize toxic industrial chemicals. This information should be used to anticipate the types of chemicals that may be encountered during a deployment and to prioritize them.

Finding. Very little information is currently available to relate long-term health effects to low-level exposures to biological agents. Almost no information is available on how combined or sequential exposures to low levels of CB agents can affect the short-term or long-term health of troops. Until DoD can accumulate and analyze information on low-level exposure or dose response, as well as on long-term chronic effects, it will be very difficult to set performance criteria for detecting and monitoring concentrations of CB agents for assessments of long-term health effects. Potential interactions among agents, which can be cumulative, synergistic, or antagonistic, add to the difficulty. For example, chemical interactions may, in fact, abate, or even destroy, a biological agent. In fact, at one time, DoD research was focused on using a chemical agent to counter a biological agent cloud.

Recommendation. The Department of Defense should increase its efforts to collect and evaluate low-level dose-response data for a broad set of biological agents. The data should include information on the infectivity of a range of both warfare and endemic biological agents. At the same time, studies should be undertaken to determine whether and which combined chemical and/or biological agent exposures should be investigated. This information should be used to define a strategy for monitoring exposures to multiple biological agents.

Finding. Current criteria for detecting CB warfare agent concentrations are designed to prevent exposures to lethal and incapacitating levels.

Often the only way to determine if individuals have been affected by exposures to harmful agents is if they have immediate symptoms. Thus, data are not provided in a form that can be used to establish or verify retrospectively the health effects of CB agents over the long term.

Recommendation. The Department of Defense should establish a plan to collect data for all types of potential agent exposures to identify potential or emerging medical problems quickly. If possible, these medical problems should then be evaluated in terms of any prior exposures to chemical and/or biological warfare agents that have been associated with that health outcome. This plan should include guidelines for who should get the information and when they should receive it.

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

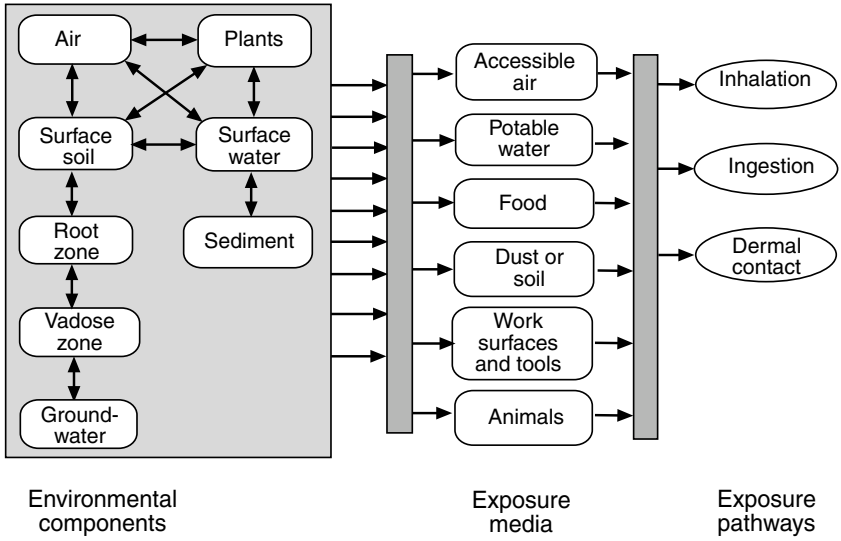

FIGURE 4-1 Links among environmental media, exposure media, and exposure routes. Source: Eisenberg and McKone, 1998.

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.

5

Detecting and Monitoring Harmful Agents

This chapter assesses current and emerging technologies and equipment for detecting the presence of harmful agents and monitoring changes in their concentration over space and time. The chapter describes DoD's current and planned techniques for (1) point and area sampling, (2) local and remote detecting, and (3) real-time and delayed analyses. More detailed descriptions of technologies and equipment can be found in Appendices D and E. The focus in this chapter is on the capabilities of technologies for detecting and monitoring agents at low concentrations.

Three key questions provide a framework for assessing detection and monitoring technologies:

1. Are current technologies for sampling and detecting harmful agents capable of answering questions on both short-term threats and the long-term health of deployed forces?
2. Will the technologies under development for sampling and detecting harmful agents be capable of answering questions on both short-term threats and the long-term health of deployed forces? (Until recently [post-Desert Storm], the requirements for chemical and biological detection systems were related only to acute exposures likely to affect a unit's ability to fight.)
3. What actions can DoD take to foster the development of and better use of sampling and detection technologies to protect the health of deployed forces?

The following criteria are used to evaluate individual technologies: reliability; sensitivity; selectivity (i.e., discrimination between the target substance and similar substances); speed; portability; and cost.

Measurements of concentrations involve physical and/or chemical techniques, such as mass spectrometry, light scattering, and enzyme interaction. The equipment includes one or more measurement technologies in a system for sampling, separating, detecting, and monitoring CB agent concentrations in air, soil, water, and food. The equipment often includes devices to record, store, transfer, and analyze data.

In evaluating technologies and equipment, a few overarching issues can be helpful. Table 5-1 shows the information needs and timing that detection/monitoring equipment must support before, during, and after a deployment. The portfolio of technologies and equipment being developed for deployments (along with doctrine for their use) should provide information that addresses these needs. The elements in Table 5-1 should be applied systematically to each class of agent (chemical warfare agents [nerve agents, blister agents, choking agents, etc.], industrial chemicals, and biological warfare agents).

Before deployment, harmful agents in the intended theater of deployment should be detected and monitored for intelligence purposes and for planning exposure assessments. During a deployment, real-time detection of harmful agents will be required to ensure that mission objectives are met and for continued monitoring. The information can be archived and used to determine low levels of chemical concentrations for dose reconstruction and long-term health risk assessments. Biological samples could also be collected for studies of postdeployment health effects.

In the sections that follow, technologies and equipment for detecting and monitoring chemical agents and technologies for recording and evaluating collected data are described. A matrix is presented showing, for each detector system (and for each chemical contaminant the system senses), the range at which contaminants are detected, the detection limit at maximum range, and the reliability of identification and quantification. Equipment for detecting and monitoring biological agents are then described. The chapter ends with descriptions of procedures and systems for recording and evaluating information.

DETECTING AND MONITORING CHEMICAL AGENTS

A wide variety of measurement equipment is available to DoD. Testing kits, detectors, and monitors of varying sensitivity (lowest level detectable) and specificity (ability to distinguish the target substance from similar substances) have been developed and/or used by the armed forces to identify concentrations of harmful agents. In addition, DoD,

TABLE 5-1 Information Needs and Timing for Measuring Short-Term Threats and Long-Term Health Risks

Information Needed	Before Deployment	During Deployment	After Deployment
Short-term threat	Intelligence and planning	Real-time measurements	Retrospective assessments
	Enemy CB capabilities	Contaminated areas	
	Means of delivery	Performance-degrading concentrations	
	Agents available		
	Enemy troop CB protection	CB agent concentrations	
	Enemy CB doctrine	Location of enemy	
	Prior CB use by enemy	CB means of delivery	
	Endemic CB threats in the region	Industrial sites with large stores of CB agents and TICs	
	Large stores of toxic chemicals	Use of protective clothing	
	Threshold concentration/time factors for any CB agents likely to cause short-term casualties		
Long-term health risk	Baseline data on exposures prior to deployment	Data that can be used to support health studies	Data on post-deployment exposures
	Susceptibility of troops to CB agents	Data on chemical concentrations and locations of these concentrations	Possible low-level exposure during deployment
	Threshold concentration/time factors for any CB agents likely to cause long-term health risks	Troop location and time histories	
		Use of protective clothing	

other federal agencies (e.g., EPA), and the private sector continue to develop technologies and equipment for detecting and monitoring concentrations of TICs in multiple environmental media.

Measuring Chemical Concentrations

Measuring the concentration of a chemical substance can be visualized as a three-step process (NRC, 1991b). First, the medium (air, soil, water, or food) containing the chemical substance is sampled. Next, the chemical substance of interest must be separated from or otherwise distinguished from other chemical species that are present. Third, the chemical is identified. In actual practice, these steps often overlap to varying degrees (see Figure 5-1). An example of a procedure with no overlap is the detection of aerosol-bound PAH compounds. First, airborne particles containing PAHs are sampled and collected on a filter. Next, the PAH compounds are separated from the particles and then separated as individual compounds by chromatography or a similar process. Finally, the individual PAH compounds are detected by fluorimetry or a similar process. Other measurement processes combine detection with separation. For example, gas chromatography with flame ionization includes separation (gas chromatography) and detection (flame ionization) in one step. Many remote or point measurement devices that use infrared beams combine sampling and detection and use software analysis to carry out the separation step. In some measurement methods, a single device does

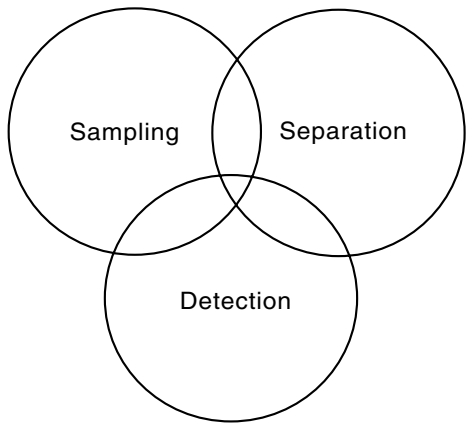

FIGURE 5-1 The three steps for measuring chemical concentrations in an environmental medium (air, water, soil, or food). Source: NRC, 1991b.

the sampling, separation, and detection. For example, a surface acoustic wave (SAW) detector draws in a sample, separates it on a membrane, and detects the agent with a single device.

Sampling

Sampling is the process of collecting the environmental or biological medium likely to contain the harmful agent. The sampling process can be active or passive; remote, stand-off, or local; mobile or stationary; personal or area. In addition, samples can be environmental or biological (e.g., breath, blood, urine, or hair).

Active and Passive Sampling

Chemicals dispersed in air as vapors or aerosols can be sampled actively or passively. (Vapor-phase chemicals are volatile chemicals found as gases in air. Aerosol-phase chemicals are either dispersed in air as droplets or are bound to particles). Active sampling requires that a person or automatic device direct and carry out the sampling. Passive sampling requires a minimum of equipment and a minimum of operator intervention. For example, airborne chemicals can be sampled actively using a pump to pull contaminants through a collection device. In contrast, passive sampling of airborne contaminants relies on diffusion to deliver airborne contaminants to the collection medium. The major advantage of passive sampling is that it does not require elaborate equipment and/or a number of well trained operators. The major disadvantage of passive sampling is the typically long time required to collect sufficient material for analysis. Passive sampling also tends to be less accurate than active sampling.

Remote, Stand-off, and Local (Point) Sampling

Remote sampling is done by equipment located at the point of interest but operated from a remote location. Stand-off sampling involves both the equipment and the operator being away from the location of interest. Local (or point) sampling is done by equipment and an operator at the location of interest. The advantage of the stand-off and remote approaches is that they provide advanced warnings by detecting agent concentrations before troops have any contact with the contaminated environmental medium. Remote and stand-off sensing of contamination can be conducted at various levels of spatial resolution using current military techniques and equipment, sometimes directed by intelligence information. Even though remote and stand-off sampling

are typically less accurate than local sampling, they are the sampling strategies of choice for protecting troops from potentially lethal clouds of agents. However, local sampling should be used for assessing low-level exposures because it provides more accurate measurements.

Mobile and Stationary Sampling

Mobile devices can provide samples of environmental media over a wide area that can be integrated to measure potential exposure. Mobile sampling increases the likelihood of finding local "hot spots." However, because mobile samplers must be light and portable, they are often not as accurate as stationary samplers.

Personal Sampling and Area Sampling

Area sampling of the air over a troop operation provides a measure of potential human exposure. However, personal sampling of the air in the breathing zone of an individual can provide a much better measure of exposure. The breathing zone is typically defined as the space within about one foot (30 cm) of the nose or mouth. For personal sampling, a small device is typically mounted on clothing that covers the chest. Measures of concentrations in the breathing zone are generally considerably higher when measured by personal sampling than when measured by area sampling, especially if the individual is engaged in activities that release or resuspend chemicals from soil in the area or from accumulated contamination on clothing.

Biological Sampling of Potentially Exposed Personnel

Personal badges and monitors can provide sufficient information to warn of certain gases and aerosols that could produce acute responses. However, for agents that can penetrate the skin after dermal exposure, or for some agents that are cumulative and produce delayed effects, biological monitoring of blood, urine, or hair can be analyzed for the presence of the agent metabolites, enzymes, and adducts in endogenous proteins or DNA. The utility of biological monitoring depends largely on knowing which metabolites are relevant. Most, if not all of these analytes, are likely to vary greatly in biological concentrations, and analyses can be quite expensive (Zhitkovich and Costa, 1998). Biological sampling and exposure assessments for deployed forces are discussed in detail by Lippmann (in press).

Sampling for Separation and Detection Technologies

Sample collection requirements vary greatly for different technologies. For example, active samplers linked to a gas chromatography/mass spectrometry system use small pumps to draw air through a collection medium, such as a filter or a vapor trap. Some detection devices require only a small amount of agent, others require much larger amounts. For some separation and detection technologies, the samples must be carefully stored and treated with a solvent before analysis.

Separating and Detecting Chemical Agents

Separation and detection technologies make use of the attributes of chemicals that distinguish them from other chemical compounds and make them detectable. These attributes include the mass-to-charge ratio of the molecule or atom; absorption and scattering of electromagnetic energy (particularly in the infrared to microwave region); chemical reactions that cause color changes; reactions with enzymes; physical characteristics that allow separation processes; electrochemical properties; and reactivity that causes unique emissions, such as chemiluminescence. Many detection technologies (e.g., mass spectometry) are based on some form of spectrometry, the use of the absorption, emission, or scattering of electromagnetic radiation by atoms, molecules, or ions to detect target substances qualitatively or quantitatively. A sensor is a device that produces a measurable response to a change in a physical condition (e.g., temperature or thermal conductivity), chemical concentration, or electronic charge. In Appendix D of this report, a number of technologies for detecting vapor-phase and aerosol-phase chemical agents, as well as chemicals in other media (e.g., water, soil, or food), are described.

Detecting and Monitoring Vapor-Phase Chemicals

The threats posed by many chemical warfare agents and TICs are most significant in the vapor phase. Analyses of samples of vapor-phase concentrations can reveal not only which agents are in the air but can also signal the presence of these agents in other media. Because the presence of vapor-phase chemicals is often transient, they must be detected quickly and accurately. Technologies that can detect chemical warfare agents in air, water, and food can, for the most part, be adapted to also detect industrial chemicals and other harmful chemicals likely to be found in the deployment environment.

Many toxic chemicals partition between the vapor phase and the condensed phase (including condensing onto the surface of airborne

particles), which can affect the health consequences of exposure to these chemicals. Thus, ideally, the amount of agent in the aerosol and vapor phase should be detected independently. Samples must be taken carefully to ensure that the procedure does not alter the distribution between the vapor and condensed phase.

A large number of technologies are available for detecting vapor-phase chemicals in the atmosphere, including color-change technologies, ion mass and mobility spectrometers, technologies based on infrared absorption and emission spectroscopy, chromatography, optical emission/absorption methods, physical- and chemical-process-based sensors, and enzyme methods.

Point (Proximate) Detection of Vapor-Phase Chemicals

Technologies capable of local detection of airborne chemicals are infrared spectroscopy methods. These include Fourier transform infrared (FTIR) spectroscopy and tunable infrared laser absorption spectroscopy, mass spectrometry, ion mobility spectrometry (IMS), enzyme methods, and phosphorous chemiluminescence detection (PCD). Each of these methods has advantages and limitations. Although FTIR is a mature technology, it requires a trade-off between speed and sensitivity. Mass spectrometry, which uses chemical ionization and quadrupole ion trap technology, is likely to outperform other technologies, but portability and speed can be problems. IMS has not demonstrated a level of performance that would justify its selection over other technologies. Enzyme immunoassays will never be fast and are likely to remain finicky to use but are as specific as any technology available. In laboratory studies, PCD has demonstrated the necessary speed (as little as one second response time), the necessary sensitivity, and no problems from interference. The response time will be longer if a gas chromatography step is required, which is likely in many situations. PCD is not likely to be included in hand-held or portable devices in the near future, however. Immunoassays can probably not be developed for all agents of interest because of variations in immunogenic properties among different agents. As a localized air-sampling technique, microwave spectroscopy appears to offer unambiguous chemical identification in real time without pretreatment. However, portability is a problem, and this technique does not work for medium or large molecules.

SAW is a promising technology, but it has not been tested in a wide range of field conditions, and sensitivity/specificity trade-offs are still a significant problem. SAW could provide a rapid, portable technology for personal monitoring but has the disadvantage of requiring that each agent

have a specific SAW coating on the surfaces where the acoustic detection occurs (DoD, 1997b). The SAW device will be difficult to adapt for the detection of TICs and other harmful chemicals because the device operates on the basis of target chemicals dissolving into the SAW's surface coatings. Because the span of solubility values is limited and not narrow valued, the number of target chemicals has to be restricted accordingly; interferences can compound the problem. The SAW device can detect and identify a wide range of chemical agents with only six different coatings. However, more coatings may be needed to achieve higher degrees of specificity for large target populations, such as TICs. If new agents respond to existing coatings, it will be fairly simple to change the detection software to recognize them. If not, new coatings will have to be developed.

Stand-off Detection of Vapor-Phase Chemicals

Currently, only FTIR and light detection and ranging (lidar) can be used for stand-off detection of vapor-phase chemicals (Stedman, 1999). FTIR provides passive detection, but it cannot detect all chemicals of interest. FTIR relies on spectral pattern recognition software to translate individual species concentrations out of complex multicomponent spectra. Thus, an important issue for detecting and monitoring TICs is that the equipment and software be properly calibrated for detecting specific chemical agents. In addition, operators must be trained to monitor chemicals other than chemical warfare agents. Calibration and training should be done before deployment. Like many other detection technologies, the specificity and sensitivity of lidar depend on proper calibration. Lidar is considered an active detection system.

Microwave spectroscopy has been considered but not yet demonstrated as a stand-off technique. One problem with microwave spectroscopy is extracting detailed information from pressure-broadened spectral signatures. It may also be difficult to separate the detection signal from microwave "noise" in the deployment arena.

Stand-off technologies, such as FTIR, have been used by EPA and private sector organizations to monitor air emissions. FTIR has the capability of measuring more than 100 of the 189 HAPs listed in Title III of the Clean Air Act. However, detecting multiple agents requires spectral-recognition software that can translate mixture spectra into component concentrations. This could limit the use of FTIR for complex mixtures of pollutants in low concentrations. When the Clean Air Act amendments were passed in 1990, measurement methods had only been developed for 40 HAPs.

Problems with Pollutant Interference

The problem with all vapor-detection technologies is that they must be able to distinguish one pollutant from another in a complex chemical environment. The problem is especially difficult for stand-off detectors, which work best when they can be calibrated to environmental conditions and types of chemicals. In most deployments, however, calibrating the equipment for the local conditions will be impractical, if not impossible. Because the specific target chemicals may not be well known, it will be difficult to calibrate detection devices for the hundreds of chemicals that could pose a threat to the deployment force.

Selectivity has also been a serious problem for most current local (point) detection equipment and all of the stand-off detection equipment. Selectivity will be an important capability of emerging technologies.

Aerosol-Phase Detection

Many harmful chemical agents, including chemical warfare agents and TICs, are dispersed in the atmosphere as aerosols or attached to atmospheric aerosols. Important characteristics of particles include size distribution, internal versus external mixing, and differences between the size distribution and composition of toxic particles and ambient particles. Identifying harmful agent particles requires defining the attributes of target particles, such as particle mass, particle number, and organic carbon content.

Detecting aerosol-phase chemicals requires either collecting and analyzing aerosol particles or using particle spectroscopy (i.e., infrared or lidar). Scientists are working to develop portable advanced instruments that can measure the size, mass, and chemical composition of individual airborne particles in real time. Currently, aerosol mass spectrometry is used to characterize atmospheric aerosols. However, many emerging technologies have the potential for assessing the size distribution and chemical composition of atmospheric aerosols.

Current Methods

Aerosol mass spectrometers, which measure particle size, are currently used to characterize atmospheric aerosols. Mass spectrometers work in two stages: particle sizing followed by mass spectroscopy (Gard et al., 1997; Green et al., 1998; Johnston, 1999; Noble and Prather, 1996; U.S. Army SBCCOM, 1998). Particle sizing is achieved by different methods. One approach is to measure particle time of flight by timing light-scattering signals from different laser-beam probes. When

the difference in mass-to-charge ratio of ionized aerosol particles is used to characterize chemical composition, mass spectroscopy is used after the aerosol particles are vaporized. Composition attributes that can be derived from the mass spectra include the dependence of composition on particle size, comparison of surface composition to total composition of the particle and (in some cases) composition of the organic molecule.

The goal of aerosol mass spectrometry is to provide on-line, real-time chemical analysis of individual aerosol particles, which are characterized in terms of bulk composition, surface composition, organic chemical species, and inorganic chemical species. An on-line system minimizes sampling artifacts caused by condensation, evaporation, and/or chemical transformation. A real-time system provides high temporal resolution and can monitor rapid changes in particle composition.

Only a few adequate on-line techniques are available for detecting and characterizing small aerosol particles. Conventional methods involve isolating particles on filters followed by analysis in the laboratory. The isolation processes often disturb the aerosol and thus render the data questionable because particles can evaporate or react before analysis. Aerosol spectrometers use lasers or hot surfaces to volatilize aerosols. Newer spectrometers that use gentler vaporization strategies will probably overcome this problem. An example of an emerging technology based on aerosol spectrometry is aerosol time-of-flight spectrometry (ATOFMS), which provides the size and chemical composition of individual aerosol particles in real time (Noble and Prather, 1996). With sufficient development funding, ATOFMS could be made field portable in the next decade. It is not likely, however, that it could be made small enough to be used by an individual soldier.

Criteria for assessing the performance of aerosol-agent detection devices include reliability, sensitivity, selectivity, speed, portability, and data archiving. Current on-line methods for assessing aerosol-phase chemicals are becoming more reliable, and field measurements are now routinely performed by aerosol mass spectrometry. One concern about the reliability of this technology is whether the laser/particle beam alignment will remain stable under the extreme conditions of a deployment. The sensitivity of these devices is improving. Historically, chemical concentrations were determined empirically from particle characteristics; now, the chemical composition of individual particles can be better analyzed, and particles can be quantitatively grouped by composition and counted. In addition, if organic chemicals on particles are not badly fragmented from volatilization, individual chemical concentrations can be determined to the parts-per-thousand level for individual particles.

Particles can currently be quantitatively grouped by composition only if internal mixing does not occur. Distinguishing among organic species

remains difficult because water and other contaminants in the air may alter the observed spectra. Up to 10 particles per second can now be routinely analyzed under favorable conditions. New systems using hot surface vaporization instead of laser vaporization can size and then chemically assess thousands of particles per second (Jayne et al., 1998).

Portability remains a problem for current systems. Field aerosol mass spectrometers using laser vaporization typically require more than 30 amps of continuous power and weigh a few hundred pounds. Smaller versions are under development. Devices that use surface vaporization can be smaller and require less power. The use of an IMS may reduce the power requirements to 5 amps and the weight to 10 pounds.

Current mass spectrometer systems are compatible with archiving real-time data. Single-particle mass spectra are digitally recorded and can be analyzed automatically.

Emerging and Future Developments

Technological improvements are likely to increase the reliability, sensitivity, selectivity, speed, and portability of devices for detecting aerosol-phase agents. Enhancements to basic methods of mass spectrometry will be one important source of improvements. SAW technologies have the potential for detecting aerosol-phase chemicals and are being investigated although the coating solubility problem will have to be overcome. Lidar is being considered for stand-off assessments of particles and has the potential for detecting aerosol-phase chemicals. Lidar would require the development of absorption spectra for particles and aerosol-phase chemicals.

Detecting Chemicals in Water, Food, and Soil

Some of the chemical detection technologies used for detecting vapor-phase chemicals can also be used for detecting chemicals in water, food, and soil. Chemiluminescence can take place in either the solution or vapor phase and thus can be used for detecting chemicals in water. Determining the presence of chemical agents in food and water is most often performed with the assistance of a gas chromatograph/mass spectrometer following an extraction step. Liquid chromatography, which is used to separate analytes in a solution, works with both metal ions and organic compounds. The mobile phase of the separation column is a solvent, and the stationary phase is a liquid on a solid support, a solid, or an ion-exchange resin. Most agents in food and soil cannot be detected directly or in real time but require a solvent-extraction step.

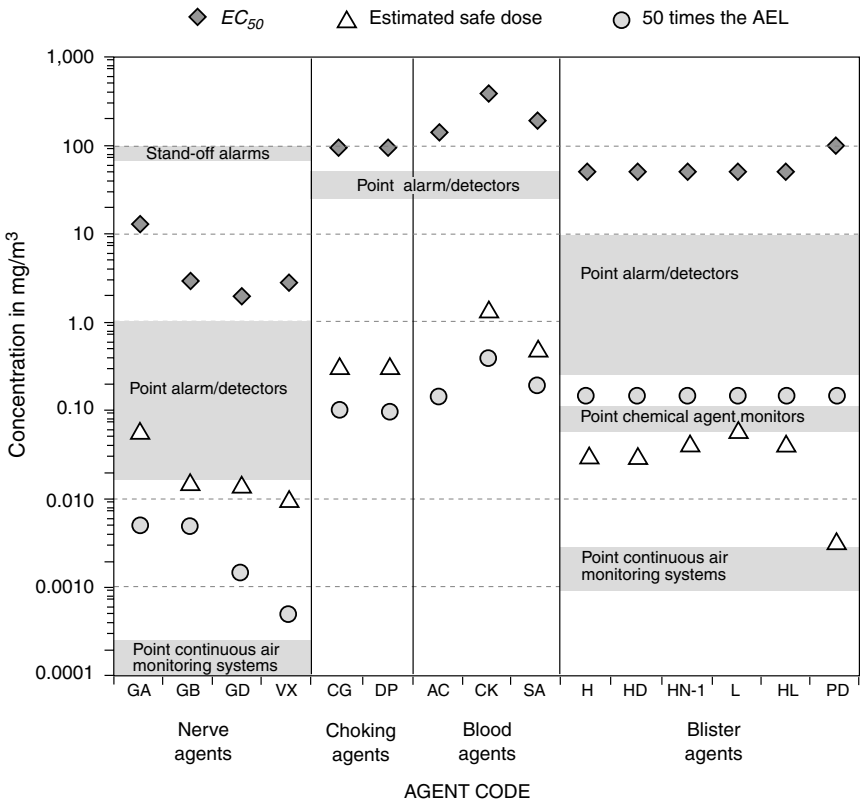

FIGURE 5-2 Detection sensitivities for detection equipment compared to the EC_{50} (the 30-minute average air concentration that would result in the LCt_{50}), DoD's estimated safe concentration, and the AEL.

Summary Evaluation of Chemical Detection Technologies

DoD's stated strategy for chemical detection is to use a suite of complementary technologies to ensure enough warning time for contamination avoidance (JCS, 1996). Figure 5-2 provides a summary review of the chemical detection/monitoring technologies and other devices discussed in this chapter. A comparison of the lethal levels and DoD's "safe" concentrations to device sensitivities shows that current technologies do provide a margin of safety from lethal exposures. However, only complex, nonportable systems have sufficient sensitivity to detect the AELs.

Detecting concentrations near the AEL will be a measure of the value of emerging equipment for detecting low-level exposures. For example, the joint chemical agent detector (JCAD) will be more selective, more sensitive, and more portable than current equipment but may not be sensitive enough to fully address low-level exposures. Sensitivity at AEL-level concentrations has not been demonstrated in field tests for any emerging technology.

Current equipment is designed primarily to detect nerve and blister agents. Choking, blood, riot-control, and psychochemical agents, as well as biological toxins and TICs, are not high priorities in the design specifications of available equipment. The only devices explicitly capable of detecting these agents are large gas chromatography systems. The priorities for future equipment continue to focus on nerve and blister agents. The speed of detection is likely to continue to increase for all detection technologies.

DETECTING AND MONITORING BIOLOGICAL AGENTS

At present, the capability of detecting biological agents is limited. However, DoD has identified the need for local (point) and stand-off, real-time biological agent detection and has given the development of this capability a high priority for the near future. The following discussion provides a review of several existing and emerging technologies and tools for detecting biological agents during deployments. More detailed descriptions of these systems are provided in Appendix E. This appendix includes a review of each system's local and stand-off sampling capability, personal sampling capability, use or calibration with biomarkers, and use of surrogate samples.

Measuring Biological Organisms

Numerous methodologies are currently available for detecting biological material collected from environmental samples. No one analytical method is likely to support all requirements for all situations, however, so selection criteria will help in the selection of an appropriate analysis method. Table 5-2 is a summary of major criteria and supporting considerations for detection and monitoring devices at fixed sites as well as mobile facilities.

Sample Matrix

An analysis of environmental samples for microbial contaminants encompasses a variety of matrices (i.e., substances that contain biological organisms), including air, water, surfaces, and food products. Collection

TABLE 5-2 Criteria for Selecting Analytical Methods for Detecting Biological Contaminants

Criterion	Considerations
Matrix sampled	Collection medium Temporal and spatial variability Interference from indigenous microbial populations and background constituents
Type of information needed	Qualitative/quantitative data Level of specificity Level of sensitivity (detection limits)
Integrity of sample	Storage prior to analysis Archiving capability
Analysis timetable	Turnaround time/speed of analysis Continuous/real-time versus batch analysis Capability of multiple analyses
Physical design	Reliability Portability Resistance to countermeasures Nonvolatile memory
Data interpretation	Accuracy Precision Reproducibility

strategies for each matrix could involve an assortment of sample media. The analysis method must be matched to the environmental matrix and to the collection medium. In addition, the detection of microbial contaminants is confounded by the ubiquitous presence of microorganisms and their by-products in the environment. The presence, composition, and concentration of microorganisms are heterogeneous and highly variable. Except in unique indoor situations (e.g., clean rooms associated with pharmaceutical facilities), the concentration and composition of microbial populations is highly variable over time and space, often fluctuating by several orders of magnitude. Abiotic constituents in the environment may also interfere with the detection of microbial contaminants.

Type of Information Needed

Qualitative data indicate the presence or absence of biological contaminants at a predetermined threshold. Quantitative data would

provide a numerical measure of biological contaminant(s). Specificity refers to the required level of discrimination among biological agents.

The genus level of microbial taxonomy is further divided into species, subspecies, and strain classifications. For example, the genus *Bacillus* contains numerous species, but the biological contaminant of interest may be the *Bacillus anthracis* present in a background of indigenous, nonpathogenic *Bacillus* species. Sensitivity (the range of measurements achievable) is often dictated by the physical limitations of the analysis methodology. The lowest possible detection limit will minimize dilution effects of the dispersion of the microbial contaminant in the environment and in sample collection. Although zero presence of an agent may be desirable, acceptable sensitivity levels are determined by the dose of the microbial contaminant that causes adverse effects in the exposed population.

Sample Integrity

Collection and preservation requirements are critical to the detection of biological contamination, as the integrity of the microbial populations within the sample is likely to change over time. Rapid processing/analysis at the time of collection can minimize problems with the preanalysis integrity of samples. Postanalysis archiving is a problem with all current methods.

Analysis Timetable

The speed of analysis, or the number of samples that can be analyzed in a given time, includes considerations of the analysis time per sample and the number of multiple samples that can be analyzed simultaneously per instrument.

Physical Design

Reliability, portability, resistance to countermeasures, and nonvolatile memory are engineering design goals for analytical technologies. Advances in miniaturization and microcircuitry have reduced once cumbersome methods to field-portable units for use by ground troops and mobile facilities. Communication links through digital satellite-based transmission can provide rapid data distribution for remote interpretation and archiving.

Data Interpretation

Accuracy is defined as the level of agreement between measurements and an accepted reference standard. Precision is a measure of agreement among individual measurements of the same property under the same or similar conditions. The reproducibility of data is determined by analyses performed on replicate aliquots of a single sample. Although these considerations are critical to assessing the capabilities of a biological detection technology, they are often not reported in the literature.

Emerging and Traditional Detection Technologies

Traditionally, the detection of microorganisms has been based on microscopy, culturing techniques, biochemical assays, and immunoassays. Microscopy is used to detect microbial populations in a given sample without regard to the physiological state of the organism; both viable and nonviable organisms can be detected. Because classical microscopy relies on the recognition of morphology (size and shape), limitations of this technique include lack of specificity and low sensitivity. Staining with fluorescent-labeled antibodies can result in the detection of target organisms, but the lower detection limits are generally greater than 10^4 cells/ml of liquid collection medium (ideal detection strategies would detect one cell in a sample). The detection of submicroscopic viruses requires specialized instruments, such as a transmission electron microscope.

Culture-based assays are limited to the detection of organisms that proliferate under the growth conditions of the analysis design. A successful culture depends on nutritional and environmental factors, the physiological state of the organism, and the presence of interfering substances. Stresses induced during dispersal, transport, and collection can increase the difficulty of detecting organisms. Analysis time is dependent on the organism, the growth medium, and the incubation temperature. However, 18 hours is generally required for the formation of a bacterial colony. Detection limits are highly variable depending on the application of the sample to the growth medium.

Biochemical-based and immunological-based analyses have improved the identification and enumeration of specific microbial contaminants in environmental samples. Generally, biochemical assays rely on a substrate and computer-assisted analysis. Immunoassays center on specific antigen-antibody recognition. When used sequentially with culture techniques, these immunoassays afford increased specificity. However, the analysis time is prolonged. Advances in nonculture-based immunoassay are expected to result in improved specificity and sensitivity.

Emerging Technologies

Improved detection and identification of microorganisms can be achieved with advanced biotechnology-based methodologies, including polymerase chain reaction (PCR) amplification; microchips; molecular beacons; electrochemiluminescence; biosensors; mass spectrometry; and flow cytometry. Brief summaries of these technologies are provided below. More detailed descriptions can be found in Appendix E.

PCR involves the use of unique primers to amplify DNA products. Reverse transcriptase PCR is used to detect ribonucleic acid (RNA) by generating a DNA copy of the nucleic acids in a single-stranded RNA. Detection limits are affected by the physical condition and concentration of the target nucleic acids. The presence and concentrations of background biotic and abiotic material may require that samples be pretreated to minimize interference in the sample matrix. Combining PCR with immunological techniques has resulted in a rapid and efficient solution-phase hybridization of labeled targets and biotinylated capture probes.[1] Results have been reported in two hours with a detection limit of 10 targets, which is relatively good for biological agents. Other methods may take from hours to days. Further information on advanced PCR analysis methods can be found in Alvarez et al. (1995), Beyer et al. (1995), Buttner et al. (1997), Friedman and Meldrum (1998), Garner et al. (1993), Herman et al. (1997), Kai et al. (1997), Kuske et al. (1998), Lindqvist et al. (1997), Lopez et al. (1996), Rigler et al. (1998), Sandery et al. (1996), Sawata et al. (1997), Suzuki et al. (1992), and Wu et al. (1997).

Integrating microchip technology and PCR has improved detection. A microchip-PCR array with 10 silicon reaction chambers, thin-film heaters, and solid-state optics can provide real-time monitoring with low power requirements and no moving parts. For in-depth information on microchip technology, the reader is referred to Belgrader et al. (1998), Ibrahim et al. (1998), Northrup et al. (1998), Waters et al. (1998), Wilding et al. (1998), and Yershov et al. (1996).

Nucleic acid probes that spontaneously undergo a fluorogenic conformational change when they hybridize with target fluorescent probes are called "molecular beacons." These beacons are specific, that is, they fluoresce only in the presence of a complementary target. Reactions are

[1] Biotinylated capture probes are constructed using biotin conjugated to a monoclonal antibody labeled with a fluorescein or rhodamine dye, enzyme, or isotope conjugated with avidin. When the avidin-labeled monoclonal antibody-biotin structure interacts with the targeted microorganisms, the reaction is detected with immunoassay, ELISA, or radioimmunoassay, depending on the label.

carried out in a sealed tube minimizing manipulation (Tyagi and Kramer, 1996).

Electrochemiluminescence technology integrated with equilibrium immunoassay provides detection ranges from 2.5 ng/ml to 2000 ng/ml with an accuracy and precision of less than or equal to 15 percent for human protein sequence and 0.5 ng/ml to 200 ng/ml for mouse protein sequence (Grimshaw et al., 1997).

Biosensors involving immunoassays in conjunction with a flexural plate wave transducer membrane have been used for the detection of bacteria. Current detection limits are relatively high (3.0×10^5 to 6.2×10^7 cells/ml) (e.g., Harteveld et al., 1997; Pyun et al., 1998).

Gas chromatography-ion trap tandem mass spectrometry and conventional quadrupole gas chromatography/mass spectrometry have been used to detect 3-hydroxy fatty acids (e.g., endotoxin; bacterial lipopolysaccharide in gram-negative cells), muramic acids (e.g., peptidoglycan in gram-positive and gram-negative bacterial cells), and ergosterol (fungal biomass) as indicators of the presence of microbial contamination. For discussions of advances in mass spectrometry, the reader is referred to Kaufmann (1995), Koster et al. (1996), Krahmer et al. (1998), and Larsson and Saraf (1997).

Flow cytometry utilizes simultaneous measurements of light scatter to determine cell size and structure. Fluorescence increases the capabilities to include quantitation of cellular components, antigen detection, and estimations of cell physiology (see, for example, Davey and Kell, 1997; Fouchet et al., 1993; Lange et al., 1997; and Perez et al., 1998; Seo et al., 1998). Instrumentation permits the measurement of 500 to 5,000 objects per second with the results displayed in bivariate histograms. Even though the combination of flow cytometry and fluorescent *in situ* hybridization has increased detection by two orders of magnitude over culture-based assays, detection rates below 10^2 cells are beyond the capabilities of currently available detectors. Immunomagnetic separation with fluorescent antibody-labeled beads and flow cytometry is also being used (Seo et al., 1998).

Fielded Equipment for Biological Agents

Current biological detection equipment is not as mature as chemical detection systems in terms of reliability, sensitivity, selectivity, speed, and portability. Rapid, remote detection of biological agents is based on analysis and the collection of aerosols. Point samples of soil or of aerosol currently must undergo microscopy and culture methods for a definitive identification and count of biological organisms. Some currently available detection equipment is listed below (DoD, 1999a; U.S. Army SBCCOM, 1998):

- the biological integrated detection system, a collection of components used to provide mobile detection capability (Berry, 1998)
- the interim biological agent detector, a point detection system used to detect background changes indicative of human-made biological warfare agents
- the XM94 long-range biological stand-off detection system, which provides long-range, large-area aerosol cloud detection and ranging and tracking capability
- the FOX nuclear, biological, and chemical reconnaissance system, a lightly armored, wheeled vehicle that can collect samples for laboratory analysis but is not capable of detecting or identifying biological material.

Emerging Equipment

An effective defense against biological warfare agents will require real-time, preexposure detection, discrimination, and identification of the threat. To address this requirement, several agencies, including the Defense Advanced Research Projects Agency, are focusing on the development of robust, unattended, real-time (less than 1 minute), highly sensitive (2 to 10 particles), small (less than 5 pounds), low cost (less than $5,000/unit) detection systems. The detection of biological warfare agents on the battlefield in real time with a very low rate of false alarms is a crucial requirement. However, with the possible exception of upconverting phosphor-diode laser technology, no technology currently under development is expected to meet these needs in the next five years.

DATA COLLECTION, RECORDING, AND STORAGE

Detection and monitoring systems provide valuable information for personnel in the immediate area of the equipment, as well as for forces and support personnel in the wider theater of deployment. Some existing equipment and many developing technologies not only provide a warning alarm, but also record, store, and transmit information on levels of chemical agents. Information storage and retrieval are crucial to postdeployment assessments of exposures.

Warning and reporting are the critical links between CB detection and CB protection and medical support. In addition to detection and monitoring, commanders need accurate, timely information about the concentrations of harmful agents. Collecting, evaluating, reporting, and storing information are critical issues in contamination avoidance. Currently, collection and transmission of information on threats are managed

through conventional communications channels. However, DoD is pursuing the development of dedicated hardware and software to collect, transmit, integrate, and evaluate CB information. These systems will also provide information management and control functions. The multipurpose integrated chemical alarm (MICAD) and JWARN are systems designed to perform these functions. Another concept, the joint biological remote early warning system (JBREWS) is planned to be a "system of systems" that will integrate several other systems, as well as miniature detectors.

Multipurpose Integrated Chemical Alarm

MICAD is an emerging integrated nuclear, biological, and chemical detection, warning, and reporting system. It automates the gathering of NBC contamination data from fielded detectors and sensors and automatically gives alarms and transmits reports up the chain of command. MICAD is not a detector; it is a system that collects, stores, and transmits information received from an array of detection devices, such as the M22 automatic chemical agent detection alarm chemical detectors.

Joint Warning and Reporting Network (JWARN)

The JWARN is being designed to provide joint forces with a comprehensive analysis and response capability to minimize the effects of NBC attacks or accidents/incidents (DoD, 1997b, 1999a; U.S. Army SBCCOM, 1998). JWARN will provide the operational capability to use NBC warning technology that can collect, identify, analyze, and disseminate threat information. The new system, which will be compatible with and integrated with other joint service systems, will be located in command and control centers and used by NBC defense specialists and other designated personnel. It will transfer data automatically to and from the detector or sensor and provide commanders with analyzed data for decisions on disseminating warnings to the level of individual soldiers on the battlefield. It will provide data processing, plans and reports, and access to specific NBC information for optimal use of limited resources.

JWARN is a three-phase program. Phase I includes the procurement of analysis software, the development of detector protocols, and the development of an interim field capability. Phase II will provide the total JWARN capability by integrating detectors and additional NBC software modules into the services command, control, communications, computer, intelligence, surveillance, and reconnaissance (C4ISR) systems. Phase III will upgrade JWARN communications and software to work with the next generation of detectors.

System Goals

An important purpose of systems such as MICAD and JWARN is to increase the warning time by eliminating the manual and voice transmission of data and replacing it with automated transmissions. With increasing numbers of detectors in the deployment theater and increasing sensitivities, these systems will be useful for assessing both immediate threats and low-level exposures to CB agents and TICs. However, because of the large amount of information, screening and prioritizing will be necessary to keep from overwhelming commanders. Even with computer automation, decisions will have to be made about who collects CB information, when and how it is transmitted, how the information is archived, and how and when it is retrieved. Incorporating nonvolatile memory in the data management system will be another important goal of these systems.

MONITORING, SIMULATION, AND DECISION MAKING

The information obtained from detecting and monitoring devices will be very valuable both for anticipating and avoiding potential exposures and for determining the distribution of exposures in postdeployment health studies. Monitoring exposures for individuals requires tracking the time sequence of chemical concentrations in one or more media (air, soil, water, food, etc.) at a specific location. It also requires tracking the locations and activities of individuals to assess their level of interaction with the contaminated media.

Not all media, all locations, and all time periods can be monitored for all potentially harmful agents. Obtaining that information would probably require more troops and equipment than the deployment mission itself. Thus, assessments will have to be based on exposure information and extrapolated from a limited number of samples. Also, decisions about contaminant avoidance, the use of protective equipment, and the need for medical surveillance will have to be based on uncertain or incomplete information.

To reduce uncertainties, sampling strategies should maximize the amount of information that can be obtained from a limited number of detection devices, and computers should not only log and display the information but also make simulations on the levels of risk patterns of detected concentrations and weather conditions.

TESTING EQUIPMENT AND FIELD DEMONSTRATION

Testing equipment is an important aspect of each stage of the R&D process. Site visits and reviews of the technology development process during this study revealed that substantial testing and demonstration of new equipment has been done. Nevertheless, these tests are typically designed only to demonstrate that a technology can work. Many field tests are restricted to Dugway Proving Ground or White Sands Missile Range, the only places properly equipped for full-scale field tests. Independent scientific reviews at each stage of the development and testing process appear to have not been done, which could limit the quality and reliability of the final product.

The most important attributes of detection and monitoring systems for field use are reliability, sensitivity, selectivity, speed, portability, resistance to countermeasures, and nonvolatile memory. A definition of these functional attributes should include the following issues. Reliability should include operational reliability, informational reliability (integrity), and a failure mode (warning or no warning). Sensitivity refers to the detection limit of an analytic technique and is a relative concept. For harmful CB agents, the sensitivity of a detection or monitoring device varies with the concentration of the agent being detected or sampled. Most harmful agents have a threshold concentration at which the likelihood of health effects exceeds an acceptable value. A useful detection device for a harmful agent should be sensitive at concentrations that correspond to the thresholds of likely health effects. Selectivity should be assessed in terms of how comprehensive the device is (i.e., how many agents can be detected), the rejection of interference chemicals, and identification of multiple harmful chemicals from a large set of chemicals in the environment. Speed should relate not only to how quickly an agent can be detected but also how quickly the device can be made operational in the field. Portability should be specified in terms of person-portability or vehicle-portability. Resistance to countermeasures must be defined by how well the device performs in the presence of decoys or electronic jamming. Nonvolatile memory refers to the ability of a device to retain data that has been recorded in case of a power failure or other disturbance.

FINDINGS AND RECOMMENDATIONS

Finding. Overall, the capabilities of technologies and equipment either in use or under development are severely limited in their measurements of concentrations associated with long-term health risks. A significant reason for this problem is that no formal requirements have been established for detecting and monitoring low-level, long-term exposures. Until acceptable low-dose exposures are specified, performance goals for

low-dose detection technology cannot be established. Specifications would provide designers, developers, and operators of detection and monitoring equipment with goals for their research.

Recommendation. The Department of Defense should establish criteria for detecting and monitoring low-level exposures to chemical and biological warfare agents and toxic industrial chemicals. These criteria should specify three detection levels: (1) immediate, dangerous, and life-threatening hazards; (2) short-term hazards; and (3) long-term health risks.

Finding. Because different technologies have different strengths and weaknesses, no single technology should be relied on for detection. By using complementary and redundant technologies and sensor fusion techniques, which are commonly used in other areas of the military (e.g., air defense and antisubmarine warfare), the risk of false alarms could be reduced, and agents could be detected at lower limits.

Recommendation. At least two different but complementary technologies should be used, along with sensor fusion techniques, for the detection of a given type of agent. This combination could significantly reduce the number of false positives and false negatives.

Finding. Most of the equipment currently available, as well as most of the equipment under development, for sensing CB agents is designed for detection and warning only. Detection devices typically give off audible or visible signals when the concentration is above the sensitivity level of the device or above a preset value. These devices are valuable for protecting troops from immediate harm but do not provide the kind of monitoring needed to assess less-than-debilitating exposures or to assess exposures that might have delayed health effects.

Not enough attention has been given to archiving the measurements from different detectors. In some cases, archiving is not possible because of the nature of the device. Devices operated for "warning only" cannot be used in combination with systems like the multipurpose integrated chemical alarm and JWARN to determine the spatial and temporal trends in agent concentrations—essential information for determining the evolution of a threat or for confirming the absence of an agent.

Recommendation. The Department of Defense should develop a comprehensive plan for collecting and archiving data and samples based on a matrix of short-term threats and long-term health risks for situations before, during, and after deployment. This matrix could be used to prioritize the different types of information required.

6

Tracking the Locations and Time-Activity Budgets of Deployed Military Personnel

Various methods used to track and describe the locations and time-activity budgets of the general population could also be used for tracking deployed military personnel, including subpopulations of individuals at higher risk of exposure to harmful agents. However, each method has capabilities and limitations that must be evaluated in terms of assessing life-threatening exposures to CB agents or industrial chemical stockpiles and of quantifying low-level exposures to CB agents and environmental contaminants for the purposes of current and retrospective exposure assessments and health and medical surveillance.

ACTIVITY PATTERN DATA

Exposure to an air pollutant in a specific environment is defined as the product of the concentration of the pollutant and the time (duration) an individual spends in that environment (Duan, 1982; Ott, 1982). Thus, the length of time an individual is in contact with the pollutant is as important for estimating exposure and risk as the pollutant air concentration. For dermal exposures, the duration of skin contact is as important as the concentration of the pollutant in the air or water that contacts the skin. Consequently, accurate data on the time individuals spend in specific locations and their activities during the day are critical to accurate exposure assessments. Time-activity pattern data and associated data from questionnaires can be used in three ways:

- as input data in exposure models for time spent in different

TABLE 6-1 Time Spent in Major Locations by U.S. Adults over 17 Years of Age

Location	Percentage of Time
Indoors at home	68%
Indoors not at home	19%
Outdoors	7%
Enclosed transit	6%

Source: Klepeis et al., 1996.

locations or environments (Johnson, 1995; Koontz et al., 1998; Ott et al., 1988)

- to identify the extent of close, personal proximity to sources of environmental contaminants, which can yield evidence of significantly greater exposures than environmental measurements and general population time-activity data (McBride et al., 1997; Ott et al., 1997); ideally, exposure models should use proximity data for exposure estimates
- to provide information on physical activity levels to improve estimates of pollutant intake, such as inhalation rates (Adams, 1993; EPA, 1997; Koontz et al., 1998; Layton, 1993)

Several major studies of activity patterns in civilian populations have been conducted in the last decade for estimating exposures to pollutants (Jenkins et al., 1992; Klepeis et al., 1996; Wiley et al., 1991a, 1991b). However, because of significant differences between the activities of deployed military personnel and the civilian population, much of the information collected on the general population cannot be used for exposure estimates for deployed troops. For example, as shown in Table 6-1, American adults over 17 years of age spend an average of 87 percent of their 24-hour day indoors and only a small amount of their time outdoors. Based on the duties of deployed troops and the nature of most deployments, most deployed personnel spend a much greater portion of their time outdoors. They also spend somewhat less time eating and sleeping and more time working. Thus, data specific to deployed personnel will be necessary for accurate estimates of exposures.

METHODS OF OBTAINING TIME-ACTIVITY DATA

A complete characterization of an exposure requires knowledge of the person's location and activity, both in terms of the geographical

location and of the microenvironment at that location (outside or inside a vehicle, building, etc.). Geographical location can be obtained from GPS, but data on the microenvironment requires other methods, such as activity diaries or logs, questionnaires, videotaping, or observation. These methods provide both real-time and retrospective information. Prospective questionnaires can also be used for specific purposes. Technologies such as GPS (Battelle Memorial Institute, 1997, 1999; Brauer et al., 1999; Maszle, 1998; Spear, 1998), the total isolated by microenvironment exposure (TIME) monitor (Moschandreas et al., 1993, 1994), and various motion sensors and data loggers (Brauer et al., 1999; Haskell et al., 1993; Pate, 1993; Schutz and Chambaz, 1997; Waldman et al., 1993) have been used increasingly in recent years to record or substantiate specific types of activity/location information for exposure research, as well as to record real-time data on a user's usual activities. All of these methods could be used to improve exposure estimates for deployed military personnel.

Time-activity methods were used in occupational health studies as early as the 1970s. However, despite the increased collection of time-activity data in exposure and health studies, the science of this field is still relatively young. Methods are still being developed, and no guidelines or standards for collecting and using data in exposure assessments have been widely accepted. The EPA has developed general exposure assessment guidelines (EPA, 1992b) and the *Exposure Factors Handbook* (EPA, 1996b) that provide general guidelines. However, no activity-pattern methodology is considered ideal, and the methods of choice are dictated by the specific data required, the application for which they are intended, the funds available, and the capabilities and characteristics of the subject population.

Global Positioning System

GPS is a satellite-based system that provides worldwide, continuous position, velocity, time, and related data to civil and military users. GPS has a large and growing number of applications in the fields of marine, land, and aerospace navigation and precise time and time transfer. These applications include nearly all uses of position, velocity, and precise time, such as in surveying, geodesy and mapping, precision farming, air traffic control, asset location and tracking, timing of communication systems and power grids, and many other civil and military uses.

GPS has a number of different modes of operation, each with its own performance capabilities. First, GPS can be used autonomously (on a stand-alone basis). In this case, the user equipment receives and uses only the signals from the constellation of spacecraft to determine user position, velocity, time, and related parameters.

GPS can also be used in a differential mode in which known navigation data at a reference point and time are compared with GPS measured data at the same point and time. The corrections from this process are then applied to the GPS measured data taken at a remote point. For real-time operation, a data link between the reference receiver and the remote receiver is normally used to communicate the corrections. This process has the great advantage of canceling the fixed (bias) measurement errors that have the same effect on both locations. The differential correction technique, which other navigation systems have also used to improve performance, performs well with GPS. The differential corrections can be used immediately or stored and used later with postprocessing methods.

Although GPS has performed extremely well and has generally exceeded expectations, some significant improvements can be made. A number of committees representing both government and civil communities have investigated the system's deficiencies over the past decade to determine the capabilities and features of a future GPS that would meet the needs of military and civilian users (McDonald, 1998).

GPS has been used in several recent exposure and activity studies (Battelle Memorial Institute, 1997, 1999; Brauer et al., 1999; Maszle, 1998; Spear, 1998) and can provide very useful information on the exact location of an individual, a unit, or a vehicle. Civilian GPS devices have consistently decreased in size and price over recent years, and are expected to be available in a small, lightweight wristwatch style the next year (McDonald, 1998).

The baseline GPS constellation consists of four spacecraft (and occasionally more) in each of six equally-spaced orbit planes. The spacecraft are at an altitude of 10,898 nautical miles (20,180 km) above the earth. The nearly circular GPS orbits are inclined at about 55 degrees to the equatorial plane providing users continuous worldwide access (if unobstructed) of between 6 and 12 GPS spacecraft.

DoD has also contracted to purchase the first group of a planned purchase of 33 fourth-generation, follow-on GPS spacecraft planned for replacement of the replenishment spacecraft. These 33 spacecraft will carry the GPS constellation well beyond 2010. The four generations of spacecraft are: I (developmental); II-IIA (current operational); IIR (replenishment); and IIF (follow-on). A summary of the basic GPS operating characteristics is given in Table 6-2.

Activity Diaries and Logs

Many different types of diaries and logs have been used to obtain activity and location data for exposure assessments. Typically, diaries and logs are in written form, but they may also be recorded directly into

TABLE 6-2 Expected Evolution of GPS Performance

	GPS Bands						
	RNSS		ARNS		Diff.	Position	
Mode of Operation (M or P/Y-code)	L1[a]	L2[a]	L3c[b]	SA	GPS	2000	2010
Conventional civil stand-alone SPS: C/A-code	<			≤		50–100 m	5–25 m
Code Differential SPS: C/A-code					<	1–5 m	30 cm–1m
Real time Kinematic (RTK) SPS: C/A-code, carrier phase meas.				≤	<	10–50 cm	3–20 cm
Survey: Post processing; long b. SPS: C/A and carrier phase (with 2f)	<	<		≤	<	0.5–10 cm	0.1–3 cm
Conventional civil stand-alone SPS: C/A-codes	<	<				NA	3–6m
Code differential *SPS: C/A-codes	<	<			<	NA	30 cm–1m
Precision stand-alone 2000 *SPS: C/A, & F-codes (10.23 Mcps)	<	<	<			NA	1–3 m
Real time Kinematic (RTK) *SPS: C/A C 10, carriers Φ meas.	<	<	<		<	NA	1–10 cm
Precision attitude measurement *SPS: C/A & F (10.23)—codes, carriers	<	<	<		< <	1 m radian 0.2 m rad	NA
Military receiver (1f) PPS C/A+P/Y or M-code	<<	<<				5–25m	3–20m
Military receiver PPS C/A+P/Y or M-codes	<<	<<				4m	0.5–1m
Military DGPS receiver PPS C/A+P/Y or M-codes	<<	<<			<	1m	20–50 cm

[a] Civil codes in 2010: L1, L2 (L2c) are C/A-codes.
[b] L3c assumed to be new F-code at 10.23. Mbps.

Note: Accuracy estimates for 95 percent confidence in horizontal; vertical accuracy is about 2.4 × horizontal dimension.

Source: McDonald, 1998.

Velocity		Time		
2000	2010	2000	2010	Comments
15–30 cm/s	10–20 cm/s	170–350 ns	40–100 ns	Iono dependent No SA in 2010
10–20 cm/s	3–10 cm/s	30–60 ns	20–30 ns	Iono dependent No SA in 2010
5–10 cm/s	1–5 cm/s	NA	NA	Iono dependent No SA: short b
NA	NA	NA	NA	L2 carr Φ in 2000 Baseline (b) dep.
NA	10–20 cm/s	NA	40 ns	No L2c in 2000
NA	5–10 cm/s	NA	20 ns	No L2c, in 2000
NA	2–10 cm/s	NA	10 ns	No L2c, L3c in
NA	0.5–3 cm/s	NA	NA	No L2c, L3c in 2000
NA	NA	NA	NA	No L2c, L3c in 2000 Attitude, angle Θ
0.1 m/s	0.05 m/s	100 ns	40 ns	E.g., PLGR (P/Y) Iono dependent
0.1 m/s	0.05 m/s	80 ns	25 ns	Std. 2f rec-(P/Y) Future 2f rec-(M)
5 cm/s	2 cm/s	50 ns	10 ns	Diff. GPS 2f rec S/C, alt. DL msg

an electronic data logger (e.g., a small device like the personal information carrier[1] [PIC] being developed by the Army) at specified intervals or into a computer file; the data entry can be performed manually or automatically. Diaries and logs can contain either current or retrospective data. For a more detailed discussion of the PIC and other major medical information systems, see reports by DoD (1999b), the Institute of Medicine (IOM, 1999), and the National Science and Technology Council (1998).

Written/Hard Copy Forms

Hard copy diaries or logs are typically carried by a subject throughout the period of interest, usually a day or more, and entries are made either with each major change of location or activity or at specified intervals, such as every hour. Alternatively, they may be filled in at the end of the study period (such as at night or within 24 to 48 hours following the period of interest) by recall either by the subject alone or in conjunction with an interviewer; 24- to 48-hour recall has been found to be relatively accurate (Freeman et al., 1991; Robinson, 1985), particularly when the entire day is covered in sequence. Self-reported diaries (filled in by the subjects without assistance from an interviewer) are common but have been found to be somewhat less accurate than interviews, especially for males. Females appear to provide more detailed and more accurate information in self-reported diaries (Stock and Morandi, 1989).

Quality control is achieved by pretesting the diary or log instrument with a few members of the subject population (i.e., a focus group) and through careful explanation of how the diaries or logs should be filled in. Careful review of the completed diary or log by a technician or interviewer also helps to ensure that no data are missing and allows for corrections.

The major advantages of hard copy diaries are that they are usable by anyone who can read and write, they are generally economical, and they can be used as backup files once responses have been entered into a data file. Disadvantages include the time and cost of coding and entering the data into computer files, errors due to misunderstanding of directions or undisclosed illiteracy problems, and incorrect coding and transfer of information from the diary to the computer file by the data management technician. Another disadvantage is the potential breach of security if diaries were to fall into enemy hands.

[1] The PIC is a matchbook-sized flash memory card that can be worn around the neck (like the former "dog tags") to store personal identification and medical data (DoD, 1999c; Investor's Business Daily, September 29, 1999; IOM, 1999).

Electronic/Computerized Diary and Logging Methods

Electronic or computerized diary or log data recording has several advantages over hard copy methods but may not always be suitable. Electronic methods eliminate the need for the coding and transfer of hard copy responses to a computer file. However, electronic methods can only be used for study populations that are comfortable with technological devices or studies in which interviewers or technicians enter the data. Also, if the electronic device malfunctions, all of the data for that participant may be lost.

Data Loggers

Data loggers are electronic devices used to record a person's activities. Typically, a limited number of activities and locations must be preprogrammed into the device, which limits the amount of detailed information that can be obtained by the investigator. Data loggers are most suitable for cooperative, technologically comfortable populations and studies that require only basic, limited data or gross estimates of time spent on major activities and locations. Because of early problems with malfunctioning devices, data loss, and practical problems, most investigators have chosen to rely on hard copy diaries. With recent advances in palm-sized data loggers and GPS technology, researchers have begun to re-evaluate their usefulness for exposure studies (Akland, personal communication) and have begun to use them more in field research (Brauer et al., 1999; Cohen and Cotey, 1997; Haskew et al., 1995; Wilkins et al., 1997).

TIME Sensor

One electronic monitor still being refined that may be of use to the military in the future in a modified form is the TIME (total isolated microenvironment exposure) monitor, a personal sampling device that has several capabilities designed to measure microenvironmental exposures to VOCs in four primary microenvironments (Moschandreas et al., 1993, 1994). One component, a "shadow sensor," identifies and records the user's location every 30 seconds in one of four categories: indoors nonoccupational; indoors occupational; outdoors; and inside a vehicle (in transit). The device uses an ultrasound transducer and electronic logging package to measure the vertical distance from the device to any obstruction or "ceiling" above it and interprets and records the data accordingly. Distances of more than 11 feet are interpreted to mean the user is outdoors; distances of 4 to 11 feet are considered indoors; and distances of less than 4 feet are logged to indicate that the user is inside a car, bus,

train, or other vehicle. To differentiate indoor occupational from indoor nonoccupational locations, the respondent must press a button upon entry to each indoor environment (the device sounds a reminder chime upon entry into an indoor location).

The second component of TIME determines the path of air to be sampled and the sampling rate, based on the location identified. The third component is the sampling system, which consists of four cartridges or tubes corresponding to the four microenvironments. The electronic sensor opens the valve to the correct cartridge for the current environment, and air is drawn through the carbon-based, multisorbent beds in the tube at a predetermined rate. The sample is later analyzed by gas chromatography to provide information on the individual's exposure levels of 42 VOCs in the four environments. The TIME monitor weighs about 1.6 pounds and measures about 7 x 4 x 1.5 inches.

TIME has been field tested and found to provide accurate estimates of time spent in the four major locations (with differences of only a few percent compared to data collected by other means), as well as improved measures of personal exposures over those determined by other measurement and modeling approaches (Moschandreas et al., 1994). TIME could be refined to meet specific needs and applications for deployed military personnel (Moschandreas, personal communication).

Questionnaires

Questionnaires are commonly used as adjuncts to diaries or activity logs to obtain data on specific activities that may involve the use of, or close exposure to, potential contaminant sources. Questionnaires are also used to obtain information on socioeconomic and demographic characteristics and household and building factors, such as heating sources and types of structures. They are also used to elicit specific data on the use of known sources of a particular pollutant of interest (for example, all indoor sources known to emit fine particles) and to elicit retrospective or historical exposure-related data, such as occupational histories and exposures. Questionnaires can also be used to obtain current information for use in prospective studies.

A number of quality control issues are associated with the development and administration of questionnaires and the interpretation of results, but these are reasonably well known and can be addressed by accepted methods (NRC, 1991a; Visscher et al., 1989). For example, the wording of questions, and even the order in which they are presented, can be critical factors in obtaining accurate data. For this reason, questionnaires must be pilot tested by a focus group of individuals similar to, or selected from, the intended subjects. Problems with nonresponse

and noncompliance are common with questionnaires administered to the general population or a population that is reluctant to be studied. Although noncompliance and nonresponse will probably be minimal problems in a military setting, steps should be taken to maximize the number of responses. Simple instructions, rapid follow-up, various types of incentives, and other methods have been used successfully to elicit complete responses and ensure a high response rate.

Videotaping

Videotaping has only recently been used in exposure assessment studies to study children's behaviors. Videotaping may have some limited use in special situations during deployment (e.g., to monitor the perimeter of known enemy chemical agent storage facilities).

Observers

Human observers have also been used to record human activities for exposure studies. This process suffers from some of the same disadvantages as videotaping—the subjects may change their behavior under observation, and the added expense and effort may not be justified. Human observers are useful for verifying certain activities of interest, especially those that are done frequently or in a specific location. For example, observers have been used to measure the time individuals spend filling their gas tanks at gas stations to estimate the duration of elevated exposures to volatile gasoline components (Colome et al., 1992; Wilson et al., 1993). Human observers may have some limited value during deployment.

Other Methods of Tracking Activities

Several other types of devices have been used to measure one or more aspects of people's activities and movements. For example, motion sensors have recently been used with personal air samplers to verify that a subject is wearing the sampler as agreed (Rodes et al., 1995, 1996). The data collected are correlated with the diary data to confirm the time periods when the sampler was worn as a quality control measure. Because monitors detect any motion, they can also provide an accurate measurement of the time individuals are resting or immobile and the time they are active at any level. This information can be used as a general confirmation of estimated inhalation rates for an individual by confirming the number of hours spent at rest.

FACTORS THAT DETERMINE HUMAN ACTIVITIES AND LOCATIONS

The activity patterns of any defined human population vary greatly. Capturing that variability requires that the primary determinants of the activities of individuals within the population of interest be identified and that studies be designed to obtain sufficient, preferably representative, data on these activities. For the general U.S. population, the following major factors determine people's activities, locations, and to some extent, their exposures to pollutants: age, gender, occupation, socioeconomic status, season of the year and day of the week, and geographic region or country. For deployed military personnel, the strong determinants of activities and movements from one location to another are very different. These factors would most likely include: the purpose of deployment (major theater war vs. noncombat small-scale contingency mission); occupation, duties, and rank of unit, squad, and individual; country and locale of deployment (e.g., desert or jungle); and branch of service (air, land, sea).

A baseline study of activity and location-time budgets of a sample of deployed military personnel could provide enough information to identify the relative significance of these and other factors as determinants of deployed troops' exposures to environmental pollutants and indirect (noninhalation) exposures to CB warfare agents. Once sufficient data have been obtained and the major factors identified and/or confirmed, subgroups at higher risk can be more easily identified and should become the focus of subsequent studies.

However, the assumption that a time-activity budget of deployed personnel is representative could be misleading. The duties and activities of different specialists require that subpopulations who have roughly similar work environments be identified. Any study of time-activity budgets of military personnel should be based on random sampling that provides representative samples of the specific population or subpopulation of interest. Random sampling provides a way of constructing a representative sample of the population of interest, at least for the factors most likely to determine exposures.

EVALUATION OF CURRENT AND EMERGING TRACKING METHODS

DoD has two purposes for obtaining tracking data: (1) averting immediate threats from acute exposure to CB agents and accidental releases; and (2) estimating long-term exposures to low levels of environmental

pollutants and CB agents. In evaluating the utility of methods for tracking activities and locations of deployed personnel, DoD should consider the following factors:

- the relative utility or value of the data that would be obtained for (1) the prevention of acute exposures, (2) the prevention of long-term exposures, and (3) the retrospective estimates of low-level exposures during deployment, particularly for CB agents and environmental pollutants
- the burden placed on individuals in terms of the size and weight of tracking devices that must be carried; the time required for record keeping/participation; and security issues
- data management issues, including costs, feasibility and ease of transmission, storage, handling, retrieval, and analysis

Preventing Acute Exposures

Any activity/location-tracking method that provides early warning of possible CB agent contact will be valuable to deployed personnel. Because of recent advances in miniaturization and accuracy, GPS appears to be an obvious choice for providing rapid information on the location of units, squads, and even individual soldiers. In the next year, civilian GPS devices may be miniaturized to wristwatch size (McDonald, 1998). Comparable miniaturization of military GPS devices would reduce the burden on users and allow individual soldiers to use and benefit from GPS. Combined with a miniaturized data logger, GPS could provide activity/location information useful for preventing acute exposures, as well as for estimating long-term exposure.

In a deployed military setting, miniaturized video cameras in unmanned aerial vehicles could be used to confirm the presence or absence of personnel in high-risk locations or to estimate the time spent conducting high-exposure activities. Assuming that the video could be securely transmitted to the commander's staff or command center, unmanned aerial vehicles could facilitate timely warnings to personnel at high risk of exposure to CB attacks or accidental releases. The value of information would be high, and the burden on individual soldiers would be low.

In general, diaries, logs, and questionnaires would not be directly relevant to improving the military's ability to identify and prevent possible exposures to imminent threats, such as CB warfare agents or industrial accidents.

Estimating Long-Term Exposures

DoD must have representative, baseline data on the activity and location-time budgets of the subpopulations of deployed troops. These data could be used to identify groups and individuals at higher risk of exposure either to industrial or environmental toxins for conducting retrospective exposure assessments to all types of harmful agents. At a minimum, these data would provide much-needed information on time spent indoors, outdoors, and in enclosed transport vehicles by various categories of deployed military personnel.

Not every individual has to be studied. Either a sufficiently large sample could be selected randomly from an entire population of deployed personnel, or a representative sample could be selected of cohorts (groups) based on the major factors indicated above (e.g., purpose of deployment, occupation/duties, etc.). The latter approach, which is essentially a stratified sample approach with random selection within strata, would probably yield data most immediately useful because units believed to be at higher risk could be studied first. Data for long-term exposure assessments should be collected for periods of several days and, where relevant, in all four seasons.

Written or electronic diaries completed at the end of the day or at the end of a "shift" provide the most feasible approach to obtaining data in the near term because they are currently available. A hard copy diary that provides basic activity and location information could be completed by each subject in 10 to 15 minutes per day. A more detailed electronic diary and questionnaire, such as one administered by an interviewer, could take up to 45 minutes per day. However, electronic data are immediately coded as they are input by the interviewer, eliminating the need for subsequent coding.

The most promising automated approach for obtaining data for estimates of long-term exposures of troops to low levels of environmental pollutants and warfare agents appears to be the selected use of a modified TIME device or similar data logger in conjunction with GPS. The TIME device provides the core information most critical to exposure estimates—the geographic location of an individual or unit across time and estimates of the time spent indoors, outdoors, and in transport vehicles. Initially, perhaps, one soldier per platoon or company should carry paired units; eventually, as miniaturization advances, more individuals could be provided with such units. The small group of individuals should be carefully chosen to ensure that they are representative of the larger group.

DoD should consider two options for using the TIME device. First, a much smaller, lighter device could be developed that records only the location of the user and does not record any pollutant data. (Data on

exposure to VOCs could be more easily obtained by passive badges, which are lighter and more feasible in a military setting than the active air-sampling portion of the current TIME device.) A second option would be to use the current TIME device with a reduced pollutant monitoring capability (one tube instead of four) to obtain a single 24-hour air sample in conjunction with the location data. The device could be worn by one individual per unit to measure exposures to many VOCs. This would provide accurate baseline data on actual exposures of various military groups to toxic environmental and occupational VOCs.

As a near-term alternative to the TIME device, a palm-sized data recorder could be used in conjunction with a GPS locator to record both the geographic location of the user (and the user's unit) and time spent in specific environments. The advantages of palm-sized recorders over the TIME device are that some commercially available palm-sized recorders appear to be more readily compatible with GPS than TIME, and they can be programmed for entry of data on the user's activities in addition to information on the major locations visited. The main advantage of the TIME monitor is that it records location automatically.

FINDINGS AND RECOMMENDATIONS

Finding. GPS is a critical component of an effective system for predicting and preventing exposures to CB agents, including accidental agent releases. Currently, only one individual per unit or squad carries a GPS receiver. Once GPS devices have been miniaturized and militarized, each individual could carry one. The location of each individual and the individual's proximity to identified or suspected releases of CB agents could then be identified, and orders for preventive actions could be directed to the individuals at greatest risk.

Recommendation. The Department of Defense should continue to support the development of miniature (e.g., wristwatch style) military global positioning system receivers. Given current technology, these could be fielded within five years. The decision to equip every deployed unit or individual with a GPS-based receiver should be based on the results of trade-off analyses.

Finding. A miniaturized, multifunctional device that can detect CB agents and TICs, determine location and time, and record the data would be extremely valuable both for protecting deployed troops and for analyzing past exposures. These devices could detect threats from harmful substances, locate the wearer in time and space, and store the data until it could be downloaded. There are, of course, many technical challenges

(e.g., size, weight, power requirements) to achieving this capability. Very small devices already exist, however, that can partly meet these goals. The Army's MIST Program, for example, uses a passive sampler no thicker than a common adhesive bandage and less than one inch square. On balance, establishment of a goal to develop these devices would offer, at a minimum, a valuable target for researchers and developers.

Recommendation. The Department of Defense should support the goal of developing a miniaturized, multifunctional device for detecting agents, determining location, and storing data.

Finding. Individuals may have performed jobs prior to or during their deployment that involved higher-than-average or longer-than-average exposures to toxic pollutants. Predeployment information could be used to identify individuals whose prior exposures put them at higher risk from additional exposures during deployment, as well as to identify possible prior exposures to harmful agents that otherwise might be believed to have occurred during deployment. The postdeployment information would provide a concise record of major duties performed and the use of, or proximity to, possible or confirmed sources of pollutants.

Recommendation. The Department of Defense should implement measures to identify individuals whose predeployment exposures might put them at higher risk of harm from additional exposures during deployment. The information should include major duties performed and the use of, or proximity to, possible or confirmed sources of pollutants during deployment.

7

Strategy Considerations

Based on the operational requirements for deployed forces, DoD's current strategy is designed to (1) detect, monitor, and avoid exposures to incapacitating or life-threatening concentrations of CB and other harmful agents; and (2) provide enough warning time for troops to take protective action (e.g., don masks and suits) if exposure is necessary or inevitable. For the most part, DoD's strategy, doctrine, equipment, and training are focused on conventional chemical agents (e.g., blister and nerve agents).

DoD has dramatically expanded its biological defense programs since Desert Storm, but new technologies and doctrine are still under development. Currently, DoD has only a limited capability to detect concentrations of biological agents. Current detectors are only sensitive to life-threatening exposures and cannot provide results in real time. Although the strategy is to avoid known concentrations of biological agents, that is not a realistic option with current technology. Therefore, DoD vaccinates troops in advance against anthrax and other biological agents (although they provide only partial protection) and continues to research methods of detection and more effective vaccines.

DoD has made only limited progress in terms of strategies, doctrine, equipment, and training in detecting, monitoring, and tracking of low levels of chemical agents. Low-level exposures, either from single or multiple chemical agents, could cause health effects well after a deployment is ended. Congress has now directed that DoD policies and doctrine be modified to protect personnel from low levels of agents in combination with other exposures and that a research program be focused on the effects of low-level exposures (1999 Defense Authorization [P.L. 105-261] Section 247).

RECOMMENDED ADJUSTMENTS IN STRATEGY

Based on the results of this study, DoD should consider adjusting its overall strategy for detecting, monitoring, and tracking harmful CB agents in two respects:

1. More emphasis should be put on developing and fielding practical methods of detecting and monitoring concentrations of biological agents in conjunction with troop deployments.
2. The detecting and monitoring of a broader range of CB agents, TICs , and endemic-disease organisms and tracking low-level exposures to them should be addressed comprehensively.[1]

These adjustments require (1) better integration of data from various sensors deployed on the ground, in the air, or on the troops themselves during deployments; (2) monitoring concentrations of agents by stand-off means and tracking troop movements; and (3) maintaining accurate and accessible databases on exposures of troops to different agents that might, singly or in combination, cause long-term health effects. As these capabilities indicate, DoD will need a comprehensive communications and information processing, storage, and retrieval capability to accompany its strategic decisions.

DoD could benefit from civilian sources of data on TICs, environmental and occupational contaminants, and endemic biological organisms. Civilian groups preparing for terrorist attacks would benefit from DoD's data on CB agents. Of course, security considerations (national and personal) would have to be satisfied. DoD is investigating the possibility of establishing a national chemical biological data center, which would exchange appropriate data with the civilian community.

For DoD to improve its detection, monitoring, and comprehensive assessments of low-level exposures to biological agents, the following actions will be necessary:

- the development and procurement of technical means of assessing potential and actual exposures (e.g., real-time, field-usable detectors for biological agents and better detectors for low levels of chemical agents)
- the development of doctrine and training protocols for conducting military operations (based on better information about exposures) that would still accomplish the military mission

[1] For some biological agents, any exposure could potentially result in severe health effects.

- the collection of information on the health of troops who were deployed, regardless of whether they remain in the military or return to civilian status

TECHNICAL ASPECTS

Current biological detection equipment is not as advanced as chemical detection equipment in terms of sensitivity, speed, and portability. DoD is pursuing research on new techniques for the real-time detection of very small amounts of biological agent by small, rugged (hence, field-usable) devices. These devices will probably not be developed for at least five years, although stronger support for R&D could hasten their availability.

Assessing potential exposures of deployed troops to low levels of harmful agents is difficult, especially because an array of CB agents and TICs might be encountered during typical deployments. Currently, very little information relates low-dose exposures and long-term health effects to single agents or combinations of agents. Technologies for detecting and estimating concentrations of agents have been focused mostly on high concentration levels. Current equipment that can function at low levels is cumbersome, complex, and often too delicate for use during deployments.

However, detection capabilities are improving, as are modeling and simulation capabilities and the analysis of weather effects on agent "clouds." Miniature GPS receivers could help track the movements of individuals or groups at much higher space and time resolutions. DoD could take advantage of rapid advances in communications and information technologies, fueled principally by commercial developments, to improve its processing, storage, and retrieval of data (1) for synthesizing information from various detectors and monitors; (2) tracking the locations of troops relative to these concentrations; and (3) assessing the potential exposures of troops before, during, and after deployments. Coupled with retrospective epidemiological studies, these data could be used for diagnosing and treating troops after deployments.

RECOMMENDATIONS

Defining Needs

Recommendation. The Department of Defense should formulate an integrated approach to assessing the threats of chemical and/or biological agents. The approach should include: (1) a near-term and long-term perspective; (2) data collection; (3) estimates of the relative importance of various threats (e.g., biological threats, chemical threats, and chemical

toxins derived from organisms) in a variety of overseas theaters; and (4) data on the effects of low-level doses of a broad range of agents.

Determining Exposure

Recommendation. The Department of Defense (DoD) should proceed with a robust program to develop chemical detectors and biological detectors that can detect and measure low-level as well as high-level concentrations. The first priority should be the development of improved passive sampling devices based on existing technologies that could be fielded quickly. The DoD should also develop a support structure for using the devices and for archiving the data.

Recommendation. The Department of Defense should expeditiously develop the capability of identifying and archiving continuous data on the operational location of each small unit—and, if practical, each individual—as well as the unit or individual's proximity to actual or suspected releases of potentially harmful agents. Technical assessments and cost-benefit analyses should be used to determine the best ways to accomplish these functions in the near term (e.g., supplementing the miniature global positioning system receiver to achieve the desired result).

Recommendation. The Department of Defense should establish a long-term goal to develop very small devices that could be deployed with each individual to measure and record automatically exposures to one or more of the most threatening agents, the location of the individual, the activity of the individual, the microenvironment, and the time.

Recommendation. The Department of Defense should develop and field improved meteorological measuring and archiving systems to provide finer data grids of wind, temperature, and atmospheric stability in the theater of operations. These data will be necessary for improved transport modeling and for after-action analyses of data on the movements of chemical and biological "clouds."

Recommendation. The Department of Defense should support research to clarify how chemical and biological processes affect the rate of transformation of agents in different environmental media under a variety of conditions.

Handling Data

Recommendation. The Department of Defense should develop a

representative activity-location database for different types of units, major military duty categories, and high-risk subpopulations of personnel likely to be deployed. This database, along with models and simulations, should be used to predict and evaluate potential exposures associated with specific deployments.

Recommendation. The Department of Defense should develop its data-handling capability to track the locations of all individuals (or, at least, the smallest units) during future deployments and compare them to the locations of actual or potential agent concentrations at the same point in time. The data-storage capacity should be increased simultaneously so that these locations can be recalled and analyzed after each deployment (e.g., data could be recalled from a high-capacity personal information carrier).

Recommendation. In the future, the Department of Defense should characterize the variations in exposures of members of groups believed to have been exposed during their deployment. To help accomplish this, location data and agent-concentration data for individuals or small units should be analyzed thoroughly, using statistical methods where applicable.

Recommendation. The Department of Defense should study the ramifications of establishing a national chemical and biological hazardous agent data center.

Doctrine, Training, and Administration

Recommendation. Doctrine and training for taking protective action should be reviewed to ensure a proper balance between military necessities and the risks of harmful exposures. The Department of Defense should reevaluate its doctrine and training for handling and reporting alarm activations and false alarms and revise them, if necessary.

Recommendation. Doctrine and training should take account of predeployment exposures that might put some individuals at greater risk during deployment. This information, along with data gathered on actual or suspected exposures or on the locations of individuals or units and the locations of concentrations of agents, should be used to assess the risk to individuals.

Recommendation. The Department of Defense should review its doctrine and training protocols governing the interactions of offensive operations and protective measures. If an offensive operation may cause exposure to troops nearby, this information should be factored into the decision.

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Appendices

Appendix A

Defining the Decision Framework and the Value of Exposure Information in Military Deployments

Thomas E. McKone and Detlof von Winterfeldt[1]

A great deal of effort is being expended by the U.S. Department of Defense (DoD) to develop technologies for detecting chemical and biological agents and for tracking military personnel during deployments. The types and extent of exposure information needed depend largely on how the information will be used to take health-protective actions. As a hypothetical example, assume that a device could report the full spectrum of environmental concentrations for all known chemical and biological agents in real time. Although such a device would be an enormous technological breakthrough, it would not solve the problem of selecting the information to use, managing that information, and, most importantly, acting on the information. To be of value to the decision makers in the field whose judgments affect the success of a deployment and the short-term and long-term health risks to deployed forces, the output of such a device would have to be assembled, collapsed, organized, and summarized.

The first question that must be considered is the purpose of tracking, detection, and monitoring information. Clearly, the information could be used for many purposes, including planning military missions, improving decisions on the battlefield, protecting soldiers from exposure to harmful agents, and making better decisions about medical care during and

[1] The following material was prepared for the use of the principal investigator of this study. The opinions and conclusions herein are the authors' and not necessarily those of the National Research Council

after deployment. To provide a better understanding of these purposes, a member of the advisory panel developed a taxonomy of situations that would benefit from improved tracking, detection, and monitoring of information. The taxonomy distinguishes between the use of information in the predeployment phase (e.g., for selecting protective equipment for use in a mission), during the deployment phase (e.g., for responding to immediate threats from harmful agents), and in the postdeployment phase (e.g., for reconstructing exposures and determining medical care).

The usefulness of tracking, detection, and monitoring information depends on its impact on decision making, the so-called "value of information" (VOI) (e.g., Clemen, 1990; von Winterfeldt and Edwards, 1986). Information that only adds marginally to what is already known is not useful in the decision-making context. Too much information can be a nuisance and an obstacle to good decision making. VOI depends on two factors: (1) how well decisions can be made with readily available tracking, detection, and monitoring information; and (2) how much decisions can be improved by collecting information with new technologies. A formal definition of the VOI is the difference between the expected value of the decision with the information and the expected value of the decision without it (e.g., Clemen, 1990). The technologies that provide information have attributes, such as cost, size, and weight that must also be evaluated to assess the trade-offs among these attributes.

The three sections of this appendix are focused on the three topics of a taxonomy: (1) information needs, (2) VOI, and (3) attributes of new technologies.

INFORMATION NEEDS

Potential exposures to chemical and/or biological (CB) agents has been an important concern of military commanders throughout most of this century. Until recently, attention was focused almost excessively on lethal or incapacitating exposures, and little attention was paid to gathering information on low-level exposures to CB agents, toxic industrial chemicals (TICs), and other harmful agents. Since the emergence of the Gulf War, attention has been focused on correlations between reported symptoms and various types of exposures. DoD has initiated projects to track cumulative exposure information and collect health records for all military personnel as part of a comprehensive medical surveillance program.

Predeployment Stage

In the predeployment stage, information about the nature of possible threats, locations of plants that could emit toxic agents, terrain, weather,

and prevailing wind directions can be used for planning a deployment and equipping troops. For example, the type of protective gear could be based on an assessment of the enemy's CB warfare capabilities. The location of chemical plants and the prevailing weather and wind directions are important factors in the timing of attacks on these plants, as well as for determining the preferred routes of ground forces. Information about local diseases, agricultural pesticides, and local air pollution would be useful for decisions about predeployment vaccinations and medical provisions.

Deployment Stage

In the deployment phase, especially on the battlefield, the most important information is whether or not a harmful agent is present and poses an immediate threat to troops. This information affects decisions about the use of protective gear, the evacuation and routing of troops to avoid harm, and short-term medical responses. The information must be reliable and available quickly but does not necessarily have to provide a detailed time-profile of individual exposures.

Joint Vision 2010 (JCS, 1996) describes how a commander includes information about potential CB agents in the overall mission strategy to ensure that troops have full dimension protection. Exposure information is also important to other concepts in *Joint Vision 2010*, including dominant maneuver, focused logistics, precision engagement, and information superiority. The commander, therefore, needs exposure information to protect troops from acute and severe health risks, to determine where to send troops and when to relocate them, to determine when and where to collect samples, and to decide when to call for the donning of protective gear. During deployment, especially on the battlefield, exposure information can be used to make decisions about evacuations or rerouting troops to avoid exposure, provisions of medical equipment and support, and giving an "all clear." Medical staff also make decisions based on exposure information, such as how to deploy medical resources and which treatments will be most effective.

Postdeployment Stage

In addition to reducing the risk of severe health consequences in the theater of deployment, comprehensive exposure assessments are now being used by DoD to monitor and improve the overall health status of personnel, which requires information on low-level exposures. Assessing the risk to troops during a past deployment, such as the Persian Gulf War, requires detailed information about the types of exposures, especially low-level exposures, the nature of the agent(s), and the time profile of

individual exposures. This information, which does not have to be available immediately, can be collected and stored for studies to reconstruct exposures after the deployment.

When troops return to garrison, those responsible for monitoring and maintaining their health status will also need exposure information to determine the appropriate level of health surveillance and medical support. They must also decide how to respond to questions about health complaints and the potential health hazards of deployment operations. Postdeployment medical personnel often need more information on combinations of low-level exposures than on peak concentrations. They need information on a much larger number of individuals and harmful agents than the field commander, whose concerns are survivability, troop performance, and fulfillment of the deployment mission. Long-term dose reconstruction, especially based on low-level exposures to a multitude of agents, requires detailed time-profiles of individual exposures. After deployment, exposure information can be used to determine retrospectively whether soldiers were harmed by exposures to CB and other harmful agents to make informed decisions on long-term medical care and compensation and to resolve legal claims.

As the previous discussion shows, a key distinction in the taxonomy is the phase of the deployment. Two other important distinctions are: (1) the time for health effects to appear, which ranges from immediate effects from acute exposures to long-term and delayed effects; and (2) the agent class of the substance to which troops are exposed, ranging from CB warfare agents to other agents available in the deployment environment, including TICs, endemic biological agents, and background chemical agents (e.g., high levels of naturally occurring metals, such as arsenic, lead, cadmium, etc.) All three distinctions are incorporated into the taxonomy of decisions and exposure information shown in Figure A-1. Each of the 12 cells in the diagram will lead to different decisions and requires different information.

UNCERTAINTY AND THE VALUE OF INFORMATION

The previous section focused on collecting information to improve decision making. This section is focused on measuring improvements in decisions. A first-order approximation of the VOI is the reduction of uncertainties. Figure A-2 shows schematically how information collected by tracking, detection, and monitoring devices influences uncertainties about health effects, a key factor in the decision to take (or not to take) protective action. Of course, these decisions are also influenced by other factors, such as mission objectives and degradation of troop performance as a result of donning protective gear.

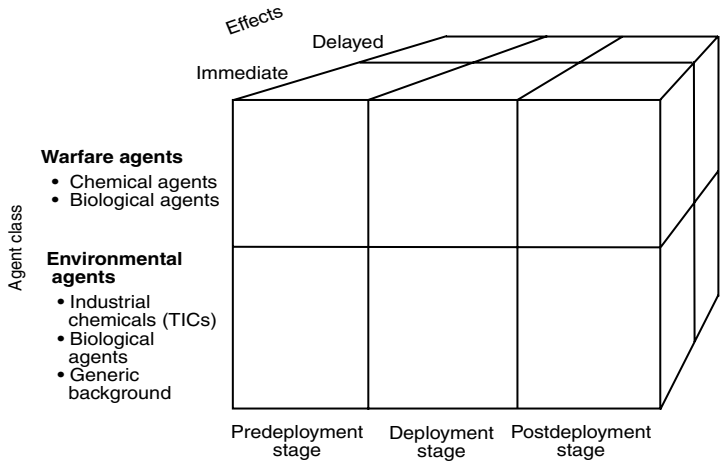

FIGURE A-1 A taxonomy of information needs.

Perfect information would completely describe the true state of each variable in each ellipse. In reality, uncertainties can be reduced but not eliminated. As they are reduced, decisions about health effects are likely to improve. However, two important caveats must be kept in mind. First, reducing, or even eliminating, uncertainty in any one of the variables influencing exposure and health effects may not eliminate uncertainty about health effects. Some uncertainties, such as the relationship between doses and responses, may be far more important than other uncertainties. Therefore, reducing uncertainties through tracking, detecting, and monitoring information may not substantially improve decision making.

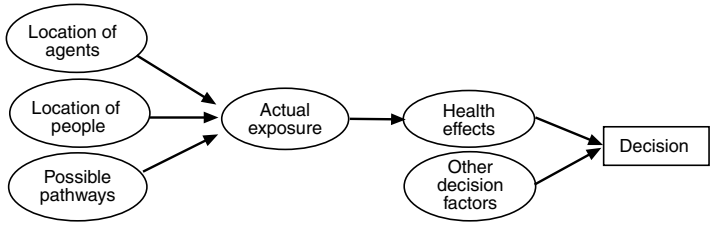

FIGURE A-2 Influence diagram showing the relationships and effects of uncertainty on exposure information, health effects, and decisions.

Second, reducing uncertainty is a necessary, but not sufficient, condition for improving decisions. For example, if a mission always requires that soldiers wear protective gear in an area near a toxic facility (known through predeployment information), knowing more about the nature, concentration, and location of toxic agents in the area will not change this decision. In general, if a decision cannot be changed by the information, the information has no value for that decision.

Example 1. Potential Exposure and Protective Clothing

To determine the VOI, the decision without the information must first be evaluated. The concept of the VOI can be illustrated with a simple decision tree (Figure A-3), which provides a logical structure for evaluating a decision by laying out interim decisions (square nodes), subsequent events (round nodes), and consequences (triangular nodes).

In this example, prior evidence suggests that a harmful chemical agent has been released and is threatening 100 soldiers. It is assumed that the agent is not lethal but will incapacitate the soldiers for five days by causing severe intestinal problems. Based on prior evidence, the probability of the release of the agent is 20 percent. The commander must decide whether or not to order soldiers to don protective clothing.

This decision clearly depends on the consequences of the decision-event combinations. If the commander decides not to order the use of protective clothing and the harmful agent is present, 100 soldiers will be incapacitated for five days, resulting in a loss of 500 soldier days. If the commander decides to order his soldiers to use protective gear, their performance will be degraded, leading to an equivalent loss of soldier days. The equivalent loss is based on the assumption that soldiers would be required to wear protective gear for six hours (25 percent of a day) and that during that time they would only be 50 percent effective. For 100 soldiers,

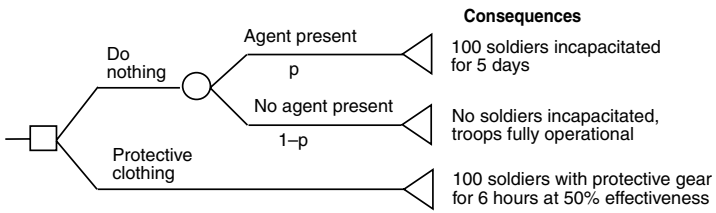

FIGURE A-3 Decision tree for using protective clothing. Squares are decision nodes, circles are chance nodes, and triangles are end nodes.

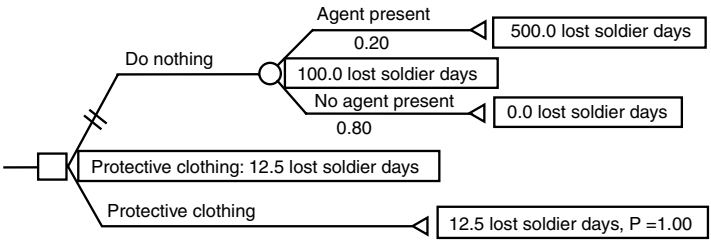

FIGURE A-4 Analyzed decision tree for using protective clothing.

this would lead to 12.5 "equivalent lost soldier days" (100 x 0.25 x 0.50). The consequences are assigned to the end nodes of the decision tree.

The decision tree is then analyzed by multiplying the consequences (lost soldier days) by their respective probabilities (Figure A-4). As a rule, the best decision minimizes lost soldier days. In this case, the decision to do nothing results in 100 lost soldier days, and the decision to use protective clothing results in only 12.5 lost soldier days. Thus, if there is a 20 percent chance of a real threat, using protective clothing is clearly the best decision.

Now assume that perfect information is available concerning the presence of a harmful agent. Figure A-5 compares a decision based on

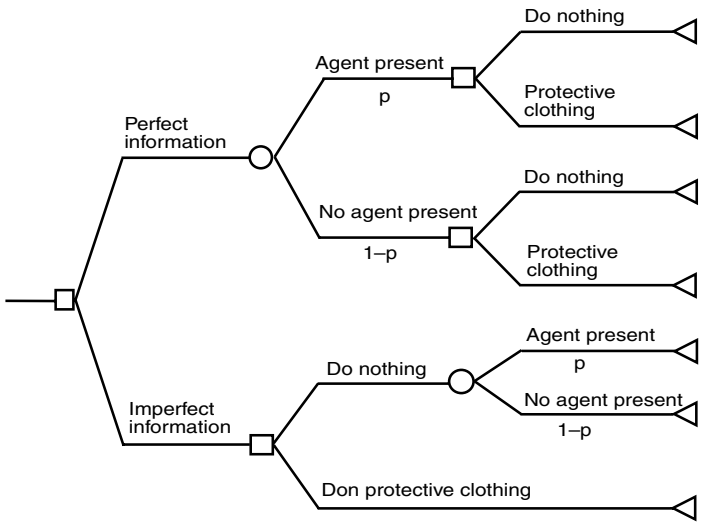

FIGURE A-5 Decision tree with perfect information.

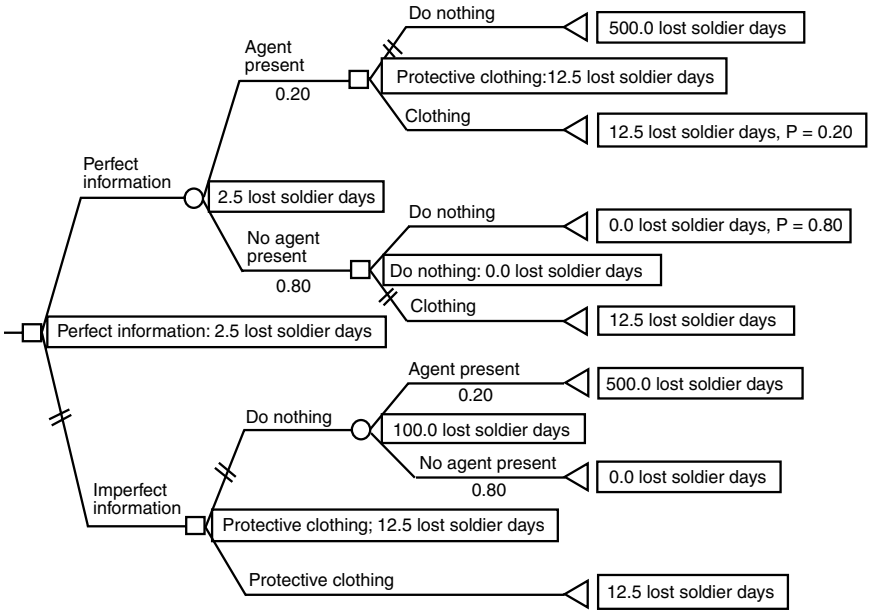

FIGURE A-6 Analyzed decision tree with perfect information.

perfect information with a decision based on prior evidence, but not perfect information. With perfect information, a commander would know for sure whether or not the agent was present. This scenario is analyzed in Figure A-6. Clearly, if the agent is present, the best decision is to order troops to put on protective gear. The expected lost soldier days with perfect information are now reduced to 2.5 (compared to 12.5 with imperfect information). Thus, perfect information "saves" 10 soldier days. In concrete terms, the commander should be willing to give up 10 of his soldiers for one day or one soldier for 10 days to obtain this perfect information.

Perfect information provides an upper bound to the VOI. Unfortunately, information is never perfect. Figure A-7 shows the situation in which an agent may or may not be present, and the device used to detect the agent is fallible. At any given time, the sample information may either "detect" an agent or "reject" it. Quotation marks indicate that detection can occur even though no agent is present and that rejection can occur even though an agent is present. The marginal probability of "detecting" the agent is q, of rejecting it is $1–q$. The conditional probability that an agent is present, given that it is "detected," is r. The marginal probability that an agent is present, given that it is "rejected," is s. With $r < 1$ and

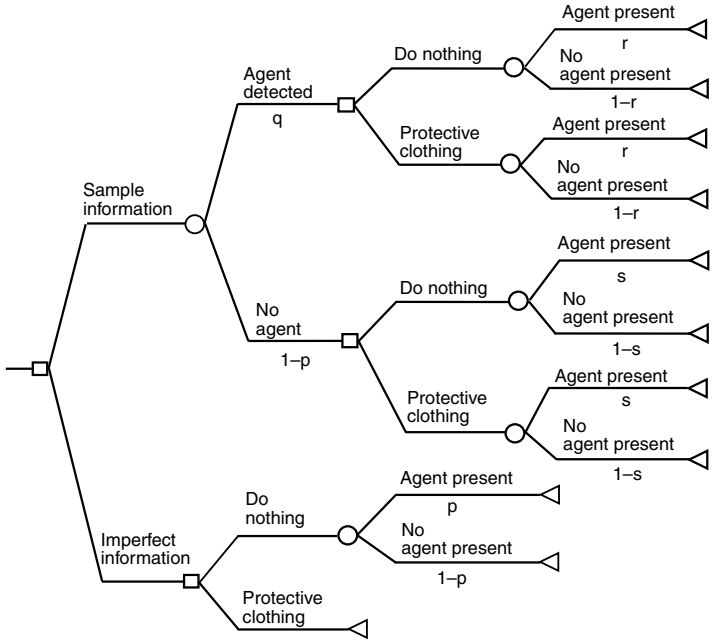

FIGURE A-7 Decision tree with imperfect information.

$s > 0$, the detection device is imperfect. Therefore, the commander will still have to make a decision based on some uncertainty about the presence of the agent.

Figure A-7 is the standard textbook example of a decision made with imperfect or "sample" information (e.g., Clemen, 1990; von Winterfeldt and Edwards, 1986). In the current context, we can assume that the commander will order the use of protective clothing if the sample "detects" an agent and that he will do nothing if the sample information "rejects" the presence of an agent. This leads to the somewhat unorthodox but simpler decision tree shown in Figure A-8. Note that in this tree the presence of the agent is considered first and then whether or not the sample detects it. After obtaining the sample information (but without knowing for sure whether or not the agent is present), the commander makes a decision. If the sample information detects an agent, he orders the use of protective clothing; otherwise he does nothing.

Although this representation is unorthodox, it has exactly the same solution as the more conventional tree in Figure A-7, as long as the optimal decision is based solely on the sample information. The quality of the sample information can be characterized by four conditional probabilities:

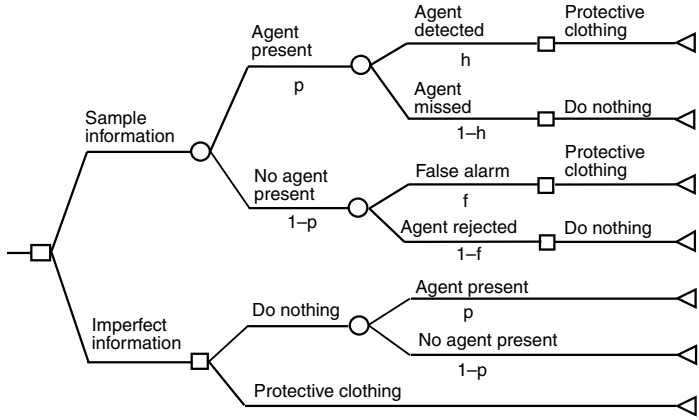

FIGURE A-8 Decision tree with imperfect information (simplified).

- *h,* the probability that an agent is present and the device detects it (a "hit")
- *m*, the probability that an agent is present, but the device fails to detect it (a "miss")
- *f*, the probability that an agent is not present, but the device detects it (a "false alarm")
- *c*, the probability that an agent is not present, and the device fails to detect it (a "correct rejection")

Since $h = 1 - m$ and $f = 1 - c$, detection devices can be characterized by h and f alone. Good devices maximize the probability of hits (h) and minimize the probability of false alarms (f). A device that delivers perfect information has a hit rate of 1 and a false alarm rate of 0. In this example, the hit rate is 0.98, and the false alarm rate is 0.10. Using these rates, Figure A-9 analyzes the decision tree with imperfect information. The decision to obtain imperfect information leads to 5.5 expected lost soldier days (three more than with perfect information), and the difference between imperfect information and no special information is reduced to seven lost soldier days. The reduction of the VOI reflects the hit and false alarm rates.

Example 2. Purchasing Detection Equipment

Figure A-10 shows a simple decision tree for deciding whether or not to purchase a new technology for detecting and monitoring harmful

agents on the battlefield. How valuable is the information provided with this new technology compared to the old technology? The VOI depends on the decision at hand, which has to be made in light of uncertainties about whether or not the agent is present.

To determine the VOI with the new technology, the expected value of the decision to use it must be compared to the expected value of making the decision with the old technology. With the new technology, a threat may occur at a given time with probability *p*. If the threat occurs, the new technology may detect it (a hit) or miss it with the respective probabilities labeled *h(new)* and 1– *h(new)*. The new technology may also detect a threat even though it does not exist (false alarm), *f(new)*, or correctly reject the existence of the threat with probabilities 1–*f(new)*.

In the case of a hit, the commander will appropriately order protective action, which will save lives but reduce the effectiveness of the troops. In the case of a miss, no protective action will be taken, and lives will be lost. In the case of a false alarm, the commander will order the use of protective equipment, thus unnecessarily reducing troop effectiveness. In

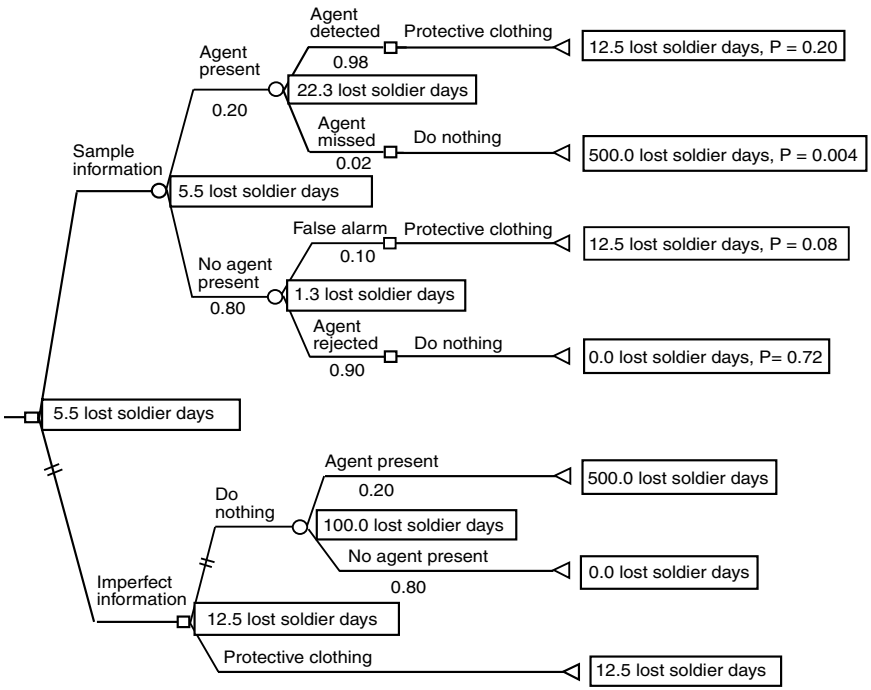

FIGURE A-9 Analyzed decision tree with imperfect information (simplified).

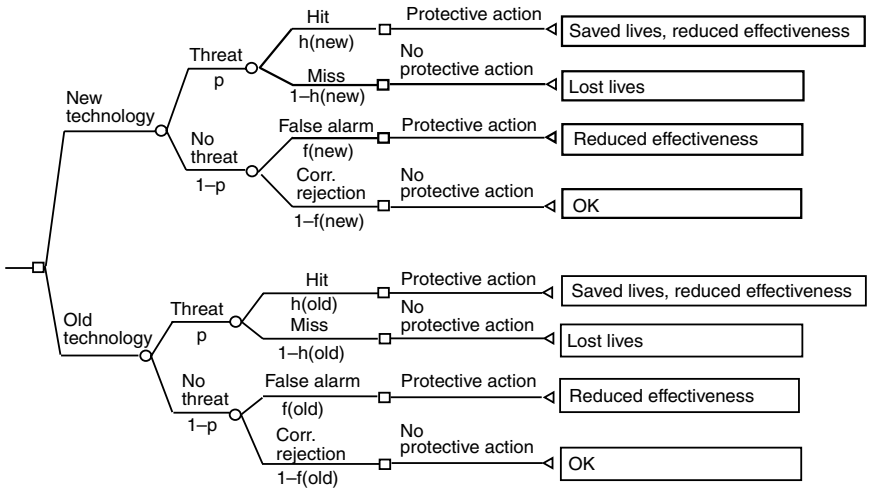

FIGURE A-10 Decision tree illustrating the value of new information.

the case of a correct rejection, no protective action will be taken, no lives will be lost, and the troops will remain fully effective.

The same sequence of decisions and events occurs in the lower part of the decision tree, starting with the decision to use the old technology. The only difference is in the probabilities *h(old)* and *f(old)*. Presumably, the hit rate, *h*, is higher for the new technology, and the false alarm rate, *f*, is lower. These differences in hit and false alarm rates completely determine the differences in the expected value of the old and new technologies and thus determine the incrementally higher VOI of the new technology.

To conduct a formal VOI analysis for real monitoring, detection, and tracking technologies is, of course, impossible. These technologies could be used in many decisions and situations, and assessing the probabilities and consequences for all of them would be extremely difficult. However, a qualitative VOI analysis can be conducted based on the following questions:

- What decisions are influenced by the information provided by the old and new technologies?
- What are the stakes in the decision (i.e., the range of consequences)?
- Would perfect information change the decision?
- What are the hit and false alarm rates of the new technology compared to the rates with the old technologies?

For example, if perfect information would not change the decision, the value of an imperfect device will be zero. If perfect information would

change the decision but the range of consequences would be small, the value of an imperfect device would be small. If perfect information could change the decision and the range of consequences is large, the potential VOI for an imperfect device would be large depending on the hit and false alarm rates.

Evaluations with Multiple Attributes

In the preceding examples, the VOI was the only measure used to characterize the consequences of a decision. However, in actual decisions about the use of monitoring, detection, and tracking technologies, other attributes of the devices are also important. These include cost, size, and weight. In deployment situations, devices must be small, lightweight, and unobtrusive to minimize interference in a soldier's performance on the battlefield. Before evaluating these detection and monitoring devices, the attributes that distinguish between them should first be defined. The following attributes may be relevant:

- VOI before deployment
- VOI during deployment
- VOI after deployment
- maturity of the technology
- size of the device
- weight of the device
- cost of the device

An evaluation matrix that lays out alternative devices against these attributes should then be filled out with numbers (e.g., for size and cost) and words (e.g., VOI may be characterized as "high" or "low"). This type of matrix is similar to a typical *Consumer Report* description of the advantages and disadvantages of consumer products.

This matrix may be sufficient to make choices among alternative monitoring, tracking, and detection devices. However, devices that perform well on some attribute (e.g., small size and weight) may not perform well on others (e.g., cost). In these cases, a multiattribute utility analysis can be used to quantify crucial trade-offs and evaluate the alternatives with a single number, their utility (Keeney and Raiffa, 1993). A multiattribute utility analysis can also be combined with a VOI analysis so that all consequences of the alternative devices could be counted at the end of the decision tree. A multiattribute utility analysis would be used to convert the vector of consequences into a single utility number, and the VOI calculation would be based on the utility numbers.

SUMMARY

Before undertaking the development of new detection, tracking, or monitoring devices, they should be evaluated in terms of the information they will provide. Evaluations should be based on how the information will be used and the VOI. If the information, even if perfect, is not necessary to a decision, the device should have low priority for development funds. Criteria for evaluating the VOI are the effects and class of agents and the deployment stage of the operation. Other criteria are the maturity of the technology and the size, weight, and cost of the device. Using a matrix to compare alternative devices can help decision makers set priorities.

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Appendix B

Harmful Properties of Chemical Agents

ESTIMATED SHORT-TERM SAFE DOSE AND AIRBORNE EXPOSURE LEVELS

Tables B-1 and B-2 list available short-term safe doses, EC_{50}, estimates of safe short-term doses, and current allowable exposure levels (AELs). The EC_{50} is the airborne concentration sufficient to produce severe effects in 50 percent of those exposed for 30 minutes (NRC, 1997a). An estimate of a short-term safe dose is obtained by dividing the incapacitating dose (ICt_{50}) by 480 minutes (eight hours) and then dividing by a safety factor of 10. The estimates are not considered recommendations but suggest concentration levels that would define an all-clear. The AEL is the maximum chemical concentration of an agent in air that is safe for continuous exposure during an eight-hour work day (ERDEC, 1996). The AEL is a general term indicating a level of exposure that is unlikely to result in adverse health effects.

LETHAL AGENTS

Nerve agents

Nerve agents are chemicals that disrupt the mechanism by which nerves transfer messages to organs. The disruption is caused by blocking the activity of acetylcholinesterase, an enzyme that normally destroys and stops the activity of acetylcholine, a neurotransmitter. Nerve agents, organophosphorus compounds originally developed by German scientists during the 1930s as

TABLE B-1 Lethal Chemical Warfare Agents

Agent	Code	Median Lethal Exposure, LCt_{50} (mg-min/m^3 except where noted)
Nerve Agents		
Tabun	GA	400 (resting inhalation) LD_{50}: 1 to 1.5 mg/person (dermal dose)
Sarin	GB	100 (resting inhalation) 70 (mildly active inhalation) 15,000 (dermal)
Soman	GD	70 (mildly active inhalation) 10,000 (dermal estimated)
Fluoride-containing organophosphate	GF	N/A for inhalation path LD_{50}: 16 to 400 µg/kg in mice
Standard V-agent	VX	100 (resting inhalation) 6 to 360 (dermal-clothed)
Vx or V-gas	Vx	Similar to VX
Binary nerve agents	GB2 VX2	Similar to GB Similar to VX
Pulmonary (Choking) Agents		
Phosgene	CG	3,200
Diphosgene	DP	3,000
Blood Agents		
Hydrogen cyanide	AC	Varies with concentration: 2,000 mg-min/m^3 at 200 mg/m^3 4,500 mg-min/m^3 at 150 mg/m^3
Cyanogen chloride	CK	11,000
Arsine	SA	5,000

Sources: Boyle, 1998; ERDEC, 1996; NRC, 1997a; U.S. Army et al., 1990.

Median Incapacitating Exposure, ICt_{50} (mg-min/m^3 except where noted)	EC_{50} estimated short-term safe dose AEL (in mg/m^3)	Important Physical Properties
300 (resting inhalation)	13	Colorless to brown liquid
not known, ~ 30,000 (dermal)	0.06	Colorless gas
	0.0001	Persistence ~ days
		Volatility 1/20 H_2O
75 (resting inhalation)	3	Colorless liquid
35 (mildly active inhalation)	0.01	Colorless gas
8,000 (dermal)	0.0001	Persistence < GA
		Volatility ≈ H_2O
~ GB	2	Colorless liquid
N/A (dermal)	0.01	Colorless gas
	0.00003	Persistence ~ days
		Volatility 1/20 H_2O
N/A	N/A	Colorless liquid
		Colorless gas
		Persistence ~ days
		Volatility ≈ H_2O
50 (resting inhalation)	3	Amber oily liquid
LD_{50}: 10 mg/person (dermal)	0.01	Persistence ~ weeks to months
	0.00001	Volatility 1/1500 H_2O
Similar to VX	3	Amber oily liquid
	0.01	Persistence ~ VX
	0.00001	Volatility 1/150 H_2O
Similar to GB		Similar to GB
Similar to VX		Similar to VX
1,600	100	Colorless gas
	0.33	Volatile/not persistent
	0.002	
1,600	100	Colorless oily liquid
	0.3	Less volatile and more
	0.002	persistent than CG
Varies with concentration	150	Colorless liquid
	N/A	Evaporates quickly
	0.003	Rapid detoxification
		Highly volatile
		Not persistent
		Disperses rapidly in air
7,000	400	Colorless liquid
	1.5	Evaporates quickly
	0.008	Not persistent
2,500	200	Gas
	0.5	Ignites easily
	0.004	Not persistent

TABLE B-2 Debilitating and Incapacitating Chemical Warfare Agents

Agent	Code	Median Lethal Exposure, LCt_{50} (mg-min/m^3 except where noted)
Vesicants (Blister) Agents		
Levinstein mustard	H	Same as HD
Distilled mustard	HD	LD_{50}: (estimate) 7 gm/person 1,500 (respiratory) 10,000 (dermal))
Nitrogen mustard	HN-1	1,500 (respiratory) 20,000 (dermal)
Nitrogen mustard	HN-2	3,000 (respiratory)
Nitrogen mustard	HN-3	LD_{50}: (estimate) 0.7 gm/person (dermal) 1,500 (respiratory)
Mustard-T mixture	HT	None established, assume similar to HD
Lewisite	L	LD_{50}: 30 mg/kg 1,400 (respiratory) 100,000 (dermal)
Mustard-lewisite mixture	HL	~1,500 (respiratory) >10,000 (dermal)
Phenyl-dichloroarsine	PD	2,600 (respiratory)
Ethyl-dichloroarsine	ED	3,000 to 5,000 (respiratory) 100,000 (dermal)
Methyl-dichloroarsine	MD	No accurate data, likely similar to ED
Phosgene oxime	CX	3200 (estimated)

Median Incapacitating Exposure, ICt_{50} (mg-min/m^3 except where noted)	EC_{50} estimated short-term safe dose AEL (in mg/m^3)	Important Physical Properties
Same as HD	50	Same as HD
	0.03	
	0.003	
150 (respiratory)	50	Oily liquid
100–200 (eye injury)	0.03	Colorless gas
2,000 (dermal))	0.003	4–6 hour delay for effects
		Very persistent
200 (eye injury)	50	Oily liquid
9,000 (dermal))	0.03	Colorless gas
	0.003	~12 hour delay for effects
		Very persistent, but < HD
100 (eye injury)	50	Dark liquid
~ 6,000 (dermal)	0.03	~12 hour delay for effects
	0.003	Similar to HD
200 (eye injury)	50	Oily liquid
2,500 (dermal)	0.03	~4–6 hour delay for effects
	0.003	Longer than HD
None established, assume similar to HD	50	Yellow liquid
	0.03	Delayed action but not well known
	0.003	More persistent than HD
< 300 (eye injury)	50	Colorless to brown liquid
> 1,500 (dermal)	0.06	Rapid acting
	0.003	Less persistent than HD
~200 (eye injury)	50	Liquid
1,500 to 2,000 (dermal)	0.04	Rapid acting skin irritation,
	0.003	blisters in 13 hours
		Less persistent than HD
0.9 mg/m^3	100	Liquid
(respiratory irritation)	0.003	Rapid acting
16 (as vomit agent)	0.003	Persists days to weeks
0 (as vesicant)		
5 to 10 (respiratory)	N/A	Colorless liquid
		Rapid acting nose/throat irritation, blisters in 12 hours
		Not persistent
25 (respiratory)	N/A	Liquid
		Rapid acting nose/throat irritation, blisters in several hours
		Not persistent
Becomes unbearable to the eyes at ~ 3 mg/m^3	N/A	Solid (liquid above 39°C)
		Rapid acting
		Persists for hours in soil

TABLE B-2 Debilitating and Incapacitating Chemical Warfare Agents (continued)

Agent	Code	Median Lethal Exposure, LCt_{50} (mg-min/m^3 except where noted)
Sternutators (Vomiting Compounds)		
Diphenyl-chloroarsine	DA	15,000 (estimated)
Diphenyl-cyanoarsine	DC	10,000
Adamsite	DM	~ 11,000 (variable)
Lacrimators (Tearing Compounds, Riot-Control Agents)		
Bromobenzyl-cyanide	CA	8,000 to 11,000 (estimated)
Chloroaceto-phenone	CN	~ 11,000
CN + chloroform	CNC	11,000
CN + carbon tetrachloride + benzene	CNB	< 11,000
CN + chloropicrin + chloroform	CNS	11,400
o-chloro-benzylidene malonitrile	CS CS-1 CS-2 CSX	61,000
Dibenz-(b,f)-1, 4-oxazepine)	CR	None reported
Chloropicrin	PS	2,000
Psychochemical (Incapacitating Agents		
3-quinuclide-dinyl benzilate	BZ	200,000

Median Incapacitating Exposure, ICt_{50} (mg-min/m^3 except where noted)	EC_{50} estimated short-term safe dose AEL (in mg/m^3)	Important Physical Properties
12	N/A	Solid (crystals) Not persistent
30 (30-sec exposure) 20 (5-min exposure)	N/A	Solid (crystals) Not persistent
22 to 150	N/A	Yellow/green solid (crystals) Not persistent
30	N/A	Yellow solid or liquid Can persist 1-2 days
N/A	Solid powder	Not persistent
~ 80	N/A	Liquid Not persistent
~ 80	N/A	Liquid Not persistent
60	N/A	Liquid Not persistent
10-20 1 to 5 mg/m^3 (eye effects)	N/A	Solid, powder, or liquid Persistence depends on form
[p]0.15 mg/m^3 0.002 mg/m^3 (respiratory threshold) 0.004 mg/m^3 (eye threshold)	N/A	Yellow powder in solution Persists up to 60 days
9 (irritation threshold)	N/A	Colorless, oily liquid Not persistent
112 2 mg/m^3 (inhalation threshold)	N/A	White crystalline solid Very persistent in soil and water

insecticides, were developed into chemical weapons by the Nazi military. Since then, nerve agents have been the main chemicals stockpiled as chemical weapons. The physiological symptoms associated with nerve agents begin seconds or minutes after skin contact or exposure to the vapors or aerosols of these compounds. At lower levels of exposure, symptoms range from dripping nose, tightness in the chest, and pinpoint pupils to excessive salivation, sweating, and nausea. At higher levels, symptoms range from vomiting, cramps, twitching/jerking, staggering, headache, confusion, and loss of muscle control to coma, convulsions, and death. When liquid agents are applied to the skin, the onset time is longer (up to 18 hours) than with inhalation (10 minutes) (Boyle, 1998).

The primary military nerve agents are tabun (GA), sarin (GB), soman (GD), GF, and VX. Vx is similar to VX, but 10 times more volatile. The binary nerve agents GB2 and VX2 are forms of GB and VX formed in binary reactions. A summary description of nerve agents is provided in Table B-1. In general, it is assumed that an area exposed to G agents will decontaminate itself in a few days because of the agents' volatility, which is about equal to the volatility of water (the volatility of GA and GF is about 1/20 that of water). However, V agents, the most potent nerve agents, are more stable and less volatile and thus can remain on the ground for several weeks. V agents are also rapidly absorbed by plants. VX, for example, can remain on materiel, equipment, and terrain for long periods. The uptake of V agents is mainly through the skin but also through inhalation of the gas or aerosol. Uptake of G agents is primarily through inhalation.

Pulmonary (Choking) Agents

A pulmonary agent, or choking agent, is a chemical that damages the membranes separating the alveolus (air sac) of the lung from the capillaries. A number of common chemicals can cause this type of damage. Phosgene (CG), the prototype of this class, is a common industrial chemical with a moderately lethal dose. Diphosgene has a toxicity similar to CG but is less volatile. Choking agents were the most commonly used agents during World War I, but they have lost much of their advantage since the advent of nerve gases. A summary description of pulmonary agents is provided in Table B-1.

Cyanide ("Blood") Agents

Cyanide-based compounds are the main components of blood agents. A characteristic of cyanide poisoning is red skin, which is caused by blood going through the capillary bed without unloading oxygen. Cyanide in moderate amounts can produce nausea and feelings of dizziness,

weakness, and anxiety. Blood agents are highly volatile and nonpersistent even at low temperatures.

Hydrogen cyanide is a slightly more lethal than CG but is less effective because of its rapid rate of evaporation and its rapid rate of detoxification. Loss of consciousness and death can occur after even very brief exposures to high concentrations of hydrogen cyanide, but because of rapid detoxification, the toxicity of hydrogen cyanide varies with the exposure concentration. Because of its high volatility, the large doses required, and the fact that it is lighter than air, hydrogen cyanide is a less-than-ideal compound in ambient air, although it can be very effective in enclosed spaces. Cyanogen chloride has strong irritating and choking effects and slows breathing and is not as toxic as hydrogen cyanide. Arsine is used as a delayed-action casualty agent. Arsine is lethal at relatively high doses; at lower doses, it damages the liver and kidneys, can cause anemia, and is a carcinogen. A summary description of blood agents is provided in Table B-1.

OTHER TYPES OF HARMFUL WARFARE AGENTS

Vesicants (Blister Agents)

Blister agents, or vesicants, are intended to cause injury by blistering rather than cause death. Levinstein mustard (H) was used extensively during World War I. Vesicants attack and burn the eyes, mucous membranes, respiratory tract, and skin, causing the formation of blisters. When absorbed through the lung, gut, or skin, they cause vomiting and diarrhea. The severity of vesicant damage is directly related to exposure levels, that is, the duration of contact and the concentration in the contact medium (air, water, food, surfaces, etc.). All of the blister agents are persistent, and all of them can be used as gases or liquids. Blister agents can be used to poison food and water supplies and to make other supplies dangerous to handle. A summary description of the blister agents is provided in Table B-2.

There are three categories of blister agents—mustards, arsenicals, and urticants. Mustards include the sulfur mustards (H, distilled mustard [HD]), and nitrogen mustards (HN-1, HN-2, HN-3). The mustards penetrate well into skin and other materials, such as wood, clothing, rubber, and paints, and are very persistent in cold and temperate climates. Because mustards have delayed effects (4 to 6 hours or more), unprotected individuals can be exposed to large doses without immediate response.

Arsenical vesicants have delayed action, but, unlike mustards, they tend to produce immediate pain to whatever part of the body they contact. The principal arsenical of military interest is lewisite (L). Other arsenicals

are the mustard-lewisite mixture (HL) and the substituted double-chlorinated arsines (phenyldichloroarsine, ethyldichloroarsine, and methyldichloroarsine). Urticants are vesicants with disagreeable and penetrating odors that cause an immediate and severe burning sensation, as well as intense pain, numbness, and swelling. The only urticant of current military interest is phosgene oxime (CX).

Sternutators and Lacrimators

Vomiting compounds, or sternutators, and tear-producing compounds, or lacrimators (known as riot-control agents), are used for short-term incapacitation. Unless used indoors or where ventilation is extremely poor, these compounds are not fatal. The effects are short lived, and therefore do not incapacitate troops for very long.

Chemical vomiting agents produce strong, pepper-like irritations in the upper respiratory tract and eyes, which results in uncontrolled sneezing, coughing, nausea, and vomiting. Military sternutator agents include diphenylchloroarsine, diphenylcyanoarsine, and adamsite. A summary description of vomiting agents is provided in Table B-2. Sternutators, which are solids at ambient conditions, vaporize when heated into aerosols that are dispersed in the air. Sternutators are not persistent, but the aerosols can be rapidly dispersed and deposit slowly out of the air. The median incapacitating concentrations, ICt_{50}, for these agents vary from 12 mg-min/m for diphenylchloroarsine and 30 mg-min/m for diphenylcyanoarsine to 22-150 mg-min/m for adamsite. Outdoors these agents are debilitating; indoors they can cause serious illness and even death.

Tear-producing compounds, or lacrimators, cause a large flow of tears and some irritation to the skin and respiratory tract. Because the effects are only transient, lacrimators are used for training and riot control. The principal tear-producing agents are bromobenzylcyanide (CA), chloroacetophenone (CN, also used as mace), o-chlorobenzylidenmalonitrile (CS), dibenz-(b,f)-1,4-oxazepine (CR), and chloropicrin (PS). There are three CN solutions—CNC (CN with chloroform), CNB (CN with carbon tetrachloride and benzene), and CNS (CN mixed with chloropicrin and chloroform). There are also different forms of CS—CS-1 (CS blended with silica aerogel), CS-2 (CS blended with silicone-treated silica aerogel), and CSX (a liquid form of CS). The lacrimators currently in use by the U.S. military are CS, CS1, CS2, CSX, and CR. However, any of the lacrimators could be used against U.S. troops. These agents are not persistent, with the exception of CR, which can persist for up to 60 days under some circumstances. A summary description of the many tear-producing agents is provided in Table B-2.

Psychochemical (Incapacitating) Agents

Psychochemical, or incapacitating, agents are chemicals that cause temporary, reversible physiological or mental effects. Unlike the effects of riot-control agents that last only a few minutes, the effect of psychochemical agents last for hours or days. Psychochemical agents include both central nervous system (CNS) depressants and CNS stimulants.

CNS depressants block the activity of the CNS and disrupt the transmission of information across nerve synapses. An example of this class of compounds is 3-quinuclidedinyl benzillate, which affects the ability to remember, solve problems, pay attention, and listen to instructions. Cannabinols and phenothiazines lead to sedation and lack of motivation rather than impeding the ability to think. Fenyls are opiates that act like morphine but are 10,000 times as potent.

CNS stimulants cause excessive nervous activity, usually by increasing or facilitating the transfer of nerve impulses that might otherwise not cross certain nerve synapses. The effect is to flood the brain with too much information, which makes concentration difficult and results in indecisiveness and the inability to sustain actions.

EMERGING CHEMICAL WARFARE THREATS

The types and chemical properties of agents currently being developed or likely to be developed in the next five to ten years should be a subject of inquiry:

> There are thousands, maybe even tens of thousands, of "chemical compounds" in existence or proposed that could be considered for use in war depending upon the action required of them from the military point of view, including all the various drugs that are prescribed and taken and those that are not prescribed and taken. Many of these are lethal and incapacitating, even in small doses (Boyle, 1998, p. 7).

Bioregulator chemicals, for example, could be a threat in future deployments. These chemicals mimic or disrupt hormone signals and could be effective at very low doses.

OTHER POTENTIALLY HARMFUL CHEMICAL AGENTS

Toxic Industrial Chemicals

In addition to warfare agents, a large and growing number of potentially harmful chemical compounds can be found in or introduced into

the environments of deployed forces. For example, troops could be exposed to propellents, explosives, and pyrotechnic (PEP) hazards, a growing number of toxic industrial chemicals (TICs) and chemicals associated with military materiel. TICs are now a common component of military deployment and military training.

An extensive literature is available on the identification, evaluation, and control of human exposures to harmful industrial/commercial chemicals in both occupational and nonoccupational settings. The number of chemical substances in these categories is large and growing. About 20 million chemical compounds have been identified; 80,000 industrially and commercially used chemicals, 600 pesticides, and 100 new chemicals being introduced each year (Chemical and Engineering News, 1999; GEO-CENTERS and Life Systems, 1997; NTP, 1999). Not all of these are harmful chemicals. Approximately 400 chemical substances have been identified by regulatory agencies as potentially toxic and requiring some limitations on exposures. Currently, only 188 substances are listed by the Environmental Protection Agency (EPA) as hazardous air pollutants (EPA, 1998), and 85 chemicals have federal and/or state health-based concentration standards (NRC, 1999). However, these lists continue to expand. Thousands of chemicals have not yet undergone even a screening-level analysis of their potential toxicity, and thousands more have only undergone limited toxicity studies.

TICs can be organized according to their chemical properties and sources. Table B-3 provides a list of categories of chemical compounds containing chemicals that have been labeled toxic to humans. The list is not complete, but it gives a sense of the types of substances that should be detected and monitored and the concentrations that should be measured. In each category, examples of toxic chemicals are listed along with the chronic oral reference safe dose (*RfD*) in mg/kg/day, the chronic reference concentration (*RfC*) in mg/m, and (if available) the cancer potency (kg-day/mg). These measures indicate the chemical concentrations that should be detected and monitored to protect troops from low-dose health effects.

The last column of Table B-3 provides concentrations of the substance in water and air corresponding to the safety factor and/or potency factor. For water, an *RfD*-based concentration is calculated based on the assumption that a 70-kg adult drinking 2 L[1] of water per day should be at or below the *RfD*. Water concentration based on the cancer potency is based on the assumption that a 70-kg adult drinking 2 L of water per day will

[1] Two liters per day may be low, however, because TB Med 577 assumes military consumption of water as either 5 L/day or 15 L/day, depending on heat stress.

TABLE B-3 Chemical Categories of Toxic Industrial Chemicals

CAS ID	Pollutant	*RfD* (mg/kg/day) *RfC* (mg/m^3)	Cancer Potency [a]	Corresponding Concentrations mg/l water mg/m^3 air
Volatile Halogenated Hydrocarbons				
56-23-5	carbon tetrachloride	*RfD* 7E-4	0.13	0.02 mg/L
		RfC N/A		0.04 mg/m^3
67-66-3	chloroform	*RfD* 0.02	0.0061	0.7 mg/L
		RfC N/A		0.8 mg/m^3
87-68-3	hexachlorobutadiene	*RfD* N/A	0.078	0.6 mg/L
		RfC N/A		0.06 mg/m^3
Alkenes				
106-99-0	1,3-Butadiene	*RfD* N/A	0.28 per mg/m^3 air risk	N/A
		RfC N/A		0.005 mg/m^3
Mono-Aromatic Hydrocarbons				
71-43-2	benzene	*RfD* N/A	0.029 oral	1.7 mg/L
		N/A		0.17 mg/m^3
100-42-5	styrene	*RfD* 0.2	N/A	7.0 mg/L
		RfC 1.0		1 mg/m^3
108-88-3	toluene	*RfD* 0.2	N/A	7 mg/L
		RfC 0.4		0.4 mg/m^3
Polycyclic Aromatic Hydrocarbons (PAHS)				
50-32-8	benzo(a)pyrene	*RfD* N/A	7.3 oral	0.007 mg/L
		RfC N/A		0.0007 mg/m^3
206-44-0	flouranthene	*RfD* 0.04	None	1.4 mg/L
		RfC N/A		N/A
Halogenated Aromatics				
108-90-7	chlorobenzene	*RfD* 0.02	None	0.7 mg/L
		RfC N/A		N/A
106-46-7	1,4-dichlorobenzene	*RfD* N/A	None	N/A
		RfC 0.8		0.8 mg/m^3
118-74-1	hexachlorobenzene	*RfD* 0.0008	1.6	0.03 mg/L
		RfC N/A		0.003 mg/m^3
Biphenyls and Halogenated Biphenyls				
92-52-4	biphenyl	*RfD* 0.05	None	2 mg/L
		RfC N/A		N/A
1336-36-3	polychlorinated biphenyls (aroclors)	*RfD* N/A	1 to 2	0.03 mg/L
		RfC N/A		0.003 mg/m^3
Chlorinated Dibenzo-p-dioxins and Dibenzofurans				
1746-01-6	2,3,7,8-tetrachlorodibenzo-p-dioxin	*RfD* N/A	130,000	4E-7 mg/L
		RfC N/A		4E-8 mg/m^3

TABLE B-3 Chemical Categories of Toxic Industrial Chemicals (continued)

CAS ID	Pollutant	*RfD* (mg/kg/day) *RfC* (mg/m^3)	Cancer Potency[a]	Corresponding Concentrations mg/l water mg/m^3 air
Alcohols and Phenols				
95-48-7	methylphenol (o-Cresol)	*RfD* 0.05 N/A	None	2 mg/L N/A
67-56-1	methanol	*RfD* 0.5 N/A	N/A	18 mg/L N/A
Halogenated Phenols				
87-86-5	pentachlorophenol	*RfD* 0.03 N/A	0.12	0.4 mg/L N/A
95-95-4	2,4,5-trichlorophenol	*RfD* 0.1 N/A	N/A	4 mg/L 0.4 mg/m^3
88-06-2	2,4,6-trichlorophenol	*RfD* N/A *RfC* N/A	0.011	0.44 mg/L N/A
Nitrophenols, Nitrotoluenes and Related Compounds				
51-28-5	2,4-dinitrophenol	*RfD* 0.002 *RfC* N/A	N/A	0.07 mg/L N/A
121-14-2	2,4-dinitrotoluene	*RfD* 0.002 *RfC* N/A	N/A	0.07 mg/L N/A
Nitrogen and Sulfur Compounds				
107-13-1	acrylonitrile	*RfD* N/A *RfC* 0.002	0.54	0.09 mg/L 0.009 mg/m^3
91-94-1	3,3'-dichlorobenzidine	*RfD* N/A *RfC* N/A	0.45	0.1 mg/L 0.01 mg/m^3
96-45-7	ethylene thiourea	*RfD* 8E-5 *RfC* N/A	N/A	0.003 mg/L N/A
Acids				
79-10-7	acrylic acid	*RfD* 0.5 *RfC* 0.001	N/A	18 mg/L 0.001 mg/m^3
79-43-6	dichloroacetic acid	RfD N/A *RfC*	Under review	
Ethers, Ketones, Aldehydes, and Related Compounds				
75-07-0	acetaldehyde	*RfD* N/A *RfC* 0.009	0.0022 per mg/m^3	N/A 0.009 mg/m^3
542-88-1	bis(chloromethyl) ether	*RfD* N/A *RfC* N/A	222	0.0002 mg/L 0.00002 mg/m^3
78-93-3	methyl ethyl ketone (2-butanone)	*RfD* 0.6 *RfC* 1.0	N/A	20 mg/L 1 mg/m^3

TABLE B-3 Chemical Categories of Toxic Industrial Chemicals (continued)

CAS ID	Pollutant	*RfD* (mg/kg/day) *RfC* (mg/m^3)	Cancer Potency[a]	Corresponding Concentrations mg/l water mg/m^3 air
Phthalate Esters				
117-81-7	bis(2-ethylhexyl)phthalate (DEHP)	*RfD* 0.02 *RfC* N/A	0.014	0.7 mg/L 0.4 mg/m^3
84-74-2	dibutyl phthalate	*RfD* 0.1 *RfC* N/A	N/A	4 mg/L N/A
Pesticides				
57-74-9	chlordane	*RfD* 0.0005 *RfC* 0.0007	0.35	0.018 mg/L 0.0007 mg/m^3
62-73-7	dichlorvos	*RfD* 0.0005 *RfC* 0.0005	0.29	0.018 mg/L 0.0005 mg/m^3
58-89-9	gamma-hexachlorocyclo-hexane (lindane)	*RfD* 0.0003 *RfC* N/A	N/A	0.01 mg/L N/A
Metals				
7440-38-2	arsenic	*RfD* 0.0003 *RfC* N/A	1.5	0.01 mg/L 0.003 mg/m^3
7440-43-9	cadmium	*RfD* 0.0005 *RfC* N/A	1.8 m^3/mg	0.02 mg/L 0.0008 mg/m^3
Others				
123-91-1	1,4-dioxane	*RfD* N/A *RfC* N/A	0.011	5 mg/L 0.5 mg/m^3
	particulate matter (diesel exhaust)	*RfD* N/A *RfC* 0.005	N/A	N/A 0.005 mg/m^3

[a] [mg/(kg-d)]-1 is the cancer slope factor, the result of a low-dose extrapolation procedure and is presented as the risk (mg/kg)/day. It expresses the lifetime increase in cancer risk as a result of a unit increase in lifetime equivalent dose, expressed as mg/kg-d—that is, the low-dose rate averaged over a lifetime.

not exceed a lifetime (70 years) equivalent risk of 10 during a six-month deployment. The lesser of these water concentrations is listed in the last column. Air concentration for the cancer potency is based on the assumption that a 70-kg adult breathing 20 m of air per day will not exceed a lifetime (70 years) equivalent risk of 10^{-5} during a six-month deployment. The lesser of potency-derived air concentration and the *RfC* is listed in the last column. *RfD, RfC,* and potency values were obtained from the EPA's IRIS database (EPA, 1999).

Sources of chemically toxic agents for deployed troops include smokes and obscurants, solvents, products of combustion, metals and metal products, pesticides, fuels, and other industrial and/or military compounds. The sections below provide examples of the types of chemical substances associated with these sources and examples of the sources and emissions of these chemicals.

Smokes and Obscurants

Smokes and obscurants are used in military operations to create diversions and to conceal troop movements. The National Research Council Committee on Toxicology has carried out studies on the health effects of exposures to commonly used smokes and obscurants (NRC, 1997b). White phosphorus is presented here as an example of a smoke/obscurant compound, although the smoke rises in a pillar, and is one of the less toxic smokes in use. Other examples are hexachloroethane and Russian anthracine-based smokes.

White phosphorus is a colorless, white, or yellow waxy solid with a garlic-like odor; it does not occur naturally but is derived from phosphate rocks. White phosphorus reacts rapidly with oxygen, easily catching fire at temperatures of only 4 to 8°C above room temperature. White phosphorus is used by the military in various types of ammunition and to produce smoke for concealing troop movements and identifying targets. It is also used by industry to produce phosphoric acid and other chemicals used in fertilizers, food additives, and cleaning compounds. White phosphorus can enter the environment through deliberate deployment or through accidental spills during transport or storage. In the air, white phosphorus reacts rapidly with oxygen to produce relatively harmless chemicals within minutes. In water, it reacts with oxygen within hours or days. In soil, it may stick to particles and be changed within a few days to less harmful compounds. On the skin, burning white phosporous particles not only cause severe thermal injury, but the phosphorus pentoxide formed by oxidation reacts with water in the blood to form phosphoric acid, which causes death by reacting with ionized calcium, thus depleting the blood of this essential element.

Solvents

Trichloroethylene

Trichoroethylene (TCE), an example of a volatile halogenated hydrocarbon of the chemical family of chlorinated alkenes, is commercially produced by chlorination and dehydrochlorination of 1,2-dichloroethane.

A major use of TCE is in the vapor degreasing of fabricated metal parts. It is also used as a carrier solvent in textile cleaning and solvent extraction processes, as a lubricant and adhesive, and as a low-temperature heat transfer fluid. TCE is also used in the production of polyvinyl chloride, paints, coatings, and some miscellaneous chemical syntheses. An estimated 60 to 90 percent of the TCE produced in the world is released into the environment; the primary transport process for removal is volatilization (WHO, 1984a).

Tetrachloroethylene

Tetrachloroethylene (PCE), an example of a volatile halogenated hydrocarbon, is a commercially important chlorinated hydrocarbon solvent used as a dry cleaning agent and degreasing agent. PCE is used as a solvent for fats, greases, waxes, rubber, and the decaffeination process; to remove soot from industrial boilers; and as a heat-transfer medium. PCE is used in the manufacture of fluorocarbon refrigerants, paint removers, and printing inks. PCE is a primary source for the preparation of trichloroacetic acid (WHO, 1984b). PCE typically enters the atmosphere as a fugitive industrial emission. It reaches water supplies and the soil through the disposal of sewage sludge and factory waste and from leakages from storage and waste sites.

1,4-dichlorobenzene

This compound is a halogenated aromatic produced commercially by the direct chlorination of benzene in the liquid phase. Approximately 30 to 50 percent of the 1,4-dichlorobenzene (p-DCB) produced is used as a space deodorant for toilets and refuse containers or a fumigant for moths, molds, and mildews. A significant amount of p-DCB is used in the production of resins and as an intermediate for the production of other chemicals. p-DCB is also used as a solvent for various applications, such as paint and gums (Howard et al., 1990).

Products of Combustion

Benzo(a)pyrene

Benzo(a)pyrene (B(a)P), a polycyclic aromatic hydrocarbon (PAH), is produced ubiquitously as the result of incomplete combustion. Formation occurs when gasoline, garbage, or any animal or plant material is burned. B(a)P is often found in the smoke and soot of tar-production plants, coking plants, asphalt-production plants, and facilities that burn

organic material, such as wood, coal, and oil. B(a)P is also in cigarette smoke, charcoal-broiled meat, and smoked foods. When released into the atmosphere, smoke and soots combine with dust particles in the air and are carried into water, soil, and crops (WHO, 1983). Other sources of B(a)P are coal tar pitch used to cement electrical parts and the wood preservative, creosote.

2,3,7,8 tetrachloro-dibenzo-p-dioxin

Sources of 2,3,7,8 tetrachloro-dibenzo-p-dioxin (TCDD), a chlorinated dibenzo-p-dioxin, are pulp and paper manufacturing, incineration of municipal and industrial wastes, accidental transformer fires, and accidental industrial explosions (Sittig, 1985). TCDD is a trace contaminant of chlorophenols and products synthesized from chlorophenols. It has been associated with the manufacture of hexachlorophene, 2,4,5-T, and 2,4-D, and other pesticides having these compounds as precursors. Similar to some of the chlorinated hydrocarbon insecticides, TCDD is persistent and immobile in soil.

Metals and Metal Compounds

Arsenic

More than 100 minerals and ores contain arsenic (Bodek et al., 1988). In nature, arsenic (As) is usually associated with sulfide ores. Arsenic has valence states of –3, 0, +3, or +5. The principal arsenic-bearing minerals include arsenopyrite (FeAsS), niccolite (NiAsS), cobaltite (CoAsS), tennantite ($Cu_{12}As_4S_{13}$), enargite (Cu_3AsS_4), and native arsenic. The principal arsenic compounds produced for industrial use are arsenic trioxide (As_2O_3) and arsenic metal. From these, other arsenic compounds are made. About 70 percent of all arsenic consumed by industry is used in pesticides. Other uses include wood preservatives, glass manufacturing processes, alloys, electronics, catalysts, feed additives, and veterinary chemicals (Bodek et al., 1988).

Cadmium

Cadmium (Cd) typically occurs naturally in association with zinc ores, such as sphalerite (ZnS). Greenockite (CdS) is the only mineral of any consequence that bears cadmium (CRC, 1991). Almost all cadmium used industrially is obtained as a by-product in the treatment of zinc, copper, and lead ores. Cadmium has only one valance state, +2. Cadmium forms a number of salts, including cadmium chloride ($CdCl_2$), cadmium sulfate

($CdSO_4$), and cadmium sulfide (CdS). Cadmium sulfate is the most common salt. Cadmium has a relatively high bioavailability and is accumulated and retained in the human body.

Pesticide Formulations

Hexachlorobenzene

Hexachlorobenzene (HCB) is an example of a halogenated aromatic formed as a waste product in the production of several chlorinated hydrocarbons and is a contaminant in some pesticides. HCB is released to air as a fugitive emission from hydrocarbon production facilities and in flue gases and fly ash from waste incineration. HCB is persistent in the environment because of its chemical stability and resistance to biodegradation (Howard, 1989).

Chlorpyrifos

Chlorpyrifos, a pesticide, is a white crystal-like solid with a strong odor. Because it does not mix well with water, it is usually mixed with oily liquids before it is applied to crops or animals. It may also be applied to crops in a capsule form. In residences, chlorpyrifos is widely used to control cockroaches, fleas, and termites. In agriculture, it is used to control ticks on cattle and as a spray to control crop pests. Chlorpyrifos enters the environment through direct application to crops, homes, work spaces, and pets. It may also enter the environment through volatilization, spills, and the disposal of chlorpyrifos waste. Chlorpyrifos sticks tightly to soil particles, but because it does not mix well with water, it rarely enters local water systems.

Dichlorvos

Dichlorvos, a pesticide, is a sweetish smelling, dense, colorless liquid that mixes readily with water. When used for pest control, dichlorvos is diluted with other chemicals and used as a spray. It can also be incorporated into plastic that slowly releases the chemical. Dichlorvos is used for insect control in food storage areas, greenhouses, and barns, as well as directly on livestock. It is not generally used on outdoor crops. Dichlorvos is sometimes used for insect control in work places and residences. Veterinarians use it to control parasites on pests, and it used to be the active ingredient in No-Pest Strips®. Dichlorvos enters the environment during its manufacture and use, from landfills, and from accidental

spills during transport and leaks from storage containers. It evaporates easily into the air, where it is broken down into less harmful chemicals.

Hexachlorocyclohexane

Hexachlorocyclohexane (HCH), also a pesticide, is a manufactured chemical that exists in eight chemical forms (called isomers). One of these forms, gamma-HCH, also known as lindane, is a white solid substance that may evaporate into the air as a colorless vapor with a slightly musty odor. Although lindane has not been produced in the United States since 1977, it is still imported to and formulated in the United States. Prior to 1983, lindane was used widely as an insecticide on fruit and vegetable crops (including greenhouse vegetables and tobacco) and forest crops (including Christmas trees). It is still used in ointments to treat head and body lice and scabies, but its use is restricted by the EPA, and it can be applied only by a certified applicator. In air, alpha- , beta- , gamma- , and delta-HCH can be present as a vapor or attached to small particles, such as soil or dust. Lindane can remain in the air for up to 17 weeks and travel long distances. Particles with attached HCH may be removed from the air by rain. The length of time that HCH isomers remain in soil is not known. It can accumulate in the fatty tissue of fish.

Fuels

Benzene

Benzene, a mono-aromatic hydrocarbon, enters the atmosphere primarily from fugitive emissions and exhaust connected with its use in gasoline and as an industrial intermediate (WHO, 1982). Sources of benzene are the pyrolysis of gasoline, catalytic or thermal hydrodealkylation of toluene or xylenes, and transalkylation of toluene. Coking, liquefaction, and gasification of coal are also potential sources of benzene. Benzene is used primarily in the manufacture of other chemicals, such as ethylbenzene, styrene, cumene, phenolic resins, ketones, adific acid, caprolactam, nylon, and various dyes (Clayton and Clayton, 1981).

Toluene

Toluene, a mono-aromatic hydrocarbon, is a colorless liquid with a distinctive sweet and pungent smell that occurs naturally in crude oil and in the tolu tree. One can smell toluene at 8 parts per million parts (ppm) of air and taste it in water at 0.04 ppm to 1 ppm. Toluene is produced during the process of making gasoline and other fuels from crude oil, in making

coke from coal, and as a by-product in the manufacture of styrene. It is also used in making paints, paint thinners, fingernail polish, lacquers, adhesives, and rubber, as well as in some printing and leather tanning processes.

Toluene has been found in waste sites and landfills when discarded as used solvent or in paints, paint thinners, and nail polish. It does not stay in the environment long. It is readily broken down by microorganisms in the soil, and it evaporates quickly from the soil and surface water into the air, where it combines with oxygen to form benzaldehyde and cresol, which can be harmful to people. However, this process is slow. Toluene is removed from air more rapidly by reacting with OH radicals.

Other Industrial Pollutants

Di-2-ethylhexylphthalate

Di-2-ethylhexylphthalate (DEHP), a phthalate ester, is used in large quantities in the organic chemical industry primarily as a plasticizer for PVCs and other polymeric materials (Howard, 1989). It is also used as organic pump fluid. DEHP is released to air and water during the production, disposal, incineration, and recycling of plastic materials in which it has been used. It is also continuously "volatilized" from PVC in which it is used as a plasticizer.

Vinyl chloride

Viny chloride (VC), a volatile halogenated hydrocarbon, is not known as a natural product but is commercially produced by halogenation of ethylene. About 96 percent of the vinyl chloride produced is used for the homopolymer and copolymer resins known as PVC. Environmental contamination of VC is reported to come from PVC and latex manufacturing plants that emit residual VC monomer into the air or in the effluent discharge. VC is also found in food and beverage packaging materials. When introduced into the environment, VC is quickly volatilized into the atmosphere (WHO, 1979).

Polychlorinated Biphenyls

Polychlorinated Biphenyls (PCBs) are a class of synthetic organic compounds, members of a family that contain 209 individual isomers. No PCBs have been manufactured in the United States since 1977. PCBs were widely used as coolants and lubricants in transformers, capacitors, hydraulic fluids, and vacuum pumps, and as plasticizers in rubbers and

synthetic resins. PCBs are used in adhesives, wax extenders, dedusting agents, inks, cutting oils, pesticide extenders, sealants, and caulking compounds (WHO, 1993).

Toluene-2,4-diisocyanate

Toulene-2,4-diisocyanate (2,4-TDI) is a white liquid used in the manufacture of polyurethane foams and other elastomers. 2,4-TDI constitutes roughly 80 percent of the commercial toluene diisocyanate (TDI) used in the United States, the other 20 percent being the isomer, 2,6-TDI (Howard, 1989). TDI is released to the environment as a fugitive emission from stack exhaust during the production, transport, and use of TDI in the manufacture of polyurethanefoam products. Both 2,4- and 2,6-TDI are reactive with any compound having active hydrogens (i.e. water, acids, alcohols).

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Appendix C

Harmful Properties of Biological Agents

WARFARE AGENTS

Bacteria

Bacteria are microscopic, one-celled, plant-like organisms that range from 0.1 to 10 microns in diameter. They can be classified by shape as bacilli (rod), cocci (spherical), and spirilla (spiral). Bacteria are widely distributed in nature and can grow on artificial materials in the absence of other living cells.

Among the bacteria that are considered the most likely candidates for use as biological warfare agents are *Bacillus anthracis* (anthrax), *Vibrio cholera* (cholera), *Yersinia pestis* (plague), *Franciscella tularensis* (tularemia [rabbit fever or deer-fly fever]), and *Brucellosis suis* (brucellosis or undulant fever). Many other species are less dramatic but still pathogenic, such as *Salmonella typhimurium* (gastroenteritis, known as food poisoning), *Staphylococcus aureus*, and *Shingellar dysenteriae* (dysentery). Some agents usually affect animals but can be transmitted to humans with severe effects. Examples include *Burkhoderia mallei* (glanders) and *Burkhoderia pseudomallei* (melioidosis).

Rickettsia

Rickettsia are intracellular microscopic organisms intermediate between bacteria and viruses. They are oblong and vary in size from 0.3 to

0.5 microns in length and 0.3 micron in width. Like viruses, rickettsia cannot reproduce outside of a living organism. Rickettsia that are likely candidates for warfare agents are *Coxiella burnetti,* which causes Q fever and a chronic endocarditis; *Rickettsia prowasecki*, the causative agent of epidemic typhus; and *Rickettsia ricketsii*, the causative agent of Rocky Mountain spotted fever. Table C-1 provides a summary of the disease, likely transmission pathway, lethality, and infectivity associated with selected rickettsia agents.

Viruses

A virus is a microscopic organism consisting mainly of a nucleic acid in a protein coat. Viruses are shaped like rods or spheres and range in size from about 0.01 to 0.3 micron. Viruses cannot multiply on their own, but inside a living cell they become active organisms that can multiply. The viruses considered for potential use in warfare include the Ebola virus, Hanta virus, Venezuelan equine encephalitis virus, yellow fever virus, Rift Valley fever virus, the Junin virus (Argentine hemorrhagic fever), the variola virus (smallpox), and the Dengue fever virus. Table C-1 provides a summary of the disease, transmission, pathway, and lethality associated with selected viral agents. Infectivity is not currently available for most viruses. Many are transmitted by ticks and mosquitoes. Others are transferred by human contact.

Biological Toxins

Biological toxins are harmful chemical compounds produced by living organisms. Two toxins commonly associated with biological warfare are *Botulinum* and *Clostridium perfringens*. *Botulinum*, which is extremely potent, causes respiratory paralysis; the victim suffers from asphyxia. *Clostridium perfringens* causes gas gangrene in which extremities "go necrotic" by slowly suffocating them. Table C-2 provides a summary of the sources, lethality, and required detection capability for selected toxins.

Genetically Altered Organisms

The last group of organisms that are used, or could be used, for warfare are genetically altered organisms. A group planning to develop a genetically altered organism would most likely aim for a more virulent or less treatable mutant of one of the agents described above. A toxin or substance created or acquired through recombinant technology would also be included in this category.

TABLE C-1 Exposure Factors for Selected Biological Warfare Agents

Agent	Disease	Transmission	Lethality	Infectivity	Required Detection Capability[a]
Bacteria					
Bacillus anthracis	Anthrax	Spores in aerosol	High ~ 100%	10,000 organisms	5,000 org/m^3 air
Vibrio cholera	Cholera	Food and water			
		Aerosol	Low with treatment	1 million organisms	500,000 org/L water
Yersinia pestis	Pneumonic plague	Aerosol inhalation	High unless treated	< 100 organisms	50 org/m^3 air
Franciscella tularensis	Tularemia (rabbit fever)	Aerosol inhalation	Moderate	1 to 50 organisms	< 25 org/m^3 air
Shigelladysenteriae	Dysentery	Inhalation and ingestion	Moderate	10 to 100 organisms	25 org/m^3 air 25 org/L water
Rickettsia					
Coxiella burnetti	Q fever	Aerosol inhalation Food	Very low	10 organisms	5 org/m^3 air < 5 org/kg food
Rickettsia rickettsii	Rocky Mountain spotted fever	Vectors	Low	N/A	N/A

Viruses					
Ebola virus	Ebola	Direct contact Aerosol	High for Zaire strain	N/A	
Venezuelan Equine Encephalitis (VEE) virus	Encephalitis	Vectors	Low	N/A	
Yellow fever virus	Yellow fever	Vector/tick	Low	N/A	
Rift Valley fever virus	Rift Valley fever	Vector/ mosquito	Low	N/A	
Variola virus	Smallpox	Aerosol	High to moderate	N/A	
Hanta virus	Hanta	Aerosol	43% in U.S.	N/A	N/A
Dengue fever	Dengue fever	Aedes mosquito	Low to moderate	N/A	

[a] These numbers were calculated by dividing the infectivity level by 2 m^3 (the amount of air assumed to be breathed in two hours by an active adult) or by 2 L, the amount of water consumed during a day.

Source: Boyle, 1998.

TABLE C-2 Characteristics of Selected Biological Toxins

Source	Toxin	LD_{50} (μG/kg)	Required Detection Capability[a]	Notes
Bacteria				
Clostridium botulinium	Botulinium A, B, C, D, E	~ 0.02 (inhalation) 1 (oral)	0.1 mg/m^3 0.02 mg/L (water or food)	Among the most potent toxins known. Delayed lethality. Persists in food and water. Breaks down within 12 hours in air.
Clostridium perfringens	Gangrene-causing enzyme	0.1 to 5	0.3 mg/m^3	Delayed action. Low mortality, but very debilitating.
Clostridium tetani	Tetanus toxin	~ 3	N/A	Delayed action. Relatively unstable and heat sensitive.
Cornyebacterium diptheria	Diptheria toxin	0.03	N/A	Lethal. Rapid acting.
Staphylococcus aureus	Staphylococcus enterotoxin A, B, C, D, E (Toxicity is for for type B)	0.4 (aerosol ED_{50}) 20 (aerosol LD_{50}) 0.3 (oral ED_{50})	0.058 mg/m^3 3 mg/m^3 0.007 mg/L	Rapid acting. Symptoms persist for up to 24-48 hours. Severely incapacitating. Can be lethal. Large-scale production feasible. Very stable.
Dinoflagellates				
Gonyaulax tamerensis, Gonyaulax catanella, and related species	Saxitoxin (shellfish poison)	1 (aerosol inhalation) 7 (oral)	0.01 mg/m^3 (air) 0.2 mg/L	Lethal. Rapid acting. Soluble in water. Relatively persistent.
Takifugu poecilonotuss	Tetrodotoxin	1.5 to 3 (inhalation) 30 (oral)	0.3 mg/m^3 (air) 0.7 mg/L	Lethal. Rapid acting. Stable.

Algae				
Anacystis species, Anabanea flos-aquae	Anatoxin A (VFDF)	170 to 250 (IP)[b] 5,000 (oral) 2,100 (dermal)	100 mg/L(kg) (water or food)	Very fast death factor. Very rapid acting.
Microcystis aeruginosa, Microcystis, cyanea	Microcystin (FDF)	25 to 100 (IP)[b]	~10 mg/m^3 (air) ~2 mg/L (water)	Lethal, rapid acting. Fast death factor.
Fungi				
Fusarium species	Trichothecene mycotoxins ("yellow rain")	25 to 500 (inhalation) 1,600 (oral)	40 mg/m^3 (air) 40 mg/L	Nonlethal, delayed effects. Inhalation, ingestion, dermal. Very stable. Small repeated doses are cumulative.
Plants				
Ricinus communis	Ricin	1,000	150 mg/m^3 (air) 20 mg/L (water)	Lethal, delayed action. Easily produced. Persistent.
Animals				
Palythoa (soft corals)	Palytoxin	0.08 to 0.4	0.035 mg/m^3 (air) 0.006 mg/L (water)	Lethal and rapid acting. Stable.
Conus geographus Conus magnus fish-hunting cone snails)	Conotoxins	3 to 6	~0.6 mg/m^3 (air) ~0.1 mg/L (water)	Water soluble. Highly stable. Can be used as aerosols. Easily synthesized.
Phyllobates aurotaenia and Phyllobates terribilis (Columbian frog)	Batrachotoxin	0.1 to 0.2	0.015 mg/m^3 (air)	Rapid acting and lethal. Very stable. Can be synthesized.

[a] Assumes 70-kg adult breathing at a rate of 0.016 m^3/min for 30 minutes for air or the ingestion of 3 L water or 3 kg food by a 70-kg adult
[b] IP refers to intraperitoneal injection dose to mice.

Source: Boyle, 1998.

REFERENCE

Boyle, R.E. 1998. Biological Warfare: A Historical Perspective. Contract No. LG-1597. Albuquerque, N.M.: Sandia National Laboratories.

Appendix D

Detecting and Monitoring Chemical Agents

INTRODUCTION

Separation and detection technologies make use of the attributes of a chemical that distinguish it from other chemical compounds and make it detectable by sensors (NRC, 1991). Distinguishing attributes include chemical reactions that cause color changes; the mass-to-charge ratio of the molecule; absorption and scattering of electromagnetic energy, particularly in the infrared to microwave region; reactions that cause unique emissions, such as chemiluminescence; physical separation; electrochemical interactions; and reactions with enzymes. A sensor is a device that produces a measurable response to a change in a physical condition, such as temperature or thermal conductivity, or to a change in chemical concentration (Cattrall, 1997; Janata, 1989; Taylor and Shultz, 1996).

Many detection technologies are based on spectrometry, the spectrum of mass or energy in the sampling device (Barker, 1999; Scimedia, 1999). Spectroscopy is the use of the absorption, emission, or scattering of electromagnetic radiation by atoms or molecules (or atomic or molecular ions) to qualitatively or quantitatively detect atoms or molecules (Scimedia, 1999). Mass spectrometers use the difference in mass-to-charge ratio of ionized atoms or molecules to separate them from each other. A sample is introduced into the instrument, a charge is imparted to the molecules in the sample, and the resultant ions are separated by the mass analyzer component. Mass spectrometry is useful both for determining

chemical and structural information about molecules and for quantifying the concentration of atoms or molecules in a sample. The technique requires only a few nanomoles of analyte to determine characteristic information on structure and molecular weight. Tables D-1 and D-2 provide a summary review of the chemical detection and monitoring technologies and devices discussed below.

EXISTING TECHNOLOGIES

In the sections below, common technologies for detecting vapor-phase and aerosol-phase chemical agents as well as chemicals in other media, such as water, soil, and food, are described. Vapor-phase chemicals are volatile chemicals found as gases in air. Aerosol-phase chemicals are either dispersed in air as particles or are bound to fine particles.

Color-Change Chemistry

Color-change technology is based on chemical reactions that occur when some chemical agents interact with various solutions and substrates. The most common indicator of a reaction is a color change. Color-change detectors can detect nerve, blister, and blood agents with detection tubes, papers, or tickets to whose surface a substrate or reagent solution is applied (IOM, 1999). Many detection kits are complex and include multiple tests for specific agents or families of agents. Color-change methods are primarily qualitative in that they only detect the presence of an agent above a certain concentration threshold, but they are not reliable for determining chemical agent concentrations (U.S. Army SBCCOM, 1998).

Ion Mobility Spectrometry

Ion mobility spectrometry (IMS) operates by drawing air at atmospheric pressure into a reaction region where the constituents of the sample are ionized. Air and chemical agents in vapor-phase compounds form ion clusters when they are exposed to their parent ions. The mobility of the ion clusters is mainly a function of shape and weight. The agent ions travel through a charged tube where they collide with a detector plate, and a charge (current) is registered. A plot of the current generated over time provides a characteristic ion mobility spectrum. The intensity (height) of the peaks in the spectrum, which corresponds to the amount of charge, indicates the relative concentration of the agent. IMS technology has been used in mobile detectors to detect nerve, blister, and blood agents (IOM, 1999).

TABLE D-1 Estimates of Chemical Agent Exposure Limits

Chemical Agents	Lethal Exposure Limit Estimates	Other Established Exposure Limit Estimates
Nerve Agents		
GA	13	0.0001
GB	3	0.0001
GD	2	0.00003
GF	N/A	N/A
VX	3	0.00001
Choking Agents		
CG	100	0.002
DP	100	0.002
Blood Agents		
AC	150	0.003[a]
CK	400	0.008[a]
SA	200	0.004[a]
Blister Agents[b]		
HD, L, HNs[a]	~50	0.003
HL	50	0.003
PD, ED, MD, CX	~100	0.003[a]

[a] Limited operational temperature and humidity range.
[b] Representative exposure limits but not the specific volume for any single compound.

Infrared Absorption Spectroscopy

Infrared spectroscopy is the measurement of the absorption of mid-infrared light (2.5–50 μm wavelength) which can excite molecular vibrations to higher energy levels. The wavelength of infrared absorption bands work best for identifying organic and organometallic molecules (Dean, 1995; Scimedia, 1999).

Compounds in the air that absorb infrared energy can be quantified using open-path Fourier transform infrared (FTIR) spectroscopy. An FTIR spectrometer consists of a beam splitter that divides the incoming radiation into two beams. One beam is reflected by a fixed mirror; the other is sent to a moving mirror causing a variable optical path difference. Both beams are then reflected back to the beam splitter where they recombine and interfere according to their wavelength and optical path difference. A detector measures the intensity of the interfering beam as a function of the optical path difference. The result of this process is an interferogram. The optical path difference is measured with a monochromatic laser, and

TABLE D-2 Sensitivity of Chemical Agent Detection and Monitoring Equipment

Detection Equipment`	Detection Sensitivity to Chemical Agents (mg/m^3)				
	Nerve Agents (in μ drops)	Choking Agents	Blood Agents	Blister Agents (in μ drops)	Other Agents[a]
M8 and M9 Detection Paper (liquids only)	G agents 100 VX 100			H 100 μ drops	
M8A1 Alarm (ACAA)	GA 0.1–0.2 GB 0.1–0.2 GD 0.1–0.2 VX 0.2				
M22 (ACADA)	GA 0.1 GB 0.1 GD 0.1 VX 0.05			HD 2 L 2	
M90 D1A (AMAD)	G agents 0.02 VX 0.02		Sensitivity not available	H 0.2 L 0.8	
ICAD Miniature Detector	G agents 0.2–0.5	CG 25 CK 50	AC 50	HD 10 L 10	
M21 Alarm	G agents 90				
CAM Chemical Agent Monitor	G agents 0.03 VX 0.03			HD 0.1 HN agents 0.1	
ICAM-APD	G agents 0.1			H 2 L 2	
SAW Mini-CAD Alarm	GB 1 GD 0.12			HD 0.6	
Mini-CAMS	G agents 0.0001 VX 0.0001			H 0.003 L 0.003	
Gas Chromotography Systems	G and V < 0.0001	Many possible	Many possible	HD < 0.003 Others	

[a] For example, riot-control toxins.

the interferogram is converted to a spectrum by a Fourier transformation. Although FTIR has the capability of identifying chemicals in air with parts per billion (ppb) sensitivity, each chemical requires a different reference spectrum. In addition, when used with a mix of chemicals, FTIR requires spectral pattern-recognition software to separate the concentrations of individual species out of complex multicomponent spectra.

Another technology that makes use of infrared absorption spectroscopy is tunable infrared laser absorption spectroscopy. For many types of compounds, this technology is an attractive competitive alternative to FTIR because of its higher sensitivity and selectivity.

Differential Optical Absorption Spectrometry

Infrared light absorption has proven to be quite useful for measuring concentrations of atmospheric chemicals. However, it cannot be used to measure all chemicals of interest with the necessary level of specificity and sensitivity. Thus, absorption in the ultraviolet and visible regions of the spectrum is increasingly being used to detect chemicals in air. One example is differential optical absorption spectrometry, which measures the difference between the absorption at a wavelength where the species of interest has a distinct absorption peak and at another wavelength on either side of the peak (Vandaele and Carleer, 1999).

Aerosol Mass Spectrometry

The goal of aerosol mass spectrometry is to provide on-line, real-time chemical analysis of individual aerosol particles (Johnston, 1999). The chemical analysis characterizes aerosol particles in terms of bulk composition, surface composition, organic chemical species, and inorganic chemical species. An on-line system minimizes sampling artifacts caused by condensation, evaporation, or chemical transformation. A real-time system provides high temporal resolution and allows the system to monitor rapid changes in composition. Current devices include the following instrumentation:

- an aerosol inlet that pulls sampled particles from atmospheric pressure into a vacuum and transfers them to a laser beam for analysis
- an instrument for particle detection and sizing that can synchronize the arrival of a particle with a desorption laser pulse and determine the particle size
- a mass spectrometer that can desorb and ionize constituents in the particle and obtain a complete mass spectrum from the burst of

ions produced (older instruments use lasers to vaporize the particle constituents; newer instruments use hot surfaces)

Raman Spectroscopy

When electromagnetic radiation is passed through a transparent medium, some of the radiation is scattered in different directions by chemical species present in that medium (Scimedia, 1999). The wavelength of a very small fraction of the scattered radiation differs from the wavelength of the incident beam; this is the Raman-scattered light. The wavelengths of the scattered light are shifted from those of the incident light by the energies of molecular vibrations. The mechanism of Raman scattering differs from infrared absorption so that Raman and infrared spectra provide complementary information. Raman spectroscopy is used for determining structure, multicomponent qualitative analysis, and quantitative analysis. IR can be used to detect chemical agents in air samples.

Nondispersive Infrared Spectroscopy

The infrared region of the electromagnetic spectrum between 2.5 and 25 micrometers has proven to be a valuable range for the identification and quantification of gaseous molecular species. When infrared radiation passes through a gas, radiation is absorbed at specific wavelengths defined by infrared filters. These wavelengths are characteristic of the vibrational structure of the specific gas molecules. Nondispersive infrared spectroscopy technology is used in mobile detectors to detect blister and nerve agent vapors.

Phosphorus Chemiluminescence

Chemiluminescence is a technique that uses quantitative measurements of the optical emission from excited chemical species to determine analyte concentrations. The excitation energy for analytes in chemiluminescence is produced by a chemical reaction of the analyte and a reagent. Chemiluminescence can take place in either the liquid or gas phase. Phosphorus chemiluminescence detectors (PCDs) can be used to detect many chemical agents (Stedman, 1999) and are used for gas chromatography. PCDs can detect electromagnetic radiation in a system with very low background. Because the energy necessary to excite the analytes does not come from an external light source like a laser or lamp, there is no problem from excitation source scattering. The major limitation of PCDs involves the dark current of the photomultiplier necessary to detect the analyte light emissions.

Light Detection and Ranging

A light detection and ranging (lidar) system uses laser pulses to measure atmospheric constituents, such as aerosol particles, ice crystals and water vapor, or trace gases, such as chemical agents (U.S. Army SBCCOM, 1998). Every gaseous chemical species absorbs light in a unique way. One gas absorbs light at certain wavelengths; others absorb it at different, well defined wavelengths. A lidar device transmits short pulses of laser light into the atmosphere. As the laser beam travels, its intensity decreases due to scattering by natural airborne aerosols and particles. Some of the light is backscattered to a detector adjacent to the emitting laser, which measures the amount of light that is backscattered. Because the light takes longer to return from the more distant ranges, the time delay of the return pulses can be converted to the corresponding distance between the point of scattering in the atmosphere and the lidar detectors. The result is a profile of atmospheric scattering versus distance. Vapor molecules in the air will absorb scattered light if the laser wavelength matches the molecule's absorption profile. An analysis of the absorption signal can yield information about the distribution of chemicals in the atmosphere.

Differential absorption lidar (DIAL) uses light of two different wavelengths, only one of which is absorbed by the gas under investigation, so that a differential measurement can be performed. The nonabsorbed wavelength is used as a reference to eliminate atmospheric propagation effects. Lidar provides a method for remote (or stand-off) detection of chemicals in the atmosphere.

Gas Chromatography

Gas chromatography is used to detect a variety of chemical compounds. Chromatography is a separation method that relies on differences in partitioning behavior between a flowing mobile phase and a stationary phase to separate the components of a mixture. A column (or other support) holds the stationary phase, and the mobile phase carries the sample through it. Sample components that partition strongly into the stationary phase spend a longer time in the column and are separated from components that stay predominantly in the mobile phase and pass through the column faster. As the components emerge from the column, they can be quantified by a detector or collected for further analysis. In gas chromatography, the mobile phase is a gas, and the stationary phase is usually a liquid on a solid support or sometimes a solid adsorbent. Like mass spectrometry, gas chromatography methods also offer high sensitivity and specificity in detecting chemical agents in many sample forms.

A gas chromatograph can be combined with a detection method for on-line analysis. Examples of such "hyphenated techniques" include gas chromatography/mass spectroscopy, gas chromatography/FTIR, and diode-array ultraviolet/visable absorption spectroscopy.

Surface Acoustic Wave Technology

Surface acoustic wave (SAW) technology is based on the attenuation of solid-state acoustic surface waves through chemical interactions between the analyte and a chemically selective coating on the surface. SAW sensors detect changes in the properties of acoustic waves as they travel at ultrasonic frequencies at the surface interface between the coating and a piezoelectric material, such as quartz, lithium tantalate, lithium niobate, or langasite crystals. These materials convert radio frequency electrical signals into Rayleigh surface acoustic waves through a carefully designed transducer. The basic transduction mechanism involves interaction of these waves with surfaceabsorbed gases. A second transducer detects the acoustic wave as a delayed, attenuated replica of the input electrical signal. Multiple sensor arrays with multiple coatings, each having a different molecular selectivity based on chemical solubility, and pattern recognition algorithms are used to identify agent classes and reject interferent responses that could cause false alarms (IOM, 1999).

Although SAW transducers respond to agents with no coatings, special polymer coatings are used to enhance the response (signal-to-noise ratio) from the target agents and minimize false alarms from battlefield interferents. One coating provides various responses to several different chemical warfare agents, and the differences are usually large enough for the device to differentiate among agents.

Current technology can detect and identify a wide range of chemical warfare agents with only six different coatings. However, more coatings may be needed for higher degrees of specificity for large target populations like TICs. If the new agents respond to existing coatings, it will be fairly simple to change the detection software to recognize them. If not, new coatings must be developed. SAW sensors are used in mobile detectors to detect nerve and blister agents. With further development, SAW technology could also potentially detect a large number of chemical compounds and biological agents.

Electrochemical Sensor Technology

An electrochemical sensor detects and measures changes caused by the interaction between the chemical agent and the properties of an electrical circuit (Taylor and Schultz, 1996). Fundamentally, electrochemistry

is based on a chemical reaction that occurs when the chemical agent enters the detection region and produces some change in the electrical potential. This change is normally monitored through an electrode. A threshold concentration of agent is required, which corresponds to a change in the monitored electrical potential. Electrochemical sensor technology can be used in a wide variety of configurations. Currently, it is used in mobile detectors to detect blister, nerve, blood, and choking agents.

Photo-ionization Technology

Photo-ionization detectors (PIDs) operate by passing an air sample between two charged metal electrodes in a vacuum region irradiated with ultraviolet radiation, thus producing ions and electrons. The negatively charged electrode collects the positive ions, thus generating a current that is measured by an electrometertype electronic circuit. The measured current can then be related to the concentration of the molecular species present. PIDs are used in mobile detectors to detect nerve, blister, and mustard agents.

Flame Photometry

In flame photometry, an air sample is burned in a hydrogen-rich flame. The compounds present emit light of specific wavelengths in the flame. An optical filter is used to let a specific wavelength of light pass through, and a photosensitive detector produces a representative response signal. Because most elements emit a unique, characteristic wavelength of light when burned in this flame, the flame photometer can detect specific elements. Flame photometers are commonly used with gas chromatographs. Sulfur and phosphorous flame photometry are often used to detect mustard and nerve gas, respectively.

Photoacoustic Infrared Spectroscopy

Like infrared spectroscopy, photoacoustic infrared spectroscopy (PIRS) uses the selective absorption of infrared radiation by chemical agent gases to identify and quantify the agent present. Pulses of a specific wavelength of infrared light are sent into a sample through an optical filter, and the light transmitted by the filter is selectively absorbed by the gas being monitored, which increases the temperature and pressure of the gas. Because the light entering the cell is pulsating, the pressure in the cell fluctuates, creating an acoustic wave directly proportional to the concentration of the gas in the cell. Microphones mounted inside the cell monitor the acoustic signal and send results to the control station. PIRS technology is

fairly well established, but its use for chemical warfare agent detection is fairly new. It is anticipated that a large number of agents can be detected with this technology.

Millimeter and Submillimeter Wave Detection

The molecules of many compounds absorb waves in the infrared region of the electromagnetic spectrum, and the wavelength at which absorption occurs is unique to specific compounds, which provides identifiers for different compounds. Rotational and vibrational interactions occur with electromagnetic radiations that have longer (submillimeter to millimeter) wavelengths. These regions include the far-infrared and radio frequency microwave spectrum. Research on the absorption of these wavelengths for detecting chemical agents is under way (U.S. Army SBCCOM, 1998). If the absorption of energy at these wavelengths is sufficient, microwave spectroscopy-based technologies similar to infrared spectroscopy methods may be another way of detecting chemical agents.

EMERGING TECHNOLOGIES

Aerosol Mass Spectrometry

Only a few on-line techniques have been developed for detecting and characterizing small aerosol particles. Conventional methods involve isolating particles on filters and subsequent analysis performed in the laboratory. The isolation processes often disturb the aerosol and thus render the data questionable because the particles often evaporate or react before analysis.

Newer spectrometers using gentler vaporization strategies will probably overcome this problem. An example of an emerging technology based on aerosol spectrometry is aerosol time-of-flight mass spectrometry (ATOFMS) (Noble and Prather, 1996). This technique provides the size and chemical composition of individual aerosol particles in real time. Some examples of aerosol systems that are being characterized in the laboratory using ATOFMS include secondhand tobacco smoke, suspended soil dust, sea salt aerosols, and a variety of combustion particles. In recent field studies, transportable ATOFMS instruments were strategically positioned at sites where the evolution of single particles in the atmosphere could be monitored over time. In regional and international studies, these transportable instruments are being used to study the direct effects of aerosols on visibility, pollution levels, and global radiation.

The ATOFMS uses lasers to vaporize the particle constituents. Some newer instruments use hot surfaces rather than lasers for aerosol

vaporization. Hot surface vaporization tends to preserve organic molecular structure better and prevent its fragmentation in the laser vaporization/ionization instruments. If these "hot-surface" systems can preserve molecular structure, they may be crucial to the future identification of specific chemical agents and TICs bound to aerosols.

Enzyme Methods

Enzymes can be used with immunoassays to detect the presence of, and quantify the concentration of, many chemical substances (Ngo and Lenhoff, 1985). The essential components of an enzyme immunoassay are an antibody that binds to a specific target substance (chemical agent) and an enzyme that makes detection of the bound antibody possible. Immunoassays performed in a solution, for example, respond to the initial reaction of the antibody and its chemical, which then modulates the catalytic activity of the enzyme, allowing detection. The sensitivity of an enzyme immunoassay depends on how well antibodies home in on a particular antigenic target, such as a chemical agent or a protein, a bacterial or viral antigen, or other antibodies. A detection system that combines this specificity with the catalytic ability of some enzymes to convert colorless chemicals to brightly colored products could be adapted to a wide range of applications. The best known enzyme immunoassay technique is enzyme-linked immunosorbent assay (ELISA). Immunoassays are increasingly being used to detect environmental contaminants. Enzyme immunoassays can be very sensitive (down to the parts per trillion [ppt] level) and very specific. However, they are much too slow for rapid chemical detection. Another problem is that some substances do not readily create antibodies.

CURRENT DETECTION AND MONITORING EQUIPMENT

Currently available equipment for detecting and monitoring chemical agents range from simple systems, such as detection paper, to complex mobile sampling vehicles, such as the FOX vehicle. The following subsections contain a review of the capabilities and limitations of these systems, most of which have been developed singly or jointly by branches of the military (a few have been commercially developed but are available for military use). The information for this review was provided by a number of sources, including other National Research Council reports (IOM, 1999; NRC, 1997a, 1997b); documents provided by the U.S. Department of Defense (DoD) (DoD 1997, 1998, 1999; U.S. Army, 1992, 1994; U.S. Army and U.S. Marine Corps, 1996); briefings to the principal investigator and advisory panel by the U.S. Army Soldier and Biological Chemical Command (U.S. Army SBCCOM, 1998); Jane's Guidebook (Ali et al., 1997);

and internet resources (Jane's Information Group, 1999; JSMG, 1999; U.S. Army SBCCOM, 1999; U.S. Navy, 1999).

Detection Papers

The M8 and M9 detection papers provide rapid (less than one minute), inexpensive tests for the presence of liquid mustard or nerve agents. The paper is used only for screening, and results must be verified by more accurate detection methods, particularly because of the paper's propensity to show false positive results for some substances, such as petroleum products and antifreeze.

M8 Chemical Agent Detector Paper

M8 paper is used by ground troops to detect liquid chemical agents. It is capable of detecting Levinstein mustard (H) and Lewisite blister agents and fluorine- or cyanide-containing organophosphates (G) and sulphur-containing organophosphorous compounds (V) nerve agents. It is not used as the sole basis for agent identification, however. M8 paper is supplied in the M256A1 Kit and the M18A2 Chemical Agent Detection Kit.

M9 Chemical Agent Detector Paper

M9 paper, which is similar to M8 paper, comes in a long dispenser roll. M9 paper is an adhesive-backed, tapelike material designed to be worn on the outside of clothing or placed on vehicles, equipment, or supplies that may be exposed to chemical agent droplets.

Detection Kits

Detection kits include test papers, detector tickets, and/or sample detection tubes. Current detection kits are the M256 kits and the M18 kit.

M256A1 and M256A2 Chemical Agent Detector Kits

The M256A1 contains disposable plastic sampler detectors, a booklet of M8 paper, and a set of instruction cards. The sampler detectors are enzyme-based detector "tickets" that change color to indicate low concentrations of cyanide, vesicant, and nerve agents in vapor form. The tests take approximately 15 minutes and may provide a negative reading at concentrations that are below the immediately-dangerous-to-life-and-health (IDLH) level but are still hundreds of times higher than the AEL.

The M256A2 kit contains a colorimetric device for measuring the concentration of selected airborne chemicals and has approximately the same sensitivity.

M18A2 Chemical Agent Detection Kit

The M18A2 comes with disposable tubes for detecting cyanide, phosgene, Lewisite, sulfur mustard, and nerve agents GA (tabun), GB (sarin), GD (soman), and VX. Tests for each take two to three minutes but must be conducted in series, not simultaneously.

Point (Local) Chemical Detector/Alarm Systems

Local detection systems produce an alarm or warning and work at close range (point detection). Most of these are "alarm-only" systems that do not provide any information about agent concentrations except that they are above the sensitivity level of the detector. Many do not even identify the agent that set off the alarm.

M8A1 Automatic Chemical Agent Alarm

The M8A1 is an automatic chemical agent detection and warning system designed for the point detection of nerve agent vapors or inhalable aerosols by ionization methods in a baffled-flow electrode configuration that filters out the lighter background ions from the heavier agent ions. This system has a response time of less than two minutes and can detect GA, GB, and GD with a sensitivity of 0.1 to 0.2 mg/m and VX with a sensitivity of 0.4 mg/m. The M8A1 alarm system, which uses IMS technology, is being replaced by the M22 automatic chemical agent detector alarm (ACADA), which also uses IMS technology. DoD decided to replace IMS with SAW technology in the joint chemical agent detector (JCAD) system, which will replace the M8 and M22 point detectors and the chemical agent monitor/improved chemical agent monitor (CAM/ICAM) monitors, which are also based on IMS technology.

M22 Automatic Chemical Agent Detection Alarm

The M22 is an "off-the-shelf," automatic, chemical agent alarm system based on IMS technology that is capable of detecting and identifying standard blister and nerve agents. The M22 system is man-portable, can operate automatically after system start-up, and provides an audio and visual alarm. An important feature of the M22 is that it can be linked to

other systems, such as the multipurpose integrated chemical agent detector (MICAD), to support battlefield automation systems.

M90 Automatic Agent Detector

The M90 automatic agent detector (AMAD) is a portable unit used to indicate the presence of nerve, blister, and blood agents. The M90, which uses IMS techniques, is an alarm-only device that can monitor up to 30 chemicals in parallel. The M90 is a fast-acting, relatively sensitive device that provides an alarm in about 10 seconds for nerve agents and mustard and about 80 seconds for lewisite.

Individual Chemical Agent Detector

The ICAD is an 8-ounce pocket-mounted device that simultaneously detects nerve, choking, blood, and blister agents based on electrochemical techniques. It is easy to operate, requires only minutes of training time, and has both visual and audible alarms. Sensitivities are in the range of 0.2 to 0.5 mg/m for G agents, 5 mg/m for VX, and 10 to 50 mg/m for blood, blister, and choking agents. ICAD was developed for the U.S. Marines.

Shipboard Chemical Agent Point Detection System

The CAPDS is a fixed system capable of detecting nerve agents in vapor form using a baffled-flow electrode configuration ionization technique. It generates an alarm signal that is sent to the Damage Control Central and the bridge. This system is installed on most surface combatant ships.

Stand-off Chemical Alarm Systems

Stand-off systems produce an alarm or warning from a distance, warning of an agent before troops move into the area. One stand-off system, the M21 remote sensing chemical agent alarm known as RSCAAL, detects chemical agent vapor clouds. RSCAAL was type classified standard and approved for full-rate production in March 1995. The M21 alarm detects nerve and blister agent clouds at line-of-sight distances out to 5 km. It is being issued to nuclear, biological, and chemical (NBC) reconnaissance teams for use either on a tripod or in conjunction with the NBC FOX reconnaissance vehicle. The M21 alarm, which uses passive FTIR detection technology, must be stationary to work effectively. An airborne version, called the joint service lightweight standoff chemical agent detector (JSLSCAD), is under development.

Point (Local) Monitoring Devices

Point (local) monitoring devices are designed to collect samples and monitor chemical concentrations in the environment in which troops are currently located.

Chemical Agent Monitor (CAM) and Improved Chemical Agent Monitor (ICAM)

Both the CAM and ICAM use IMS technology. These portable, handheld, point-detection instruments monitor nerve or vesicant agent vapors. They provide graduated readouts (eight bars). They detect vapors of chemical agents by sensing molecular ions of specific mobilities (time of flight) and use timing and microprocessor techniques to reject interference. The monitors, which consist of a drift tube, signal processor, molecular sieve, membrane, and expendables (e.g., batteries, confidence tester, dust filters, buzzer, and battery pack), can detect and discriminate between vapors of nerve and mustard agents. The monitors are 4-inches by 7-inches by 15-inches and weigh approximately 5 pounds. The ICAM has minimal maintenance requirements.

Response time depends on concentration but generally takes from 10 to 60 seconds. Minimum levels detectable are about 100 times the AEL for the nerve agents and about 50 times the AEL for vesicants. One obvious drawback, therefore, is an inability to check the efficacy of decontamination, both in the field and subsequently at treatment facilities.

ICAM-Advanced Point Detector (APD)

The ICAM-APD is based on IMS technology and integrates ICAM and commercial-off-the-shelf components. ICAM-APD can simultaneously detect both nerve and blister vapor and aerosol agents.

SAW Mini-Chemical Agent Detector

The SAW Mini-CAD is a commercially available, pocket-sized instrument that can automatically monitor for trace levels of toxic vapors of both sulfur mustard and the G nerve agents with a high degree of specificity. The instrument is equipped with a vapor-sampling pump and a thermal concentrator to provide enriched vapor sample concentration to a pair of high-sensitivity coated SAW microsensors. All subsystems are designed to consume minimal amounts of power from onboard batteries. Optimal use of the SAW Mini-CAD requires a compromise among the conflicting demands of response time, sensitivity, and power consumption.

Maximum protection requires high sensitivity and a rapid response. The SAW Mini-CAD has more sensitivity with increased sampling time; a faster response can be provided at a lower sensitivity setting. Testing of the SAW Mini-CAD has been performed with chemical warfare agents GD, GA, and HD at a variety of concentrations and humidity levels, and the response rate was not significantly affected by these changes (IOM, 1999). The SAW Mini-CAD can also record some data.

Gas Chromatography Systems

The state-of-the-art systems for detecting any chemical agent are laboratory-quality gas-chromatography systems, most of which are heavy (up to 100 pounds). They also require a 120 or 220 V AC power supply and, thus, have limited portability. Although gas chromatography systems take up to 10 minutes for an analysis, they are highly sensitive and very specific, and they can detect most chemical warfare and many toxic chemical agents below the AEL levels. Gas chromatography systems, which are versatile and can detect thousands of chemicals, come with extensive chemical spectra libraries. Examples of gas chromatography systems are the Viking Spectratrack GC/MS, which comes with a library of 62,000 chemicals, and the Hewlett-Packard 6890 Gas Chromatograph with flame photometric detector.

Continuous Air Monitoring Systems (Mini-CAMs)

The mini-CAM is a continuous air-monitoring system that uses gas chromatography and selected detectors and samplers to monitor for the presence of chemical agents. It weighs 10 pounds and is easily portable. Mini-CAMs were developed for monitoring air at storage and demilitarization facilities. They can detect most nerve, blood, blister, and choking agents at the Surgeon General's 8-hour time-weighted AEL. They have about a five-minute detection time and can operate 24 hours a day for up to seven days. Operation of a mini-CAM requires about eight hours of training. Mini-CAMS can be used either in a fixed laboratory or vehicle mount.

Automatic Continuous Air Monitoring System (ACAMS)

The ACAMS is used to monitor for chemical agents in plants. The ACAMS has an intrinsic response time of four to five minutes and "significantly shorter response times for most releases" (NRC, 1999, p. 30). Detection is accomplished through the use of a gas chromatograph

equipped with a flame photometric detector and is interpreted by computer analysis. However, the ACAMS is subject to frequent false alarms because it cannot differentiate well between an agent and other commonly encountered organic contaminants (e.g., fuel, diesel exhaust, and antifreeze).

Stand-off Monitoring Systems

The AN/KAS-1/1A chemical warfare directional detector is a FLIR-based electro-optic sensor that remotely detects the presence of nerve agents. It provides stand-off chemical agent detection capability for surface ships and has been adapted for fixed-site shore facilities. The AN/KAS-1/1A provides images of the infrared portion of the electromagnetic spectrum. A series of optical filters are actuated by the operator to determine if suspicious objects in the field of view are, in fact, chemical agent clouds. The AN/KAS-1/1A also has a remote video hookup for monitoring and recording the field of view from a second location, typically the ship's Combat Information Center. AN/KAS-1A systems are currently mounted on surface ships.

Vehicle-Mounted Detection Systems

M93A1 FOX Nuclear, Biological, Chemical Reconnaissance System (NBCRS)

The NBCRS is a lightly armored, wheeled vehicle capable of detecting, identifying, marking, sampling, and reporting NBC contamination on the battlefield. A three-person NBCRS crew uses a sophisticated suite of nuclear and chemical alarms and detectors that have been integrated into the vehicle chassis. With the onboard RSCAAL, the crew can detect chemical agent clouds as far as 5 kilometers away.

Water Testing Systems

The only currently available system for testing water, the M272 water testing kit, was first fielded in 1984. It is designed to detect and identify hazardous levels of chemical agents in treated or untreated water. In seven minutes, the M272 can detect and identify agents by color-changing reactions. Its detection sensitivities are 0.02 mg/L for nerve agents, 2 mg/L for mustard and lewisite, and 20 mg/L for cyanide.

EMERGING DETECTION AND MONITORING EQUIPMENT

In addition to existing point-detection and monitoring capabilities, new equipment is being explored and developed to provide more sensitive and specific point and stand-off chemical detection. The following equipment is under development.

Joint Chemical Agent Detector (JCAD)

The JCAD will employ SAW technology to detect nerve, blood, and blister agents. The system is being designed to be lightweight and portable, to reduce the number of false alarms, and to detect new forms of nerve agents. JCAD will be a detector, or network of detectors, capable of automatically detecting, identifying, and quantifying chemical agents inside aircraft and shipboard interiors, providing hand-held monitoring capabilities, and protecting individual soldiers, sailors, airmen, and marines. JCAD is planned to be available in 2002 as a modular system that will replace all current point detectors and hand-held monitors. The detector unit for individual soldiers will weigh less than 2 pounds and will be less than 40 cubic inches in size. It will be carried in a pouch attached to the load-bearing equipment. The detector unit will have a snap-on preconcentrator accessory that increases detection sensitivity to levels that will warn soldiers to take protective action against low-level hazards before mission performance is degraded. The detector unit will also have an air sampler accessory that snaps onto the detector unit and generates pulses of warm air that can liberate chemical agent molecules trapped on surfaces. The JCAD detector unit with the preconcentrator accessory will be mounted inside aircraft, vehicles, and fixed-site facilities.

JCAD will use a powerful microprocessor to analyze, evaluate, and store chemical detection units. It will be equipped with serial communication ports that can be integrated with military communication systems and the global positioning system (GPS) to send detection data to the joint warning and reporting network (JWARN) and command and control systems. The serial ports will also provide the capability of uploading unit detection data on demand and downloading software updates to individual detector units. JCAD will be able to detect TICs. DoD plans to procure 250,000 JCAD units to replace and bolster the current inventory of about 65,000 M8 and M22 alarms.

Joint Services Lightweight Standoff Chemical Agent Detector (JSLSCAD)

The JSLSCAD is a passive, infrared detection unit based on FTIR spectrometry. The JSLSCAD signal processing hardware is being designed to discriminate between chemical targets and nontoxic species in a complex battlefield environment. The device is being designed to detect nerve and blister vapor clouds at a distance of up to 5 km. It will be smaller than the M21 and will not have to be stationary to work effectively.

Improved Point Detection System (IPDS)

The IPDS is an IMS-based, point chemical-detection system with an algorithm library and embedded data processing. This system automatically detects and warns of nerve and blister agent vapors at low concentrations and has the capability of rejecting common shipboard interference. IPDS will be deployed as part of the detection suite aboard ships and is intended to replace the current CAPDS.

Joint Services Lightweight NBC Reconnaissance System (JLNBCRS)

The JLNBCRS is being designed to provide point and stand-off intelligence for real-time field assessment of NBC hazards. The system will be a vehicle-mounted suite of equipment and software that can detect, collect, analyze, mark, and disseminate NBC data and can be transported by air. Two variants, the high-mobility multipurpose wheeled vehicle and the light armored vehicle, will house the same equipment and offer on-the-move stand-off capability. Timely automated, digital information, combined with meteorological and positioning information, will provide commanders with more options for merging NBC information with their tactical, operational, and strategic plans.

Shipboard Automatic Liquid Agent Detector (SALAD)

SALAD is an automatic, exterior, liquid agent point detection and monitoring system that will detect and set off an alarm in the presence of liquid nerve and blister agents. SALAD will consist of a detector unit that uses chemically treated paper, optical scanners, and a central processing control unit to automatically set off an alarm in Damage Control Central and on the bridge.

Joint Chemical/Biological Agent Water Monitor (JCBAWM)

The JCBAWM will be a portable device that can detect, identify, and quantify agents in water. It will allow the user to sample water and receive a digital readout of the composition. The technology for this monitor is still under review.

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Appendix E

Detecting and Monitoring Biological Agents

EXISTING TECHNOLOGIES

Microscopy

Microscopy is used to detect total microbial populations in a given sample without regard to the physiological state of the organism; both viable and nonviable organisms can be detected. Because classical microscopy relies on the recognition of morphology (size and shape), limitations of microscopy include lack of specificity and low sensitivity. The detection of submicroscopic viruses requires specialized instrumentation, such as epifluorescent or transmission electron microscopes (Stetzenbach, 1999).

Differential staining microscopic analyses are useful for segregating microorganisms into broad groups but cannot identify specific organisms. Differentiating target organisms from indigenous or background populations requires discriminating beyond the genus, species, and subspecies levels. By staining with fluorescent-labeled antibodies, target organisms can be detected, but the detection limits are generally greater than 10^4 cells/ml of liquid collection medium. Although microbial viability has been determined using special stains, the reliability of these methods has not been demonstrated. Multiple analyses combined with digital imaging can reduce variability, but interference from background particulates is a serious problem with all classical microscopic analyses.

Culture-Based Assays

Culture-based assays can only be used to detect organisms that will proliferate under the growth conditions of the analysis design. A successful culture depends on nutritional and environmental factors, the physiological state of the organism, and the absence of interfering substances. The best nutritional components in the culture media, incubation temperature, and atmospheric parameters (e.g., humidity and carbon dioxide) vary with the organism. Stresses on the organism during dispersal, transport, and collection contribute to the difficulty of detecting organisms using culture assays.

The analysis time depends on the organism, the growth medium, and the incubation temperature, but generally the appearance of classical bacterial colony formation requires about 18 hours. Fungal growth in culture often requires three to five days, and cell culture for viruses takes even longer. Once a colony forms, additional time is required for identification of the microbial populations. Detection limits vary greatly with the application of the sample to the growth medium. Filtration or centrifugation of the sample can improve detection, but they concentrate all of the organisms suspended in the sample, which can result in overgrowth of the targeted contaminant.

Biochemical and Immunological Assays

With biochemical and immunological-based analyses, the identification and enumeration of specific microbial contaminants in environmental samples has been improved. Generally, biochemical assays rely on substrates and computer-assisted analysis; immunoassays center on specific antigen-antibody recognition. When used sequentially with culture-based assays, specificity is increased. However, the analysis time is prolonged. Advances in nonculture-based immunoassays have improved specificity and sensitivity. Detection and identification of microorganisms has been improved by advanced biotechnology-based methodologies.

EMERGING TECHNOLOGIES

Polymerase Chain Reaction Amplification

Polymerase chain reaction (PCR) is an enzyme reaction that amplifies specific deoxyribonucleic acid (DNA) sequences to identify specific microorganisms or groups of organisms. This methodology does not depend on the physiologic state of the organism, but it requires that gene sequences specific to the targeted contaminant be known. PCR involves repetitive

cycles of amplification in which the gene sequences are copied, increasing the amount of DNA in the sample until it can be detected. The literature on PCR and its use in detecting biological organisms is growing quickly. The summary in the following paragraphs is based on studies conducted by Alvarez et al. (1995), Beyer et al. (1995), Buttner et al. (1997), Garner et al. (1993), Kuske et al. (1998), Rigler et al. (1998), Stetzenbach (1999), and Wu et al. (1997).

Nucleic acids have been extracted from microorganisms in a variety of ways. Hot detergent treatment, freeze-thaw, and bead mill homogenization have been used successfully to extract DNA from vegetative bacterial cells, endospores, and fungal conidia. Detection limits are affected by the physical condition and concentration of the target DNA, as well as by the presence and concentrations of background DNA in the reaction mixture. Pretreatment of samples may be necessary to minimize interference from biotic and abiotic material in the sample matrix.

Standard PCR involves using two unique primers to produce a single amplification DNA product. Multiplex PCR uses several sets of primers to produce multiple amplification products thereby increasing the specificity when the products are diagnosed. Reverse transcriptase PCR is used to detect ribonucleic acid (RNA) by generating a cDNA copy of the nucleic acids in a single-stranded RNA for the first cycle. The cDNA is then used as a template for successive PCR cycles.

PCR assay of soil has shown detection limits of 1 cell/g of soil. In milk, detection has been reported at 9 cells/ml, and in bioaerosol liquid collection, fluid detection was 10 cells/ml. A detection limit of 10^3 copies of plasmid carrying the *Bacillus anthracis* edema factor and 2×10^4 spores was improved by reamplification. Previously, post-PCR manipulation was required to detect the presence of amplified sequences, often by gel electrophoresis. Recently developed instrumentation has eliminated the need for post-PCR processing by the release of fluorescent-labeled probes to signal amplification. With computer-assisted comparisons to standard curves, microbial contaminants can be quantified rapidly. A detection limit of 1 to 10 template[1]/PCR sample and 100 template for RT-PCR in a 96-well microtiter format has been reported within two hours of sample preparation. Combining PCR with immunologial techniques has resulted in a rapid and efficient solution-phase hybridization of labeled targets and biotinylated capture probes. Results have been reported in two hours with a detection limit of 10 targets. Application of fluorescence correlation spectroscopy with PCR in microtiter plate format combines reagents for amplification and detection in a single tube or well. Double-stranded

[1] "Template" refers to the segments of nucleic acid being amplified.

target DNA is detected by two amplification primers 5'-tagged[2] with two different fluorophores (Rhodamine-Green and Cy5). This method has shown a detection limit of 10 to 25 initial copy number of template.

Microchips

Combining microchip technology and PCR improves detection (Belgrader et al., 1998; Ibrahim et al., 1998; Northrup et al., 1998; Waters et al., 1998; Wilding et al., 1998; Yershov et al., 1996). A microchip PCR array with 10 silicon reaction chambers, thin-film heaters, and solid-state optics provides real-time monitoring with low power requirements and no moving parts. Detections of *Erwinea herbicola* (vegetative cells), *Bacillus subtilis* (endospores), and MS2 (RNA virus) with a detection limit of 10^2 to 10^4 organisms/ml within 16 minutes have been reported. Hybridization of fluorescent-labeled DNA on a microchip involves immobilizing an array of oligonucleotides into gel elements fixed on a glass plate. Several microchip elements are then analyzed simulaneously with a two-wavelength fluorescent microscope equipped with a charge-coupled camera.

Micromachined silicon high-efficiency reaction chambers (miniature thermal cycling chamber [MATCI]) with integrated heaters and simple electronics to control temperatures provides solid-state, diode-based detection for real-time fluorescence monitoring of product DNA. The MATCI, a briefcase-size instrument with rechargeable batteries, has detected single base-pair substitutions in orthopoxviruses (monkeypox, cowpox, camelpox, and vaccinia viruses) and human genomic DNA and viral DNA.

With a combination of cell lysis, multiplex PCR amplification, and electrophoretic sizing on a monolithic microchip, amplified products were analyzed using a sieving medium for size separation and an intercalating dye for fluorescence detection. Electrophoretic analysis was accomplished in less than three minutes after PCR. A 4.5 µl silicon microchip containing a series of 3.5 µm "weir-type" filters spanning the flow chamber has been developed to minimize interference by separating target organisms from background media.

Molecular Beacons

The analysis of samples using nucleic acid probes that spontaneously undergo a fluorogenic conformational change when they hybridize with target fluorescent probes has been called "molecular beacons" (Tyagi and

[2] This has to do with DNA strand designations. 5' refers to one end of the nucleic acid.

Kramer, 1996). These beacons fluoresce only in the presence of a complementary target. Reactions are carried out in a sealed tube to minimize manipulation.

Electrochemiluminescence Immunoassay

This technology integrates equilibrium immunoassay with electrochemiluminescense (Grimshaw et al., 1997). The format involves a biotynilated antibody sandwich with a labeled N-hydroxysuccinimide ester of a ruthenium (II) tris-bipyridine chelate for detection. Streptavidin-coated paramagnetic beads capture the antibody-antigen-antibody sandwich complex. Detection ranges for human protein sequence are from 2.5 ng/ml to 2,000 ng/ml with an accuracy and precision of less than or equal to 15 percent; for mice, the detection range was 0.5 ng/ml to 200 ng/ml.

Biosensors

Immunoassay in conjunction with a flexural plate wave transducer membrane has been used for the detection of bacteria (Harteveld et al., 1997; Pyun et al., 1998). Current detection limits are relatively high (3.0×10^5 to 6.2×10^7 cells/ml). The incorporation of a 20 MHZ piezoelectric quartz crystal sensor in a flow injection system with a polyclonal antibody detected 0.1 µg/ml of staphylococcal enterotoxin B. However, inhibition was noted at concentrations greater than or equal to 10 µg/ml.

Mass Spectrometry

Gas chromatography-ion trap tandem mass spectrometry (GC-MS-MS) and conventional quadrupole GC-MS have been used to detect 3-hydroxy fatty acids (e.g., endotoxin and bacterial lipopolysaccharide in gram-negative cells), muramic acids (e.g., peptidoglycan in gram-positive and gram-negative bacterial cells), and ergosterol (fungal biomass) as indicators of the presence of microbial contamination (Kaufmann, 1995; Koster et al., 1996; Krahmer et al., 1998; Larsson and Saraf, 1997). Endotoxin and bacterial lipopolysaccharide present in gram-negative cells is diagnosed by 3-hydroxy fatty acids. The detection of muramic acids indicates peptidoglycan, which is present in gram-positive and gram-negative bacterial cells. Ergosterol is an indicator of fungal biomass. Electrospray ionization mass spectrometry can detect proteins as indicators of microbial contamination.

Matrix-assisted laser desorption ionization (MALDI) mass spectrometry can identify gene sequences not readable using gel electrophoresis. MALDI has also been used for the detection of quasimolecular ions of

large organic molecules (up to several 100 kDa molecular mass), such as biopolymers (peptides, proteins, oligosaccharides, and nucleotides in the subpicomolar range) with an accuracy of 0.1 to 0.01 percent.

Flow Cytometry

Flow cytometry uses simultaneous measurements of light scatter to determine cell size and structure (Davey and Kell, 1997; Fouchet et al., 1993; Lange et al., 1997; Perez et al., 1998; Seo et al., 1998). The incorporation of fluorescence increases the capabilities of this technique to include quantitation of cellular components, antigen detection, and estimations of cell physiology. Instrumentation permits the measurement of 500 to 5,000 objects/sec with the results displayed in bivariate histograms. Staining techniques used with flow cytometry include fluorescent brighteners. An ultraviolet-excited fluorescent whitening agent (Tinopal CBS-X) with ethanol used as a stain for both vegetative cells and endospores was able to discriminate the target substance from background material.

The combination of flow cytometry and fluorescent *in situ* hybridization (FISH) increased detection by two orders of magnitude over culture-based assays, but detection below 10^2 cells is beyond the capabilities of currently available detectors. Immunomagnetic separation with fluorescent antibody-labeled beads and flow cytometry have also been used. This methodology has shown a detection of less than 10^3 colony-forming units for pure culture suspensions and 10^3 to 10^4 colonies of *E. coli*/ml in a mixed suspension with a one-hour analysis time. Immunomagnetic separation and flow injection analysis with amperometric detection has advantages over enzyme-linked immunoassay (ELISA) methods because only viable cells are measured rather than total bacterial concentrations, although detection limits can be high (10^5 cells/ml).

CURRENT DETECTION EQUIPMENT

Current biological detection systems are not as mature as chemical detection systems in terms of reliability, sensitivity, selectivity, speed, and portability. Current techniques for the detection of biological agents are based on the analysis and/or collection of aerosols. Point samples of soil or aerosol must undergo microscopy and culture methods for a definitive identification and count of the biological agent organisms present. The following subsections briefly describe the capabilities and limitations of these systems. The information for this review was provided by a number of sources: Ali et al. (1997), DoD (1997, 1998, 1999), IOM (1999), Jane's Information Group (1999), JSMG (1999), U.S. Army (1992, 1994),

U.S. Army and U.S. Marine Corps (1996), U.S. Army SBCCOM (1998, 1999), and U.S. Navy (1999).

Biological Integrated Detection System

The biological integrated detection system (BIDS) is a collection of components that provides mobile detection capability. The flexible BIDS design is intended to be easily updated as new technologies become available. The current BIDS includes a sampler that passes ambient air through a two-stage virtual compactor that concentrates aerosol particles. The BIDS consists of five major components: a vehicle, a shelter, auxiliary equipment, a power source, and a biological detection suite.

Interim Biological Agent Detector

The interim biological agent detector (IBAD) is a point detector system used to detect background changes indicative of human-made biological warfare attacks. IBAD is designed to provide point detection capability onboard combat ships as a near-term solution to the current lack of detection, identification, and warning devices. The IBAD is composed of a particle size sorter/counter, a wet cyclone sampler, a manual identifier, and an improved membrane colorimetric ticket (flow-through assay). The system is linked to visual and audible alarms located locally and in the ship's Damage Control Central. IBAD automatically detects real-time changes in environmental background for initial sample collection and alarm and provides agent identification within 20 minutes.

XM94 Long-Range Biological Stand-off Detection System

The XM94 long-range biological stand-off detection system provides long-range, large-area aerosol cloud detection and ranging and tracking capability. XM94 can detect aerosol clouds out to a range of 30 km, sometimes even 50 km. The XM94 uses light detection and ranging (lidar) backscatter to detect clouds but does not explicitly detect biological agents.

Nuclear, Biological, and Chemical Reconnaissance System

The nuclear, biological, and chemical reconnaissance system (NBCRS) is a lightly armored wheeled vehicle capable of detecting, identifying, marking, sampling, and reporting NBC contamination on the battlefield. The three-person NBCRS crew uses a sophisticated suite of nuclear and chemical alarms and detectors that have been integrated into the vehicle chassis. The crew can also collect samples for laboratory analysis.

EMERGING DETECTION EQUIPMENT

One critical component of effective defense is real-time, pre-exposure detection, discrimination, and identification of a biological threat. To address this requirement, agencies such as the Defense Advanced Research Projects Agency are focusing on the development of detection systems that are robust, unattended, real-time (less than one minute), highly sensitive (2 to 10 particles), as well as sensors that are small (less than 5 pounds) and low cost (less than $5,000 per unit). The goal is to enable soldiers to detect biological agents on the battlefield in real time with no false alarms. However, no technology currently under development will meet these needs in the next five years.

BIDS Update

The chemical biological mass spectrometer (CBMS) might be integrated into the BIDS in the future. In this system, samples of air are passed into an infrared pyrolyzer where small particles are trapped and heated. Off gases are then analyzed by tandem mass spectrometry (Berry, 1998).

Joint Biological Point Detection System

The Joint Biological Point Detection System (JBPDS) Program is developing a common point-detection capability for individual service platforms. The detection suite will integrate an identifier, trigger, sampler, and detector for real-time detection and identification of biological agents. In less than 15 minutes, the suite will detect biological agents at levels below the level that would affect combat effectiveness. The JBPDS will increase the number of agents that can be identified by the BIDS and IBAD systems; decrease detection time; increase detection sensitivity; provide automated, knowledge-based, real-time detection and identification; and provide a first-time point-detection capability to the Air Force and Marine Corps.

Portal Shield Advanced Concept Technology Demonstration

This program is being set up to demonstrate the military use of an air base/port biological detection capability and develop operating concepts for that capability. It is anticipated that the program will also demonstrate biological agent identification and will develop three increasingly automated systems. The air base/port biological detection system should automatically detect biological aerosol attacks and generate NBC warning reports. The biological sensor will use Navy technologies and components

(e.g., Naval Medical Research Institute's hand-held assay tickets and several Navy IBAD components).

MAGIChip (Micro-Array of Gel-Immobilized Compounds)

The MAGIChip (micro-array of gel-immobilized compounds) detector is planned to simultaneously identify a vast number of biological threat agents, including bacteria, viruses, fungi, and toxins. Both pathogenic microorganisms and plasmid-associated toxin genes that might be inserted into otherwise innocuous microorganisms will be detected. Microorganisms will be identified via unique, microbe-specific sequences of (rRNAs) and other RNAs, as well as microbe-specific gene sequences. Future detector capabilities will include probing for bacterial virulence factors. Viral microchips will identify the type of virus and the viral strain and will discriminate pathogenic from nonpathogenic strains, which can differ by only a few nucleotides in specific genes.

ANALYTICAL METHODS AND A MASS SPECTROMETER LIBRARY

The mass spectrometry approach to the classification and identification of biological threat agents is another system that offers robust capability for speed, signature bandwidth, and specificity. Two universities are collaborating on the design and execution of signature measurements of threat simulants by mass spectrometry. The objective of this investigation is to develop the experimental chemotaxonomic methods and analytical strategy for the determination of biomarkers from simulant threat microorganisms and their constituents. Specifically, simulants such as *E. coli*, *B-subtillis*, *E. herbicola*, and MS-2 capsid protein will be characterized using single and tandem mass spectrometry systems and soft ionization techniques. However, none of these is operational and, even if a system becomes operational, it will not be available in the next five years.

Phosphor-Diode Laser Technology for Biological Agent Detection

The goal of this project is to develop a new reporter material for biological agent identification and incorporate this technology into hand-held and flow cytometer instruments. The approach uses submicron microspheres of upconverting phosphor material (upconversion is a two or three photon absorption process in the phosphor to produce emission frequencies in the visible region of the spectrum upon excitation with near-infrared light), as the reporter system and a single near-infrared diode laser as the excitation source in immunoassay formats. This system

has the potential for zero optical background, and hence improved sensitivity, because nothing in nature upconverts. The compact, reliable, electrically efficient laser source, combined with the availability of many spectrally unique phosphor colors, allows for a greater degree of multiplexing (simultaneous detection of multiple antigens) than can be achieved using conventional fluorescent reporters and more complicated detecion systems. Compared to commercially available biosensors for clinical diagnostics, at least a two order-of-magnitude increase in sensitivity with very rapid response (less than five minutes) has been demonstrated in a prototype hand-held biosensor. In addition to increased sensitivity, false alarms caused by nonspecific binding, typically encountered in current devices, are expected to be reduced. Independent test and evaluation, significant gains in multiplexing, and transitioning to manufacturers for field applications are in progress. A fieldable, hand-held unit is expected in the next two to three years (Carrico et al., 1998).

Spore-Specific Phosphorescence

The focus of this research is on bacterial agents, especially on the spores of *Bacillus anthracis* and *Clostridium botulinum*. The objective is to investigate a novel technical approach involving the generation of bacterial spore-specific phosphorescence that would constitute a basis for detecting the viability and quantity of the bacterial spores of simulants of toxic biological agents (i.e., *Bacillus anthracis* and *Clostridium botulinum*). A phosphorescence-based sensor could be integrated with one or more inert matrices suitable for on-site and/or remote sensing of biological agents in liquid and aerosol modes in the sensitivity range of 100 spores or less.

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Appendix F

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Appendix G

Biographical Sketches of Principal Investigator and Members of the Advisory Panel

PRINCIPAL INVESTIGATOR

THOMAS E. MCKONE is a staff scientist at the Ernest Orlando Lawrence Berkeley National Laboratory and adjunct professor at the University of California, Berkeley, School of Public Health. He is currently serving on a number of National Research Council (NRC) committees of the Board on Environmental Studies and Toxicology, including the Committee on Toxicology and the Committee on Risk Assessment for Radon in Drinking Water. Dr. McKone is also president of the International Society of Exposure Analysis and a member of the Environmental Protectection Agency's (EPA's) Science Advisory Board. He is responsible for the development of CalTOX, a model used by the California Department of Toxic Substances Control to conduct health-risk assessments of contaminated soils and the contamination of adjacent air, surface water, sediments, and groundwater.

ADVISORY PANEL

WYETT H. COLCLASURE II received his M.S. in chemistry from the University of Illinois and is currently chairman of the Environmental Technologies Group, Inc. During his military service, Col. Colclasure (ret.) was project manager for Nuclear, Biological, and Chemical (NBC) Defense Systems of the Chemical and Biological Defense Command, Aberdeen Proving Ground; director of materiel testing, Dugway Proving Ground; and chief of the Chemical Operations Division, HQ Army Materiel Command.

He has conducted analyses of environmental studies, led a field and laboratory testing organization, prepared U.S. Department of Defense (DoD) reports for Congress, and directed the writing of concepts guiding the development of new chemical defense doctrine and equipment.

MARGARET (PEGGY) L. JENKINS, the manager of the Indoor Air Quality and Personal Exposure Assessment Program at the California Air Resources Board, received her M.S. in ecology from the University of California, Davis. Ms. Jenkins has pioneered studies of human time-activity patterns as they relate to pollutant exposures and has extensive experience in exposure assessment methods and monitoring. She was a member of the Peer Review Panel for the Human Exposure Research Program for the National Exposure Research Laboratory, EPA, and is currently a representative to the California Indoor Air Quality Interagency Working Group. She has also served on a variety of other peer review and advisory panels. Ms. Jenkins has received the California Environmental Protection Agency Customer Service Award and the German Marshall Fund Travel Award. Her professional affiliations include the Air and Waste Management Association, the American Public Health Association, and the International Society of Exposure Analysis, in which she holds the office of secretary.

TREVOR O. JONES, a member of the National Academy of Engineering (NAE), is chairman and chief executive officer (CEO) of BIOMEC, Inc., a biomedical engineering device company, and of International Development Corporation, a private management consulting company; he was past chairman of the board of Echlin, Incorporated, a supplier of automotive components primarily to the aftermarket; and chairman, president, and CEO (retired) of Libbey-Owens-Ford Co., a major manufacturer of glass for use in automobiles and construction. Previously, he was an officer of TRW, Inc., serving in various capacities in the company's Automotive Worldwide Sector, including vice president of engineering and vice president of the Transportation Electronics Group. Prior to joining TRW, he was employed by General Motors in many aerospace and automotive executive positions, including director of General Motors Proving Grounds; director of the Delco Electronics Division, Automotive Electronic and Safety Systems; and director of General Motors' Advanced Product Engineering Group. Mr. Jones is a life fellow of the American Institute of Electrical and Electronics Engineers and has been cited for "leadership in the application of electronics to the automobile." He is also a fellow of the American Society of Automotive Engineers, a fellow of the British Institution of Electrical Engineers, a registered professional engineer in Wisconsin, and a chartered engineer in the United Kingdom.

He holds many patents and has lectured and written on automotive safety and electronics. He is a former member of the NRC Commission on Engineering and Technical Systems. Mr. Jones has served on several other NRC study committees, including the Committee for a Strategic Transportation Research Study on Highway Safety, and chaired the NAE Steering Committee on the Impact of Products Liability Law on Innovation. He holds an HNC (higher national certificate) in electrical engineering from Aston Technical College and an ONC (ordinary national certificate) in mechanical engineering from Liverpool Technical College.

MICHAEL D. LEBOWITZ graduated from the University of Washington with a Ph.C. in preventive medicine and a Ph.D. in epidemiology and international health and environmental health sciences. He is a professor at the University of Arizona in the section of Pulmonary and Critical Care Medicine and a professor and director of the Epidemiology Unit of the Arizona Prevention Center. Dr. Lebowitz's research interests include the epidemiology of pulmonary and other chronic diseases; air pollution health effects; and respiratory response to particulate matter, ozone, indoor pollutants, and allergens. He has received many honors and awards, including the Arizona Clean Air Health Award, was elected fellow of the American College of Epidemiology, an academician of the International Academy of Indoor Air Science, and senior international fellow of the Italian National Research Council. He is an associate editor for the *Journal of Exposure Analysis and Environmental Epidemiology* and *Toxicology and Industrial Health* and a member of the editorial boards of the *American Journal of Respiratory and Critical Care Medicine* and *Archives of Environmental Health.*

KEITH MCDONALD is president of Sat Tech Systems and technical director for Navtech Seminars, Inc. Previously, Mr. McDonald directed the Federal Aviation Administration's Aeronautical Satellite Division and managed the satellite applications and technology program. He was also the scientific director of the DoD's Navigation Satellite Program during the formative stages of the global positioning system (GPS). Mr. McDonald has been active in the Radio Technical Commission for Aeronautics (RTCA), preparing guidelines for the use of satellite systems in aviation, and has received the RTCA Citation for Outstanding Service. He has published more than 90 technical papers. He received the Institute of Navigation's (ION) Norman P. Hays Award for outstanding contributions to the advancement of navigation and was president of ION in 1990–1991. He is currently president of the International Association of Institutes of Navigation. Mr. McDonald was a member of the NRC Committee on the Future of the Global Positioning System.

ROBERT E. SHOPE received his M.D. from Cornell University and is currently a professor of pathology, microbiology and immunology, and preventive medicine and community health at The University of Texas at Galveston. He is also codirector of the World Health Organization World Reference Center for arboviruses, which characterizes viruses transmitted to people and domestic animals and researches their epidemiology. Dr. Shope has worked in the areas of emerging infectious diseases and the epidemiology of arbovirus and rabies virus infections. He was also a member of the Committee on Research and Development Needs for Improved Civilian Medical Response to Chemical or Biological Terrorism Incidents. Dr. Shope is the author of more than 70 publications.

ROBERT C. SPEAR is the founding and current director of the Center for Occupational and Environmental Health at the University of California, Berkeley. He is also a professor in the Environmental Health Sciences Division of the School of Public Health and director of the National Institute of Occupational Safety and Health Educational Resource Center. His doctoral work at Cambridge University involved the modeling and analysis of dynamic systems, an interest that he brought to environmental health sciences and which has conditioned much of his later work in exposure assessment and the modeling and analysis of environmental and occupational health problems. Dr. Spear has also been interested in statistical issues relating to the assessment of hazardous exposures in occupational settings, and his work is now focused on the characterization of multiple exposures using multivariate statistical techniques. He is a member of the American Society of Mechanical Engineers, the American Industrial Hygienist Association, and the American Public Health Association.

PAUL SWITZER is a professor in the Department of Statistics and the School of Earth Sciences at Stanford University. He graduated from Harvard University with a Ph.D. in statistics. Dr. Switzer's research interests are in the development of statistical tools for the environmental sciences, and his recent research has focused on the interpretation of environmental monitoring data, the design of monitoring networks, the detection of time trends in environmental and climatic parameters, the modeling of human exposure to pollutants, and error estimations for spatial mapping. He has served on the Research Proposal Review Committee for the National Science Foundation, the Board of Directors for the Societal Institute of the Mathematical Sciences, the EPA National Advisory Council on Environmental Policy and Technology, and the Committee on Global and Environmental Change for the American Geophysical

Union. He is a fellow in the International Statistical Institute, the American Statistical Association, and the Institute of Mathematical Statistics.

DETLOF VON WINTERFELDT is a professor of public policy and management at the University of Southern California (USC) and director of the Institute for Civic Enterprise. He is also the president of Decision Insights, Inc., a management consulting firm specializing in decision and risk analysis. Dr. von Winterfeldt, who graduated from the University of Michigan with a Ph.D. in mathematical psychology, has research interests in the foundation and practice of decision and risk analysis as applied to technology and environmental management problems. He is the co-author of two books and author or co-author of more than 100 articles and reports on these topics. He has served as chairman of USC's Systems Science Department and chairman of the Research Center at the Institute of Safety and Systems Management. He has also served on several committees and panels, including the National Science Foundation's Advisory Panel for Decision and Risk Management Science Program and the NRC Committee on Risk Perception and Communication.

CHARLES JOHN WESCHLER received his Ph.D. in chemistry from the University of Chicago. Since completing his postdoctoral studies at Northwestern University, Dr. Weschler has been a research scientist at Bell Laboratories and Bell Communications Research (Bellcore) and is a designated distinguished member of professional staff. His specialties include indoor air chemistry, indoor/outdoor relationships for selected pollutants, and the impact of ambient pollutants on electronic equipment. He is a member of the American Association for Aerosol Research, the American Society for Testing and Materials, and the American Chemical Society. In addition, he is a member of the EPA Science Advisory Board. He was a member of the NRC Committee to Review the Structure and Performance of the Health Effects Institute and the Committee on Advances in Assessing Human Exposure to Airborne Pollutants. Dr. Weschler is the author or co-author of more than 75 peer-reviewed publications.

Appendix H

Meetings and Activities

FIRST MEETING

March 2, 1998
National Research Council
Washington, D.C.

Principal Investigator and NRC Staff. No Presentations.

SECOND MEETING

August 3–4, 1998
National Research Council
Washington, D.C.

Carol Maczka, Study Director, Task 2.1
Board on Environmental Studies and Toxicology

Lorenz Rhomberg, Principal Investigator, Task 2.1
Harvard School of Public Health

Beverly Huey, Study Director, Task 2.2
Board on Army Science and Technology

Thomas E. McKone, Principal Investigator, Task 2.2
University of California, Berkeley

Jack Heller
Joint Environmental Surveillance Overview

MAJ Larry Kimm
Deployment Health Surveillance

CDR Paul Knechtges
Deployment Environmental Health Surveillance RDT&E Overview

DoD Sponsor Representatives:

Kelley Brix, Office of the Special Assistant for Gulf War Illnesses
COL Frank O'Donnell, Office of the Special Assistant for Gulf War Illnesses

Other Guests:

William Cain, University of California, San Diego
Michael Kleinman, Co-Principal Investigator (Task 2.3)
Robert Shope, University of Texas Medical Branch, Galveston
Ainsley Weston, National Institute for Occupational Safety and Health
Charles Weschler, Bell Communication Research

THIRD MEETING

September 23–24, 1998
Woods Hole, Massachusetts

Beverly Huey, Study Director
Board on Army Science and Technology

Thomas E. McKone, Principal Investigator
University of California, Berkeley

Workshop Planning. No Presentations.

Panel Participants:

COL Wyett Colclasure
Peggy Jenkins
Trevor Jones
Michael Lebowitz

Keith McDonald
Charles Weschler

Other Guest:

Michael Kleinman, Co-Principal Investigator (Task 2.3)

FOURTH MEETING

November 23–24, 1998
SBCCOM/Berger Auditorium
Edgewood, Maryland

James Baker, Acting Director, Office of the Technical Director
U.S. Army Edgewood Research, Development and Engineering Center

Beverly Huey, Study Director, Task 2.2
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Thomas McKone, Principal Investigator, Task 2.2
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PM NBC Defense Systems: NBC Digitization

Ed Conley
PM NBC Defense Systems: JWARN

Pax Williams
PM NBC Defense Systems: MICAD

Margaret Freeman
PM NBC Defense Systems: M8A1

Tom Mitchell
PM NBC Defense Systems: ACADA

Ray Leblanc
PM NBC Defense Systems: JCAD and ICAM

LTC Joe Della Silva
FOX NBC Recon

Bob Field
Lightweight NBC Recon

Kim Phan
Detection Kits

Bruce Jezek
PD for Bio Defense Systems: Overview

Patrick Berry
BIDS & CBMS

James Cannaliato
Long Range Bio Stand-off/Short Range Bio Stand-off

Richard Smardzewski
Bio Detection Integrated ATD

LTC Mark Grotke
Joint Bio Point Detection System

S. Randolph Long
Bio Detection Technology Base Program: Brief Overview
Mass Spectrometry

Cindy Swim/Ernie Webb
Early Warning Technologies

Edward W. Stuebing
Aerosol Samplers/Collectors

A.W. Zulich/M.T. Goode
Biosensors

Peter A. Emanuel
Antibody Development

Peter J. Stopa
Flow Cytometry

William E. White
Biological Threat Agents

Ngai Wong
Chemical Detection Technology Base Program

Panel Participants:

Peggy Jenkins
Keith McDonald
Charles Weschler

DoD Sponsor Representatives:

COL Frank O'Donnell
MAJ Graeme Boyette
Rich Henriques

Other Guests:

Stephen Hill, Task 2.3 Advisory Panel Member
David Moore, Task 2.1 Advisory Panel Member

FIFTH MEETING

December 9–10, 1998
Beckman Center
Irvine, California

Workshop Planning, Presentations, and Discussions:

Beverly Huey, Study Director
Board on Army Science and Technology

Thomas E. McKone, Principal Investigator
University of California, Berkeley

Keith McDonald
GPS Technologies

Robert Spear
GPS Applications

Panel Participants:

COL Wyett Colclasure

Peggy Jenkins
Trevor Jones
Michael Lebowitz
Robert Shope

WORKSHOP

January 11–12, 1999
National Research Council
Washington, D.C.

COL Mike Brown
Predeployment Operational Decision Making

Roy Reuter
Future Deployments —A Situational Framework

COL Wyett Colclasure
Advisory Panel Member

Detlof vonWinterfeldt
Decision Insights, Inc.

Thomas E. McKone, Principal Investigator
University of California, Berkeley

Donald Stedman, University of Denver
Analysis of Chemical Detection Technologies: Vapor Phase

Murray Johnston, University of Delaware
Analysis of Chemical Detection Technologies: Condensed Phase

Charles Weschler
Advisory Panel Member

Peter McMurray
University of Minnesota

Linda Stetzenbach, University of Nevada, Las Vegas
Analysis of Biological Detection Technologies

Robert Shope
Advisory Panel Member

Peggy Jenkins, California Air Resources Board
Strategies for Tracking People

Michael Lebowitz, University of Arizona
Tracking Exposures

Robert Spear
Advisory Panel Member

DoD Sponsor Representatives:

MAJ Graeme Boyett
Thomas Cardella
Rich Henriques
Dee Morris
COL Frank O'Donnell
Jeff Prather
SGT Roberto Torres
Lt COL Steve Williams

Other Guests:

Robert Boyle, Boyle Productions
LTC Don Buley, Joint Program Office of Biological Defense
Mike Callahan, U.S. EPA
Craig Curtis, Tracor
Jeff Daniels, Lawrence Livermore National Laboratory
Clement Furlong, University of Washington School of Medicine
Alfred Gschwendtner, Lincoln Laboratory, M.I.T.
Terrence Harvey, U.S. EPA
Amoretta Hoeber, AMH Consulting
Peter Jahrling, USAMRIID
MAJ Larry Kimm, Joint Staff, Medical Readiness Division
Charles Kirkwood, U.S. Army Chemical School
Michael Kleinman, Principal Investigator for Task 2.3
CDR Paul Knechtges, U.S. Center for Environmental Health Research
Lloyd Larsen, Dugway Proving Ground
Morton Lippmann, New York University Medical Center
Peter McMurry, University of Minnesota
Ludwig Rebenfeld, Textile Research Institute
John Resta, USACHPPM
Lorenz Rhomberg, Principal Investigator for Task 2.1
Philip Russell, Principal Investigator for Task 2.4

MAJ Pat Sharon
Costas Sioutas, University of Southern California
Alfred Steinberg, MITRE
Clarence Thornton, Army Research Laboratories (Ret.)
Dick Traeger, Sandia National Laboratory
Nicole Trudel, Joint Program Office of Biological Defense
Richard Wheeler, DOE Office of Nonproliferation and National Security
Marcus Wise, Oak Ridge National Laboratory
Ngai Wong, SBCCOM
Kaveh Zamani, Walter Reed Army Institute of Research

SIXTH MEETING

April 15–16, 1999
Beckman Center
Irvine, California

Beverly Huey, Study Director
Board on Army Science and Technology

Thomas E. McKone, Principal Investigator
University of California, Berkeley

Report preparation. No presentations.

Panel Participants:

COL Wyett Colclasure
Peggy Jenkins
Keith McDonald
Robert Spear
Detlof von Winterfeldt
Charles Weschler

Other Guests:

Clarence Thornton, Army Research Laboratories (Ret.)
Michael Kleinman, Principal Investigator for Task 2.3
Philip Russell, Principal Investigator for Task 2.4