4

Physical Protection

Traditional individual and collective protective techniques represent one way to avoid injury from chemical or biological weapons. An alternative approach would be to move the individual or unit out of harm's way. This approach might involve seeding clouds to cause rainfall to remove CB agents, generating wind to "blow" agents away from troops, or spreading troops out to decrease the likelihood that large numbers will be contaminated. These nontraditional techniques may be appropriate subjects for future studies but are beyond the scope of this study.

INDIVIDUAL PROTECTION

Risks and Challenges

The need to protect individuals in a CB environment was prompted by (1) respiratory and mucous membrane threats, which led to the development of masks and filters, and (2) the advent of chemical agents that attacked via the skin (percutaneously) as well as via the respiratory system, which led to the development of personal protective garments and other physical barriers. Currently, PPE consists of a mask, special overgarments, and gloves and boots. Used collectively or in various combinations, the equipment is called MOPP. Army *FM 3-4* defines various combinations of MOPP gear in terms of protection levels, depending on perceived battlefield conditions.

In an ideal situation, protective equipment could be donned in the field without encumbering the wearer. Unfortunately, state-of-the art gear is cumbersome, creates severe thermal stress, and interferes with the effective use of weapons systems. In addition, some individuals have had adverse physical reactions to the materials used in the construction of protective equipment and adverse psychological reactions to its use. To mitigate these difficulties, the Army has developed a strategy that combines doctrine, training, and equipment to enable U.S. forces to operate as effectively as possible in a CB environment.

Current Doctrine and Training

Mission-Oriented Protective Posture (MOPP)

Originally, there were five MOPP levels, ranging from MOPP 0 to MOPP 4, the highest level of protection in which all gear must be worn. In 1996, Change 2 to *FM 3-4* increased the number of MOPP levels from five to seven, as shown in Table 2-13 (U.S. Army and U.S. Marine Corps, 1992). The two new MOPP levels are MOPP Ready and Mask Only. The Mask Only level is used either when riot control agents are used and there is no CB threat, when forces are downwind of a nonpersistent chemical agent, or when a biological threat is believed to be nonpercutaneous. However, MOPP levels are not fixed or rigid. Commanders are responsible for determining the protective posture of their subordinate units and for deciding whether to modify a MOPP level. The effectiveness of MOPP training is limited by the constraints imposed by the equipment. For example, it may be impossible to go from a Mask-Only status to MOPP 4 without temporarily breaching the mask seal. To make best use of MOPP equipment, even with its drawbacks, will require effective training.

Protection of U.S. forces from the effects of CB agents must be based on an understanding of their effects, which depend on the characteristics and properties of these agents. Obviously, the most important factor is the nature of the agent, including its toxicity, its mechanism of action, its mode of entry into the victim, and its persistence in the environment. However, other factors, such as meteorological conditions, are also critical. Wind speed, wind direction, atmospheric stability (e.g., inversions), temperature, humidity, and intensity of sunlight can limit or enhance the effectiveness of the initial attack and influence the persistence and concentration of the agent in the target area.

Lethal and incapacitating doses for selected chemical agents are shown in Table 4-1. "Liquid hazard" refers to the level of liquid film that constitutes a significant hazard (10 percent of lethal dose) to unprotected personnel. Vapor challenges can occur when individuals are exposed to the initial vapor cloud and as vapor is generated by the evaporation of liquid films on contaminated surfaces. Vapor challenges are shown in

TABLE 4-1 Approximate Toxicity of Chemical Agents

	Route of Exposure	Liquid Hazard (mg/m^2)	Vapor Challenge ($mg\text{-}min/m^3$)		
			LCT_{50}	ICT_{50}	$OCT_{threshold}$
Choking Agents					
Phosgene (CG)	respiratory		3,200	1,600	
Blistering Agents					
Mustard (HD)	respiratory		900	450	60
	percutaneous	~700	1,500	750	
Blood Agents					
Hydrogen cyanide (AC)			2,000–4,500	varies	
Nerve Agents					
Tabun (GA)	respiratory		270	200	
	percutaneous	~50	30,000	15,000	2.5
Sarin (GB)	respiratory		35	20	
	percutaneous	~170	10,000	5,000	1.5
Soman (GD)	respiratory		70	35	
	percutaneous	~15	10,000	5,000	0.2
VX	respiratory		15	8	
	percutaneous	~0.5	150	75	0.06

Note: Percutaneous values are for bare skin.

Source: U.S. Army Chemical Defense Equipment Process Action Team, 1994.

units of concentration × time ($mg\text{-}min/m^3$). For example, incapacitation is assumed to be possible if an unprotected individual is exposed by inhalation to tabun (GA) at 200 mg/m^3 for 1 minute or to 20 mg/m^3 for 10 minutes.

With sufficient warning time and accessibile PPE, effective protection can be achieved. The protective gear currently in development promises significant improvements over previous models. The new mask (the joint service general purpose mask [JSGPM]) will allow for better peripheral vision, should be more comfortable to wear, and will have a somewhat flexible design to meet specific service requirements (e.g., allowing Air Force personnel to perform a Valsalva maneuver to equalize pressure in their ears). A joint service lightweight integrated suit (JSLIST), which has been developed and is being fielded, is an overgarment that can be worn in place of the regular uniform. The JSLIST is constructed of a single-layer material that allows for the transport of water through the material but traps or repels CB agents. The materials used in the construction of the gloves and boots, however, have not changed.

The previous MOPP gear had serious drawbacks, the most important of which was interference with performance at the MOPP 4 level (DoD, 1997b). To minimize the thermal stresses imposed by the vapor-impervious battledress overgarment (BDO), individuals were forced to greatly reduce their level of effort. The work-rest cycle, according to requirements documents, was 16 minutes of work followed by about 44 minutes of rest in each hour. According to specifications, the new JSLIST garment allows individuals to work for 43 minutes and rest for 17 minutes, which is a dramatic improvement in efficiency. The Joint Operational Requirements Document for the JSLIST states that the JSLIST overgarment requirements be met when the warfighter is engaged in moderate activity (450 Watts), at 32.2°C with 50 percent relative humidity, and a three to five mile-per-hour wind (U.S. Marine Corps, 1999a). In most situations, however, individuals do not wear the protective clothing throughout a deployment, and they must be able to don protective gear quickly and efficiently. Therefore, the most important link in the protection chain is the early detection and warning of an attack.

Studies of the time it takes personnel to advance to MOPP 4 were conducted at the U.S. Army Chemical School in 1992. The results are summarized in Table 4-2.[1] If personnel have sufficient warning time to reach MOPP 4 level, casualties will be minimal. To reach MOPP 4 posture at least eight minutes of warning time is required for an individual wearing no MOPP gear at all. Most currently fielded warning and detection systems cannot provide that much advance notice. In addition, some CB attack scenarios allow no time for response. For example, in the event of an attack by tactical ballistic missiles, the attack and launch early reporting to theater (ALERT) system, which was activated in 1995, can provide three to four minutes advance warning. Thus, troops at MOPP 0 directly below a burst would be exposed to chemical agents for up to eight minutes. If the agent were GD and vapor concentrations were 7 mg/m^3 for five minutes (equal to 35 mg-min/m^3 or LCt_{50}), casualties could be extremely heavy (Institute for Defense Analyses, 1999). In general, the distance of troops from the center of a CB attack will determine whether they have adequate time to don MOPP gear.

[1]Table 4-2 includes a category of protective posture, MOPP 0.5, that is not included in current doctrine. MOPP 0.5 is a protective posture recently introduced by the Air Force, at which the mask, gloves, and boots, but not the overgarment, are worn. This protective posture, which has not been adopted by the joint services, has been found to be effective for operations at a "transfer base" (Chow et al., 1998).

TABLE 4-2 Time to Achieve MOPP 4

	MOPP LEVELS					
	MOPP 0	USAF MOPP 0.5	MOPP 1	MOPP 2	MOPP 3	MOPP 4
Overgarment	Available	Available	Worn	Worn	Worn	Worn
Boots	Available	Worn	Available	Worn	Worn	Worn
Mask	Carried	Worn	Carried	Carried	Worn	Worn
Gloves	Carried	Worn	Carried	Carried	Carried	Worn
Time to MOPP 4 (min)	8	~8	4	0.5	0.25	0

Source: Chow et al., 1998.

Effective Training

Even with the old PPE, the level of protection could be increased and deficiencies reduced (although not eliminated) with proper training. Conversely, regardless of the quality of the equipment, inadequate training leads to improper use and inefficient or inadequate protection. Discussions with individuals who have served in units trained for operations in CB environments indicated that the quality and intensity of training both within and across services is inconsistent, reflecting the different priorities assigned to CB training by individual commanders (Committee on Veterans' Affairs, 1998; DoD, 1998a).

Relating Risk to Doctrine/Equipment

The risk of exposure to most CB agents are, in decreasing order, inhalation, ocular penetration, and percutaneous penetration. The order for donning protective equipment, therefore, should be mask, gloves, overgarment, and boots. Because of limitations in equipment design, however, it may not be possible to don equipment in this order. No data were found during this study to indicate that this issue has been adequately investigated.

Design criteria for PPE include withstanding challenges of 10 g/m^2 for liquid contaminants and vapor challenges of 5,000 to 10,000 $mg\text{-}min/m^3$. Modeling data have confirmed that these contamination levels may be attained in limited areas for short periods of time. However, no intelligence studies have shown that any current potential adversary could mount a battlefield attack that would attain these levels for an extended period of time or across an extended geographical area (Institute for Defense Analyses, 1999). If the requirement of protecting against this threat level were relaxed, PPE that would be more supportive of the individual soldier and less detrimental to unit effectiveness could be developed.

The underlying philosophy of the CB R&D defense programs is based on the doctrine of contamination avoidance. R&D on PPE supports the doctrine by developing equipment that provides protection while reducing negative impacts on mission-related activities. Major efforts have been devoted to the development of the fibers, cloths, and adsorbents used in the construction of PPE. R&D in these areas is briefly described in the next section (for more details see Appendix B).

In spite of the protective clothing and equipment used by deployed forces, casualties will still occur from CB agents, ballistic fragmentation, or some other source. The effective and efficient management of casualties in a contaminated environment will require that procedures be in place for first aid, other medical treatment, evacuation, and decontamination. Current U.S. Army Medical Department doctrine emphasizes the treatment of casualties as far forward as possible and the timely and efficient evacuation of casualties.

Task 2.4 of the overall deployed forces study addresses the medical treatment of casualty management (IOM, 1999a). However, protocols and equipment for patient protection, transporting casualties, and decontaminating casualties are also necessary. Current doctrine addresses these issues only on a general level, leaving much of the decision making to unit commanders. The doctrine for casualty management can be found in various places, including: (1) Joint Publication 4-02, Doctrine for Health Service Support in Joint Operations, which describes the requirements for health service support in an NBC environment; (2) NATO Handbook on the Medical Aspects of NBC Defensive Operations (NATO, 1996a, 1996b); (3) the Treatment of Chemical Casualties and Conventional Military Chemical Injuries (*FM 8-285*) (U.S. Army et al., 1995); (4) Medical Evacuation in Specific Environments (*FM 8-10-6*) (U.S. Army, 1991a); (5) Health Service Support in an NBC Environment (*FM 8-10-7*) (U.S. Army, 1993); and (6) NBC Decontamination (*FM 3-5*) (U.S. Army and U.S. Marine Corps, 1993).

Casualties serious enough to warrant evacuation are transported by three basic modes: personnel, ground vehicles, and aircraft (aircraft are the least available transport vehicles). According to doctrine, once a vehicle is contaminated, it is restricted to working in "dirty" environments so they do not have to be decontaminated while they are needed in operations and they do not contaminate clean environments.

Textiles and Garments

Textiles and garments are the "second skins" of a soldier, the barriers between soldiers and the surrounding environment. Although the global and national political climate has changed, and defense concepts and doctrines with them, the basic role of clothing in protecting the soldier has remained the same. In the increasingly complex battlefield environment, the fundamental question is whether textile and garment manufacturing technologies are keeping pace with current and future demands.

This section reviews the requirements for CB protection, current barrier concepts, current material systems, and the fabric engineering approach for improving the protective capability of textiles and garments. These descriptions are followed by an assessment of the current state of readiness of the U.S. fiber-textile-garment industry to meet the needs of future soldiers and an identification of the key issues that remain to be addressed in the development of chemical protective textiles and garments.

TABLE 4-3 Requirements for Chemical Protective Textiles

- Reduced heat stress
- Reduced weight-to-bulk ratio
- Skin compatibility
- Combat uniform configuration
- Longer service life
- Longer shelf life
- Fire resistance
- Easier laundering
- Capability of being decontaminated
- Reusability
- Durability
- Camouflage capability
- Water repellency
- Resistance to perspiration
- Resistance to petroleum products
- Nontoxicity of materials
- Compatibility with other items

Source: Roth, 1982.

The technical requirements for CB protective textiles are summarized in Table 4-3. These requirements can be evaluated in terms of four key properties: weight, bulk, durability (wear time-protection time), and comfort (which includes ease of vision, breathing, and movement, as well as heat stress).

Clothing

R&D to improve PPE has led to the development of some long-term goals (shown schematically in Table 4-4). As an example of the evolution of fabrics, the technologies used for the OG84/BDO (the ®Saratoga chemical protective overgarment), and the JSLIST are compared in Table 4-4.

Modifications in textile materials, including fibers, yarn, and fabric structures, can reduce weight and bulk, improve durability, and reduce heat stress. To reduce weight, fibers of lower density and yarn and fabric structures with low packing density can be used. Smaller fiber diameters and higher packing density can reduce bulkiness. Smaller fiber diameters can be achieved using an electrospinning process, in which a polymer solution is exposed to an electrical field that elongates the polymer jet to form fibers ranging from 50 to 150 nm in diameter (Reneker and Chun, 1996). This process has been demonstrated successfully for a wide range of polymers at the Fibrous Materials Research Center at Drexel University and at several government laboratories (Gibson et al., 1999; Ko et al., 1998; U.S. Army SBCCOM, 1999).

TABLE 4-4 Evolution of Performance Requirements for Protective Textiles

Date	Garment	Requirements
1960s	XXCC3 underwear	7 days wear 6 hours protection
1970s	CPOG	14 days wear 6 hours protection
1980s	OG84/BDO	22 days wear 24 hours protection
1990s	JSLIST	45 days wear 24 hours protection
2000s	JSLIST P31	60 days wear 24 hours protection
Army After Next	ICS	indefinite wear self-decontamination

Source: Brandler, 1998.

The combination of nanofiber and microfiber or regular multifilament fibers is a new program being initiated in the Drexel-Akron project of the Army Multidisciplinary University Research Initiative (MURI). Although a wide range of properties can be engineered into a fiber, the technology for processing nanofibers in traditional textile machines is not well established. In theory, the nanofibers would provide less resistance to air movement and greater surface area for absorption of gaseous contaminant per unit weight of nanofiber material compared to absorbers based on conventional carbon-fiber technology (Gibson and Schreuder-Gibson, 1999). Neither the dynamic interaction between nanofibers and machine surfaces nor the problems that will be encountered in chemical and mechanical finishing of fabrics containing nanofibers (e.g., snagging, adhesion, melting, agglomeration) have been investigated (ARO, 1997; Gibson and Reneker, 1998).

The durability of the garment can be improved with stronger and tougher fibers and proper design of fabric construction (such as optimization of interlacing density). To improve fabric comfort or reduce heat stress, the permeability and thermal conductivity of the fiber and structure can be increased. Experiments on skin-fabric interactions, results of which could lead to improved performance, can be readily performed. Table 4-5 is a summary of the general improvements in the material properties of fibers that can be made to achieve the design goals for CB protective textiles.

Using clothing to protect an individual from chemical agents can be approached two different ways: (1) by providing an impermeable barrier; or (2) by providing a selectively (semi-)permeable barrier. Materials that create physically impermeable barriers to chemical agents sacrifice the moisture-vapor permeability of the clothing. Although impermeable barrier materials, such as rubber and coated fabrics, allow some degree of moisture-vapor permeability, it is too low to avoid heat stress and thus decreases the wearer's ability to accomplish a mission. Therefore,

TABLE 4-5 Summary of Required Improvements in Fibrous Material Properties

Needs	Properties
Lighter weight	Lower fiber specific gravity
	Lower packing density
Less bulk	Smaller fiber diameter
	Higher packing density
Higher durability	Higher strength, toughness
More comfort	More permeability
Less heat stress	Better thermal conductivity

Source: Ko, 1999.

impermeable materials can only be used effectively for a short time. The impermeable barrier approach was used for protective clothing until the mid-1970s.

Currently, the impermeable barrier approach is used only for gloves, boots, and other special equipment intended for short-term use (such as the suit, contamination avoidance, liquid protection [SCALP] outfit, the toxicological agent protective [TAP] outfit, and the self-contained toxic environment protective outfit [STEPO]).

The newer approach is to use a semipermeable fabric and a sorptive layer that can filter out/decompose chemical agents or to use selectively permeable membrane materials. Sorption can be achieved by using carbon powder or carbon fibers. Carbon powder can be disseminated as foam, as coating on fibers, as filling in hollow fibers, or as part of melt-blown fibers. Activated carbon fibers can be used as nonwoven, flocked fabrics or laminated structures. Protection by chemical decomposition of the agents can be achieved by the use of reactive resins or reactive enzymes. The selectively permeable membrane concept is currently under development at the SBCCOM Soldier Systems Center at Natick, Massachusetts (see Figure 4-1).

The BDO consists of a coat and trousers, usually worn over the duty uniform. The BDO has an outer layer of 7-oz/yd^2 of a nylon/cotton blended twill (woodland camouflage) or 6-oz/yd^2 of nylon/cotton/Kevlar twill (desert camouflage) in a twist weave construction. The inner layer consists of activated charcoal impregnated into approximately 90-mil polyurethane foam laminated to a 2-oz/yd^2 nylon tricot liner (Figure 4-2). The inner layer components are laminated together; the top layer essentially floats and is put on as the garment is manufactured. Because of the heavy impregnation of charcoal, some charcoal may be deposited on the skin and clothing under the BDO. The BDO is water resistant, but not waterproof. It provides 24 hours of protection against chemical agents

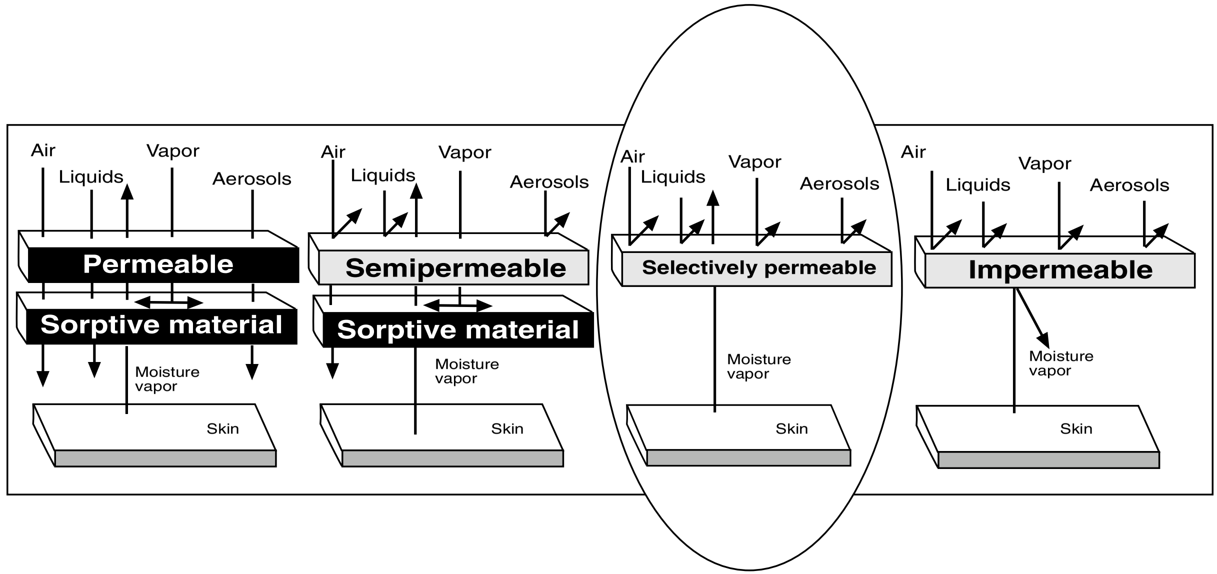

FIGURE 4-1 Construction of a selectively permeable barrier.

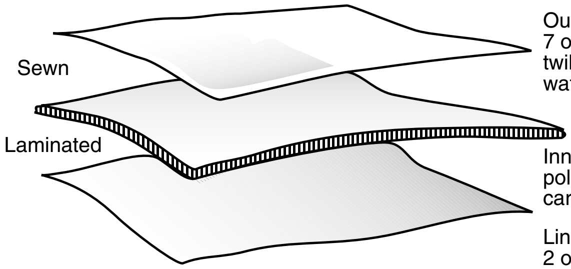

FIGURE 4-2 Components of a typical current barrier system.

once contaminated and has a field durability of 22 days (U.S. Army Office of the Surgeon General, 1997). The BDO's shelf life is 14 years if the packaging is intact.

The Saratoga overgarment (OG84/BDO) was developed for the Marines, who were dissatisfied with the BDO (Mellian, 1999). The Saratoga overgarment is designed for 30 days of continuous wear and provides 24 hours of protection against chemical agent vapors, aerosols, droplets, and all known biological agents. The overgarment consists of an outer layer of cotton ripstop material treated for durability and liquid resistance and an inner filter layer of spherical carbon absorbers laminated between two lightweight polyester materials. The coat features a full-length zippered opening covered by a single protective flap, an integrated hood, hook and pile sleeve closures, and trousers with adjustable waist tabs, suspenders, and closures on the lower outside section of each leg. The Saratoga overgarment can be worn over the duty uniform or directly over undergarments. Advantages of the Saratoga overgarment over the BDO include launderability, lower thermal burden, an extended wearlife, a 15 to 20 year shelf life, and a higher degree of comfort and durability.

JSLIST, the first of a three-phase program, was created to consolidate the programs of individual services to obtain a family of garments and ensembles to meet joint service needs[2] at the lowest practical cost. The

[2]The requirements generation system produces information for decision makers on the projected mission needs of the warfighter. The generation of requirements consists of four phases: definition, documentation, validation, and approval. The process evolves from a mission needs statement (MNS) to a capstone requirements document (if applicable) through operational requirements documents. The MNS is a continuing process that normally begins with a review of the latest national security policy, national military strategy, defense planning guidance, joint intelligence guidance, and projected threats and is generated in coordination with the applicable services and agencies, CINCs, and higher headquarters (Chairman of the Joint Chiefs of Staff, 1997).

JSLIST ensemble affords CB protection with reduced physiological heat burden and better integration with weapons systems than previous technologies. The ensemble consists of five clothing items: (1) overgarment, (2) undergarment, (3) duty uniform, (4) boots, and (5) gloves. To date, only two of the five components (the chemical protective overgarment and the multipurpose overboot [MULO]) have been type classified. The remaining items, as well as minor design modifications to the JSLIST overgarment, are being addressed in the JSLIST Pre-Planned Product Improvement (P3I) program.

Procurement for the JSLIST overgarment began in FY 1997. The JSLIST overgarment, which has a shelf life of 15 years, is designed to provide 24-hour chemical protection for 45 days of wear and six launderings. It can be worn over the battledress uniform (BDU) or as a primary garment over underwear, depending on the environment and mission. The overgarment is a two-piece, front-opening garment that has an integral hood, bellow-type pockets, high-waist trousers, adjustable suspenders, and an adjustable waistband. The material is a combination of a nylon/cotton outershell over the Saratoga filter cloth.

The JSLIST has many advantages over the BDO. It can be laundered more often (i.e., less time between washings) and more times; the outer shell materials are stronger and more durable; the sorptive liner materials are cleaner and more breathable; the integrated hood increases the protection capabilities of the suit; the raglan sleeve allows more freedom of movement; the integrated suspenders allow for optimal individual fitting; and lighter weight reduces heat stress.

In addition to improving the ratio of work to rest time, JSLIST garments are designed to be more accurately sized, fitted, and worn by both male and female service personnel. The garments have a seven-size system, in which the coat and trousers are packaged separately. (For logistical reasons, the Navy will only be using a five-size system.) An evaluation of the design, size, and fit of these components revealed that the coat retention cord kept the coat from separating from the trousers at the waistline, but 68 percent of the test participants complained that the cord was uncomfortable (Mellian, 1997). To alleviate the discomfort, the cord was lengthened and modified to be convertible so that it could be unhooked at MOPP 1, MOPP 2, and MOPP 3 levels. Complaints were also registered regarding irritation from the hook-and-pile fasteners at the hood/neck area. Modifications were made to the fasteners, but complaints were still common. It was suggested that research be conducted during the next phase of the JSLIST program to find a softer hook fastener tape (Mellian, 1997).

The JSLIST P3I overgarment program is a follow-on to the JSLIST program. The goal of the JSLIST P3I program is to incorporate mature fabric technologies that have been developed for civilian use into the existing JSLIST design. The program's goals include the development of a 60-day flame-resistant (FR) overgarment, a 30-day FR overgarment, a 30-day FR duty uniform, a 7-day FR overgarment, a 7-day FR undergarment, and a multipurpose protective sock (MPS). Operational and technical tests are being conducted on materials identified through a screening process, and a technology insertion decision is scheduled for the first quarter of FY 2000.

After extended wear, the MPS will provide 12 hours of protection against 10 g/m^2 liquid agent and 5,000 mg-min/m^3 vapor/aerosols if worn under a boot made of permeable material. It also must be comfortable, fit well, be compatible with all Special Operations Forces footwear, and retain its chemical protection after four launderings.

According to requirements, the lightweight chemical/biological protective garment (LCBPG) of the JSLIST P3I program will be designed to provide 6 hours of protection against 10 g/m^2 liquid agent and 5,000 mg-min/m^3 vapor/aerosols for 7 days of field wear in all geographical areas (U.S. Marine Corps, 1999a). The garment will not have to be launderable, but it must weigh no more than four pounds and have a maximum package size of 500 in^3. It is hoped that the LCBPG, which may be worn as an overgarment or as a primary garment over underwear depending on the environment or mission, will reduce the physiological heat burden of the BDO by at least 20 percent.

The JSLIST P3I 60-day overgarment is a joint requirement and will be worn as an overgarment for the BDU or as a primary garment over personal underwear depending on the environment and mission. According to requirements, it will provide 24 hours of protection for 60 days of field wear in all geographical environments. It must retain its chemical protection after eight launderings, weigh less than four pounds, and, like the LCBPG, reduce the physiological heat burden of the BDO.

The JSLIST P3I 30-day overgarment, an Air Force requirement, is similar to the JSLIST P3I 60-day overgarment, but it only has to provide protection for 30 days of field wear and must retain its chemical protection for only four launderings. It will be worn as an overgarment for the duty uniform or as a primary garment over underwear.

The vapor protective undergarment (VPU) is a Special Operations Forces requirement of interest to the Army, Air Force, and Marine Corps, which would provide 12 hours of protection against 10 g/m^2 liquid agent and 10,000 mg-min/m^3 vapor/aerosols for 30 days of field wear. It must retain its chemical protection after four launderings, weigh less than three pounds, and reduce the heat stress burden imposed by the current chemical protective undergarment (CPU).

The Marine Corps has a requirement (also of interest to the Army, Air

Force and Special Operations Forces) for a duty uniform that would enhance existing capability with a lighter, less thermally burdening ensemble. It would be worn by all Marines, except aircrews with special environmental or equipment interface requirements and personnel who deal with large volumes of liquid contaminants.

The joint service protective aircrew ensemble (JPACE) will provide below-the-neck protection against chemical and biological agents for rotary and fixed-wing aircrews. It will be used by all of the services and will replace the Navy/Marine Corps MK-1 undergarment, the Army ABDU-BDO system, and the Air Force CWU-66/P overgarment. Requirements for the ensemble include a 30-day wear time, launderability, compatibility with aircrew-mounted aviation life-support systems, ejection safety, and water survivability. The JPACE will be jointly tested and fielded with the joint service aviation mask and will use JSLIST and JSLIST P3I materials, designs, and documentation to the maximum extent possible. Separate garments may be considered for fixed-wing and rotary-wing aircrews.

Masks

The respiratory system is the most vulnerable human system to airborne contaminants. Some estimates for organic vapors are that 10 to 1,000 times more vapor is absorbed through the lungs than through the skin (e.g., Leung and Paustenbach, 1994). The gas exchange region of an adult's respiratory system has a surface area of 75 m^2 to 100 m^2, 40 times that of the skin, and is in direct contact with the external environment. This surface is also the thinnest membrane in the body so gases can readily diffuse through it. Thus, for many chemical contaminants, including nonvesicant chemical warfare agents, other routes of absorption are only important when the respiratory system is well protected.

Because of the importance and extreme vulnerability of the respiratory system, humans have evolved extensive natural defense mechanisms for protecting it from environmental insults. These include mechanisms in the nose, throat, and conductive airways and a system of branching tubes that conduct air to the gas exchange region to protect the more sensitive gas exchange, or alveolar, region from chemicals at low concentrations and from chemicals with low acute toxicity. These defenses cannot, however, protect against the highly toxic and rapidly acting chemical warfare agents to which deployed forces may be exposed. For these reasons, respiratory protection is a major component in the contamination avoidance doctrine, and respirators of various types have been developed and fielded.

A respirator can be defined as a covering over the mouth and nose that protects the respiratory system by reducing the amount of airborne contaminant inhaled. The two basic classes of respirators are "air-purifying" respirators and "atmosphere-supplying" respirators. The former uses lung power to draw air through a filter and into the respirator. Because the mask is under negative pressure with respect to the external environment during inhalation, facial seals must be tight to ensure protection. Atmosphere-supplying respirators rely on the delivery of clean air from another environment via an air line or compressed air tank. These respirators keep the mask under positive pressure at all times and thus prevent inward leakage of contaminated air.

Respirators differ in the types and levels of protection they provide and the degree of encumbrance they impose. Other factors that affect the level of protection include the growth of facial hair, the shape of the wearer's face, the fit, material inconsistencies, adverse reactions to adhesives or sealants, and potential incompatibility with night vision goggles.

Half-face respirators are the simplest and least encumbering. They cover the nose and mouth and seal across the bridge of the nose and under the chin. They are characterized by light weight, comfort, moderate to good filter efficiency, and the ability to speak and be understood. However, these disposable respirators provide no eye protection, which can be critical for some agents, and seal poorly against the face. Half-face respirators are similar to the masks physicians wear in an operating room. A variation of these simple respirators is the cartridge, elastomeric, half-mask respirator that covers the nose and mouth, fits and seals better, has inhalation and exhalation valves, and can accommodate different types of cartridges for different contaminants. They do not protect the eyes, however, and, therefore, do not meet the protection factor (*PF*) required for typical biological threats.

The full face-piece respirator protects the eyes, provides a better seal against the face than the half-mask, may include a speaking diaphragm, and may have an inner mask to control the flow of inhaled air to reduce lens fogging and dead volume. Some masks are attached by a flexible tube to an oversized cartridge worn on the belt or chest; others have a single filter cartridge located on one side to facilitate aiming a weapon. Most military masks are full face-piece respirators with an inner mask and a speaking diaphragm. Current U.S. masks (e.g., M40) are designed to use NATO standard filter canisters. In addition, masks must be capable of being combined with other protective clothing as part of a fully integrated protective suit, and they must provide laser and ballistic fragmentation eye protection.

Forced air-purifying respirators supply clean air through a hose. They may be used with half-mask or full face-piece masks or with a hood or helmet. They maintain a positive pressure in the mask at all times and eliminate the effort required to draw air through a filter. They provide a higher level of protection than cartridge respirators, but current versions are heavier and more cumbersome than cartridge units and require either portable air compressors and larger filter units or must be coupled to compressed air tanks. The tank-equipped self-contained breathing apparatus does not restrict mobility and can be used in low-oxygen situations. A two-stage regulator maintains positive pressure in the mask at all times.

Oxygen "rebreather" systems are sealed systems that recycle expired air. They use carbon dioxide scrubbers and add small amounts of pure oxygen to replace the oxygen removed during breathing. They have longer service life than tanked compressed air, but the mask may be under negative pressure creating a risk of fire or explosion from the use of oxygen and possible leaks of the strongly caustic materials used for carbon dioxide scrubbing if water gets into the system (e.g., during decontamination operations).

An intermediate category of respirators is the powered air-purifying respirator, which uses battery-powered pumps to draw air through a filter and delivers it under positive pressure to the mask (either half-mask or full face-piece). The pump can be carried on the belt or mounted on the apparatus in a fixed location. These devices can provide a high level of protection because the mask is under positive pressure, and they reduce the effort required for breathing. However, they are heavy, have battery life limitations, and cannot be used in an oxygen deficient atmosphere.

Level of Protection. The level of protection provided by a respirator is characterized by a protection factor, *PF*, which is the ratio of the external concentration of contaminant to the contamination level inside the mask.

$$PF = \frac{\textit{concentration outside mask}}{\textit{concentration inside mask}}$$

Thus a *PF* of 1 represents no protection, and a *PF* of 100 means the wearer's exposure is reduced by a factor of 100. Ideally, the PF will be greater than 10,000. The technical requirements for military protective masks require that they provide a PF $\geq$ 1,667 for 88 percent of the population, a PF $\geq$ 6,667 for 75 percent of the population, and a PF $\geq$ 10,000 for 68 percent of the population (Kirkwood, 1998). Nevertheless, even if properly functioning, contamination can enter by three possible routes: through the filter, through leaks in the facial seal, or through the exhalation valve. Leakage in the facial seal is the most common source of exposure in current masks (Hinds, 1999).

The weakest link in respirator performance is the quality of the facial seal, or fit of the respirator on the face. Because everyone's face is shaped differently, the fit of masks is often less than ideal; fit can also be adversely affected by the growth of facial hair. Full face-piece masks provide a better fit for a wider range of faces than half-face masks.

Three levels of tests can be used to evaluate fit. The simplest and least precise is subjective "fit checks," such as negative pressure tests and positive pressure tests. These tests are used every time the mask is donned to verify that it is properly seated on the face and is operating properly. In the negative pressure test, the wearer blocks the filter inlets with the palms of the hands and tries to suck the mask down against the face. If it can be held against the face, it passes the test; if not, it fails. In the positive pressure test, the wearer blocks the exhalation valve and tries to exhale to sense any leakage. These tests give only a gross evaluation of fit but do warn the wearer of a malfunction.

The next two levels of tests are used to determine which respirator type or size fits an individual best. Qualitative fit tests are also subjective pass/fail tests but include tests of respirator function, as well as fit. The wearer tests whether a vapor is smelled when the mask is equipped with activated charcoal cartridges and whether an irritant smoke is detectable when the mask is equipped with high-efficiency filters.

The most precise tests are quantitative fit tests, which, as the name suggests, provide a quantitative measure of fit. One test involves wearing a respirator with high-efficiency filters in a test aerosol environment and measuring the aerosol concentrations inside the respirator (by means of a probe through the respirator body) and outside the respirator. A fit factor (FF) is calculated from the ratio of these two quantities.

$$FF = \frac{outside\ concentration}{inside\ concentration\ (filter\ penetration = 0)}$$

Test aerosols include corn oil and sodium chloride and naturally occurring condensation nuclei. Another test measures leakage flow rate for a controlled negative pressure in the mask. Typical equipment can measure fit factors from 1 to 10,000, or even 100,000.

An example of a quantitative fit test is the M41 protection assessment test system, a small portable instrument designed to quantitatively validate the fit of the face piece (U.S. Army SBCCOM, 1999). This test instrument, based on a miniature condensation nucleus counter, continuously samples and counts microscopic particles both inside and outside the mask and calculates a fit factor. The Army, Marine Corps, and Air Force are fielding this test system for use with the M40, M42, and MCU-2/P series masks; the Navy is evaluating it for use with its MCU-2/P series masks (DoD, 1999).

Proper fitting of the mask can increase the level of protection by 100-fold. The Air Force has begun issuing the M41 mask fit testing unit and has established training protocols for its use (Chow et al., 1998). The Army has also begun to issue the M41 mask fit testing unit for field deployment. It is not clear, however, if the Army's mask donning training is universal or whether appropriate joint service doctrine has been developed for mask fit testing.

The Marine Corps has the lead for the development of a joint service mask leakage tester, scheduled to be fielded between FY 2004 and FY 2006, to test and validate the serviceability and fit of protective masks. This tester will be deployed at the unit level and should be small enough to be carried by one person (Rhodes and Decker, 1999).

Types of Masks. Several types of masks have been produced and fielded. The specific circumstances of an operation dictate which mask should be used. The M40 and M42 series masks, which were developed earlier but have been enhanced in the JSLIST P3I programs, have replaced the M9, M17, and M25 series masks for the Army and Marine Corps. The M40 and M40A1 were designed for use by dismounted soldiers; the M42 series (including the M42, M42A1 and M42A2) were designed for use by combat vehicle crews. All of these masks are compatible with JSLIST overgarments. The masks consist of a silicone rubber face-piece with an in-turned peripheral face seal to protect against leakage and an elastic head harness. The masks feature two ballistically-hardened, hard-coat polycarbonate, optically-corrected lenses held in place with metal eye rings to provide broad peripheral and downward vision. There are front and side voice emitters and an externally-mounted filter canister, which is easy to replace and can be mounted on the left or right side. The masks accommodate NATO standard air purification canisters, which can be worn on either cheek of the mask for compatibility with weapons systems. The internal nose cup has two check valves to prevent exhaled air from fogging the lenses. A "second skin," made of a butyl rubber impregnated fabric and worn as a hood, provides protection from liquid absorption by the mask face-blank material. The M42 series masks contain an additional externally mounted microphone and a canister attached to the end of a hose, which has an adapter for connection to a gas-particulate filter unit. Advantages of this mask over previous masks include an improved face seal, improved vision, flexibility at temperature extremes, improved comfort, longer useful life, improved voice transmission, and improved airflow path (Davis, 1998). In addition, the mask construction is modular so that some replacement parts can be used in both the M40 and M42 configurations. This has reduced costs at both the manufacturing and sustainment levels and simplified logistics.

The MCU-2A/P (a variation of the MCU-2/P), which is designed to meet the needs of Air Force ground crews, Navy shipboard and shore-based support missions, and Marine Corps rotary-wing forces, will be used until the JSGPM is fielded. The MCU-2A/P uses a replaceable, standard NATO filter canister mounted on the left or right side. The face-piece is molded of silicone rubber. Voicemitters are located in the center and on either side of the face-piece. The lens is made of transparent urethane and provides a wide field of view. Other features include external and internal drinking tubes and a nose cup that prevents the mask from fogging. This mask provides better fit, comfort, and visibility than earlier masks (DoD, 1998b).

M48/49 aviator masks are third-generation M43 masks. The M48 mask will be the only mask for the Apache aviator. The M48/49 mask consists of a lightweight motor blower (less than three pounds), a new hose assembly, and the same face-piece as the M43A1. Advantages include the capability of interfacing with night vision goggles and other sighting devices, no required aircraft modifications because the blower is worn by the user, and battery power for at least eight hours at low speed and five hours at high speed (Davis, 1998).

The M45 mask will replace the M24 and M43 Type II masks and is designed to meet the requirements of helicopter and special crews. The M45 has close-fitting lenses mounted in a silicone rubber face-piece with an in-turned peripheral seal and a detachable hood system and uses the standard NATO canister. Improvements in this mask include: fitting a larger population through interchangeable nose cups, four mask sizes, five nose cup sizes, and silicone, which is nontoxic to the skin; compatibility with night vision; easier production; longer storage life; reduced weight, cost, and logistics burden compared to the M48/49 series; and elimination of the need for a blower.

The air-crew eye and respiration protection (AERP) program is an Air Force reprocurement of an aircrew chemical defense mask system previously developed, tested, and fielded during Desert Storm. The AERP replaces the MBU-13/P-based CB oxygen mask. The objective of the AERP program is to equip all aircrews in all aircraft mission designation series (MDS) with a chemical defense capability. The mask features an under-the-helmet configuration, chemical vapor protection of the head in and out of the cockpit, and combined chemical vapor protection of the entire body when used with protective clothing and footwear. Advantages of this mask include integration with aircraft oxygen supply, communication integration with helmet and ground use intercom unit, Valsalva capability, passive antidrowning protection, and antifogging capability. The mask also has a drinking tube, a nonhelmeted modification kit, and a portable battery-powered blower unit. However, because of operational problems with the AERP (e.g., ammonia out-gassing, exhalation during periods of rapid decompression), the U.S. Pacific Air Force has prohibited its use during training (Chow et al., 1998). Therefore, additional testing and a possible redesign may be necessary to ensure that the mask meets operational needs.

The mission of the JSGPM program is to provide face, eye, and respiratory protection from battlefield concentrations of CB agents, toxins, toxic industrial materials, and radioactive particulate matter (Davis, 1998). The JSGPM is scheduled to go into production in fiscal year 2005 to replace the M40/42 and MCU-2/P series masks. The anticipated requirements for the JSGPM include: protection against conventional CB agents and toxic industrial materials; a protection factor greater than 10,000; significant reductions in weight and bulk; exhalation breathing resistance of ≤ 20 mm of water and inhalation resistance of ≤ 30 mm of water at 85 liters per minute (lpm); improved field of view; compatibility with all service individual clothing and equipment and with individual and crew served weapon systems and optics; improved communications; operation in all environments; improved comfort; and reduced physiological burden (Davis, 1998). The overall goal is 50 percent improvement over the existing M40 and MCU-2/P protective masks.

The objective of the joint service aircrew mask (JSAM) program is to provide face, eye, and respiratory protection to all joint service aviators from field concentrations of CB agents, toxins, and radioactive particulates. It will feature improved protection, reductions in weight and bulk, capability to don in flight, continuous protection against agent permeation for 16 hours, and protection against gravitational loss of consciousness at sustained G levels to +7.5Gz with +6Gz per second onset sustained for 30 seconds for high-performance aircraft. This mask is scheduled to have full operational capability by 2006.

Gloves

Current glove technology is based on the use of impermeable materials. Future developments will be able to take advantage of lighter weight materials that will provide better tactile responses and can take advantage of supplementary protection from barrier creams (described in "Barrier Creams" section below). Because the newer glove will probably have multiple layers of materials, this technology is referred to as multilaminate. In effect, multilaminate technology may permit, not just the development of new gloves, but also the development of more effective and more functional garments.

Chemical Protective Glove Sets. The chemical protective glove set consists of a butyl-rubber outer glove and a cotton inner glove. The main purpose of the inner glove is to absorb perspiration. The outer glove provides protection against chemical agents and comes in three thickness, 7 mil (0.007 inch thick), 14 mil (0.014 inch thick), and 25 mil (0.025 inch thick). The 25-mil and 14-mil gloves provide 24 hour protection and have a 14-day field wear, whereas the 7-mil gloves have 14 day wear but only provide for six hours of protection. Personnel who require a durable glove to perform close combat tasks and perform heavy labor must use the 25-mil glove. Aviators and mechanics use the 14-mil glove for good tactility. The 7-mil glove is used when high degrees of tactility and/or sensitivity are necessary, such as performing medical procedures, teletyping, or repairing electronic equipment. Problems with the glove sets include buildups of perspiration and limited durability, tactility, and dexterity (Gander, 1997).

Improved Chemical and Biological Protective Gloves (ICBPGs). The ICBPG is intended to be incorporated into the JSLIST P3I program. Key requirements for the gloves include: 24 hours of protection against $10g/m^2$ liquid agent; protection against petroleum, oil, lubricants, and standard decontaminants; self-extinguishing flame resistance; 15 days wear durability in all environments without degradation of protection; and dexterity equal to or better than the standard 14-mil and 25-mil butyl gloves (DoD, 1998b). A general-purpose glove for durability and a high-tactility glove for improved dexterity are being evaluated.

Boots

Green Vinyl Overshoes/Black Vinyl Overshoes (GVOs/BVOs). The GVO/BVO is a fitted overshoe worn over standard combat boots to provide CB and wet weather (rain, snow, and mud) protection. The overshoe is made of polyvinyl chloride (PVC) and consists of a folding gusset with three button fasteners. The outer surface is coated with a slip finish to permit easy donning and doffing. The GVOs/BVOs provide protection for up to 14 days and should be replaced within 12 hours of contamination with liquid agent. Disadvantages of the overshoes are that they are heavy, they do not provide 24 hours of chemical protection, they cannot be decontaminated, and they are not resistant to petroleum, oils, lubricants or flames (DoD, 1998b).

Multipurpose Rain/Snow/CB Overboots. The MULO provides protection from CB and environmental hazards and are worn over standard combat boots, jungle boots, or intermediate cold wet boots. The MULO is made of elastomer blend and produced by injection molding to provide protection against petroleum, oils, and lubricants, as well as providing flame resistance. The sole is designed to provide traction on various surfaces, including dirt and metal. Key requirements for the MULO are to provide 24 hours of protection against 10 g/m^2 challenge by all liquid agents; resistance to incidental splashing by petroleum, oils, and lubricants; self-extinguishing flame resistance; 60 days wear in all geographical areas without degradation of protection; and the capability of being decontaminated to an operationally safe level using standard decontaminants. Improvements of this boot over the previous GVO/BVO include more durability, lighter weight, and better CB protection (DoD, 1998b).

Barrier Creams

Barrier creams are designed to prevent or reduce the penetration and absorption of hazardous materials into the skin, thus preventing skin lesions and other toxic effects from dermal exposure. Moisturizers, which are frequently used to treat "dry" skin, as well as to maintain healthy skin, may have common characteristics and ingredients with barrier creams (Zhai and Maibach, 1998). Barrier creams could solve a number of persistent percutaneous problems by: (1) mitigating the consequences of partial closures, (2) providing early protection while protective gear is being donned, and (3) permitting transition from Mask-Only to MOPP 4 status. An ideal barrier cream would be nonirritating, nonallergenic for contact dermatitis, non-photo irritating, non-photoallergenic for contact dermatitis, nonflammable, and not likely to cause contact urticaria syndrome.

The effect of a barrier cream may depend on the dermatopharmacokinetic (DPK) properties of the chemical challenge and other factors (Packham et al., 1994; Wigger-Alberti et al., 1997). A current limitation of barrier creams is that they must be applied in large doses (e.g., 0.15 mm thickness), which could interfere with the physiological mechanisms of the skin (see Chapters 5 and 6 and Appendix C for more details).

Impacts on Effectiveness

Tests and real-world experiences with PPEs have revealed numerous shortcomings. Depending on the outside temperature and the level of work, MOPP postures above MOPP 0 can result in the following performance limitations:

- speech and communications problems
- impaired hearing
- reduced vision (e.g., acuity, field of view, depth perception)

- difficulty recognizing other individuals in MOPP
- heat injuries
- dehydration
- inadequate nutrition
- combat stress
- mood swings and claustrophobia
- impaired thinking and judgment
- reduced manual dexterity

In recent years, the impacts of the effects of wearing MOPP on combat operations have been studied extensively during combined arms exercises, field exercises, and laboratory studies. Dugway Proving Ground, for example, has administered the Chemical Biological (CB) Contact Point and Test Program (Project DO49) to quantify the effects of wearing protective clothing on the performance of military tasks. This program has five operational areas: maintenance operations, night reconnaissance operations, missile operations, armor operations, and signal operations. The following observations are examples of the decrements that have been found:

- In a variety of tasks, degradation was 20 to 50 percent (U.S. Army, 1987).
- Time to complete tasks increased (Chow et al., 1998).
- Oxygen consumption increased about 10 percent in full PPE compared to in light clothes, indicating that personnel in MOPP 4 must use more energy than personnel in MOPP 0 to perform the same tasks (U.S. Army, 1991b).
- Reduced sensory awareness made it harder for personnel to stay awake when tired (Joint Chiefs of Staff, 1995).
- Soldiers required one-and-one-half to three times longer to perform tasks requiring manual dexterity in MOPP 4 than without PPE (U.S. Army, 1991b).
- Performing a task for the first time took longer, as much as 30 percent longer in MOPP 4 (Gawron et al., 1998; U.S. Army, 1987).
- Troops tended to omit or perform certain tasks poorly (e.g., camouflage and support activities) (U.S. Army, 1986).
- The performance levels for cognitive tasks was lower (Kelly et al., 1988; Taylor and Orlansky, 1993; U.S. Army, 1991b; Williams et al., 1995). In one instance, encoding decreased by almost 23 percent (U.S. Army, 1991b).
- Leader performance declined (e.g., they became exhausted, slept less, became disoriented or lost, became irritable, and delegated less authority) (U.S. Army, 1986; 1994).

- Leaders were often the first MOPP casualties (U.S. Army, 1986).
- Unit movement formations tended to bunch up (perhaps to help leaders maintain control) (U.S. Army, 1992).
- When platoon leaders became casualties, it took four times as long for a MOPP 4 platoon to realize it was leaderless than an unencumbered platoon. The next senior soldier assumed command 85 percent less often than in non-PPE exercises (U.S. Army, 1986).
- PPE overboots provided poor footing on hilly terrain, loose ground, and wet ground (U.S. Army, 1992).
- PPE garments absorbed rain and became very heavy and cumbersome (U.S. Army, 1992).
- Rifle marksmanship dropped 15 to 19 percent for soldiers in MOPP 4 (U.S. Army, 1991b).
- Individual weapon-firing rates decreased 20 percent in defensive actions and 40 percent in offensive actions. It took twice as long and nearly twice as many soldiers to complete an attack (U.S. Army, 1986).
- The proportion of enemy personnel engaged decreased by one-third (U.S. Army, 1986).
- Weapon crews used terrain much less effectively for cover and concealment, and the number of casualties suffered per enemy defender killed increased by 75 percent (U.S. Army, 1986).
- Units in MOPP 4 tended to take greater risks, especially light and dismounted infantry (e.g., using easier routes and closer formations, not always sterilizing kill zones before crossing) (U.S. Army, 1994).
- Shots fired at friendly instead of enemy soldiers increased from 5 to almost 20 percent (U.S. Army, 1986).
- Indirect fire support was less responsive because artillery and mortar units sacrificed time for accuracy (U.S. Army, 1994). There was also a tendency to use less direct fire and more indirect fire (e.g., platoons called for three times more indirect fire). Indirect fire was more effective than individual weapons in inflicting casualties on the enemy (U.S. Army, 1986).
- Land navigation was seriously degraded (e.g., disorientation and bunching up of armored, mechanized, and dismounted soldiers), particularly at night (U.S. Army, 1994).
- Night vision devices could not be used while personnel were wearing masks (U.S. Army, 1992).
- Radio communication was difficult because of reduced clarity and volume (U.S. Army, 1992). The voicemitter made speakers sound brassy and muffled, and consonants were blurred. The hood and

background noise (e.g., from breathing, garment movement, etc.) degraded hearing (U.S. Army, 1991b).

- Communications were only about half as effective as in a non-PPE environment. Total time spent on radio traffic more than doubled. The number and length of radio transmissions rose by 50 percent (U.S. Army, 1986).
- Time to chart positions in a shipboard combat information center degraded by approximately 24 percent (Garrison et al., 1982).
- Recognition and identification of soldiers and leaders in MOPP 3 and MOPP 4 were difficult because the usual visual cues were hidden (U.S. Army, 1994).
- Logistics operations took longer and became confused (U.S. Army, 1994).
- Maintenance took longer, in one study about 30 percent longer (Shipton et al., 1988).
- Recovering armored vehicles took up to 20 percent longer; repairing weapons took up to 70 percent longer (U.S. Army, 1994).
- Performance of projected sortie generation capability decreased with increasing levels of individual protection (Gawron et al., 1998).
- Target acquisition was more difficult because the field of view was reduced and hearing was restricted (U.S. Army, 1994).
- Movements, maneuvers, and fire support were harder to synchronize, and many tasks took longer to perform (e.g., rates of march decreased significantly and led to increased fuel usage) (U.S. Army, 1994).
- Under some conditions, performance degraded significantly within one hour, although endurance could be extended by adjusting the ambient temperature, amount of drinking water, and/or frequency of rest periods (Taylor and Orlansky, 1993).

Reviews of studies on the effects of PPE on performance in the other services support many of these findings. However, there are problems associated with many of these studies. For example, some of the studies cited above tested out-of-date clothing system components, and these results cannot be directly extended to performance while wearing newer components of the ensemble. Also, there can be different interpretations of the same data, and it is also difficult to conclude that the findings apply to all types of tasks. This suggests that additional research is needed to determine how performance can be improved, with changes in the protective ensemble, to increase the likelihood that U.S. forces can successfully prosecute their missions in a CB environment. (For comprehensive reviews, see, for example, Carr et al., 1980a, 1980b; DoD, 1997b; Draper and Lombardi, 1986; Goldman et al., 1981; Rakaczky, 1981; Taylor and Orlansky, 1987, 1991, 1993.)

Patient Protective Equipment

As of early 1999, only three items of patient protective equipment had been fielded: the patient protective wrap, the decontaminable litter, and the resuscitation device individual chemical (RDIC). R&D on new equipment, especially in the private sector, is continuing as needs continue to be identified.

Patient Protective Wrap

Because the treatment of chemical casualties often requires removal of the PPE and precludes donning of replacement garments, a patient protective wrap has been developed. The wrap, which is designed to be used once and then discarded, is sturdy, lightweight (approximately 2.7 kg), and protects the patient from all known chemical agents for up to six continuous hours. There is a transparent window on the top sheet of the wrap and protective sleeves for passing through intravenous tubing.

The wrap is designed to be used on a litter, but, if necessary, can be used as a field litter. It is recommended, but not required, that the patient wear a mask while in the wrap. However, cardboard inserts must be placed in the wrap before the casualty to hold the window material away from the patient's face. Although the wrap is permeable to oxygen and carbon dioxide, because the rate at which typical patients produce carbon dioxide is slightly faster than the rate at which it passes through the wrap, the carbon dioxide levels slowly build up inside the wrap. Therefore, patients may not remain in the wrap for more than six hours.

Decontaminable Litter

Canvas litters, traditionally used to transport casualties after exposure to liquid blister agents, have been found to continue to desorb vapors for 72 hours after all surface contaminants were removed. This problem led to the development of a litter made of monofilament polypropylene, which has high tensile strength and low elasticity. The fabric, a honeycomb weave through which liquid passes easily, does not absorb liquid chemical agents, is not degraded by current decontaminating solutions, is flame retardant, is rip resistant, and is treated to withstand exposure to weather and sunlight. The litter has retractable handles and a metal pole frame. The metal parts have been painted with chemical agent resistant coating paint.

Resuscitation Device, Individual Chemical

The RDIC is a ventilation system consisting of a compressible butyl rubber bag, a NATO standard C_2 canister filter, a nonrebreathing valve, a cricothyroid cannula adapter, and a flexible hose connected to an oropharyngeal mask. The butyl rubber bag resists penetration of liquid chemical agent and can be decontaminated easily. There will be one RDIC for each air ambulance, one for each ground ambulance, and one at each chemical agent medical treatment facility.

Summary

Current R&D on PPE is addressing the continuing problems with JSLIST, including leaks around joints and seals; reduced, but still significant, heat loading problems; weight and bulk problems; and difficulty with decontamination and reuse. Future enhancements in textiles and fabrics could include (1) integrated detection capability to alert the wearer to the presence of contamination and to indicate the time remaining at the highest protection level, and (2) the use of advanced solid sorbents with improved properties over charcoal materials.

With the current design of the mask and the JSLIST overgarment, during the transition from Mask-Only to MOPP 4 status, the mask seal may be momentarily broken. If troops are in an area of high agent concentration, this momentary breach could result in incapacitation or death. All masks have potential problems with leakage around seals due to improper fit, the growth of facial hair, and material inconsistencies. Available technology for regenerating filters and adsorbents has not advanced greatly in the past few years, and adsorbent saturation limit the mask's effective use time. Gloves are cumbersome, reduce tactile efficiency, and don't integrate well with weapons (i.e., trigger guards on rifles, etc.). Boots are heavy and uncomfortable, and extended wear can cause dermatological problems. Barrier creams are being investigated and evaluated for use in combat.

COLLECTIVE PROTECTION

Risks, Challenges, and Requirements

CPE provides a relatively unencumbered safe environment in which eating, surgery, and other activities can be performed. Collective protective systems have been developed as stand-alone structures or overpressurized (i.e., positive pressure) vehicles and vans. Ideally, this equipment could protect against physical as well as CB threats. However, current collective protection equipment is vulnerable to physical threats, such as shrapnel and projectiles, cannot be erected easily, and is rarely available (DoD, 1999; Institute for Defense Analyses, 1999). Protection against physical threats has been sacrificed for portability.

The major challenges for stand-alone collective protective systems are availability, portability, functionality, and integrity of the barrier. Functionality includes ingress and egress that minimize or eliminate the possibility of internal contamination. Challenges for protecting crews in vehicles include integrating collective protection measures into vehicle designs. Improved protection in any environment depends on filtration and adsorbent technologies, as well as the availability of protective equipment. The number of collective protective units available for deployment is much lower than the number required for most activities in a large-scale CB environment.

Filters

The M48/M48A1 is a 100 ft^3/min filter currently used in the M1A1/A2 Abrams tank, M93 modular collective protection equipment (MCPE), CB protected shelter, and the paladin self-propelled howitzer. The M56 is a 200-ft^3/min filter currently used as the basic filter set in the MCPE and in naval applications. M56 filters can be stacked for higher airflow rates. 600 ft^3/min and 1,200 ft^3/min stainless steel fixed installation gas filters are currently used for fixed-sites where high volumes of airflow are required. They can be stacked to provide higher airflow rates.

Filter Systems

M8A3 Gas Particulate Filter Unit (GPFU)

The M8A3 GPFU is a 12-ft^3/min system that provides air to the M42A1/A2 armored vehicle crewman ventilated face mask. It is also used in the Army's M113 armored personnel carrier variants and the Marine Corps' AAVP7A1 amphibious vehicle.

M13A1 GPFU

The M13A1 GPFU is a 20-ft^3/min system that provides air to the M42A1/A2 armored vehicle crewmen ventilated face masks. It is also used on the M1A1/A2 Abrams tanks, Bradley fighting vehicles, MLRS, tank transporter, and other vehicles.

Recirculation Filter Blowers

Recirculation filter blowers are used to eliminate the risks of residual contamination through a 600 ft^3/min continuous air-filtration cycle. These blowers are portable, self-contained, and equipped with replaceable filters. They are used with the M28 and M20A1 shelter systems. The filter life can be as long as 2,000 hours depending on the contamination level (Gander, 1997).

Intellitec Biochemical Filter Blower Unit (BFBU)

The BFBU is designed to provide filtered air and overpressure to the ground-based common sensor-heavy, the XM4 command and control vehicle, and the armored treatment and transport vehicle. The BFBU can be operated in the bypass mode, the low-flow NBC mode, and the high-flow NBC mode. In nonthreat conditions, the bypass mode delivers 100 to 140 ft^3/min of make-up air and filters dust through a two-stage filtration system. The NBC modes use two standard M48 or M48A1 gas/particulate filters with precleaners and can be set at up to 140 ft^3/min in the low-flow mode and 210 ft^3/min in the high-flow mode. The unit can monitor the overpressure and can be switched between the high-flow and low-flow modes either manually or automatically on receipt of an alarm signal to maintain required overpressure at the minimum current draw. The control electronics monitor the pressure drop across the filter by delivering an analogue signal that drives an external display, allowing the occupants to monitor filter status (Gander, 1997).

Filter Residual Life Indicator

The filter residual life indicator detects an adsorption wave within the carbon bed of the filter to monitor the residual absorption capacity of in-service activated carbon air purification devices. The detector technology consists of a chemoselective polymer-coated surface acoustic wave (SAW) device. The polymer coating sorbs agent and causes a shift in signal frequency. The specificity of the coating allows for selectivity towards CB agents. This device is small (approximately 1 cm^2), has a high sensitivity, gives a rapid response, and only costs $3.00 (Katz, 1990; Morrison, 1998) but has not yet been fielded.

Protective Structures and Systems

Currently Fielded Structures and Systems

M51 Protective Shelter. The M51 protective shelter is a trailer-mounted system that is used primarily by battalion aid stations and other medical units but can also be used as a temporary rest and relief shelter. It consists of a 10-man shelter, a protective entrance, and a support system. The shelter and protective entrance support themselves through air-filled ribs. The protective entrance minimizes carryover of vapor contamination from outside the shelter and paces entries to the shelter to prevent loss of shelter overpressure. The air-handling system, which is permanently mounted in the trailer, provides filtered, environmentally conditioned air. This system can be erected by four to six people in approximately one hour. The M51 was found to be unsuitable by users because of excessive weight, excessive set-up time, insufficient usable floor space, insufficient throughput of medical patients, lack of natural ventilation and lighting, and lack of space on transport vehicles (DoD, 1999; Siegel, 1998; U.S. Army and U.S. Marine Corps, 1992).

M20A1/M28 Simplified Collective Protective Equipment. The simplified collective protective equipment is used to convert an interior room of an existing structure into a positive overpressure, NBC collective protection shelter for command, control, and communications, medical treatment, and soldier relief. The M20A1 is a room liner for existing shelters, and the M28 is a liner for the tent expandable modular personnel (TEMPER). The simplified collective protective equipment consists of a CB vapor-resistant polyethylene liner; a collapsible protective entrance that allows entry to and exit from the protected area; a hermetically sealed filter canister that provides filtered air to both the liner and the protective entrance; and a support kit. The support kit contains ducting, lighting, sealing and repair material, and an electronically-powered blower. A P3I is under way to allow more people to enter at one time and protect hospitals under tents. It will also provide liquid agent resistant liners, protective liners for tents, interconnectors, and an interface with environmental control units (DoD, 1999; U.S. Army and U.S. Marine Corps, 1992).

Chemically Protected Deployable Medical System (CP DEPMEDS). The chemically protected deployable medical system will provide environmentally controlled collective protection for field hospitals. Users will be able to perform medical treatment in a CB environment to sustain a 72-hour mission. The protection is provided through the integration of M28 simplified collective protective equipment; chemically protected air conditioners, heaters, water distribution, and latrines; and alarm systems. CB resistant gaskets replace the existing shelter seals in the DEPMEDS ISO shelter. The field deployable environmental control unit provides air conditioning, and the Army space heater provides heating. Both are protected through the addition of a CB kit. Initial operational capability is projected for the second quarter of fiscal year 2001 (DoD, 1999; Siegel, 1998).

Portable Collective Protection System. The portable collective protection system was developed by the Marines to provide an uncontaminated, positive-pressure shelter for use as a command and control facility or a rest and relief facility. The shelter holds 12 to 14 people at a time and can be erected within 30 minutes by four people wearing MOPP 4 gear. The system includes a protective shelter, a support kit, and a hermetically sealed filter canister. The shelter consists of a tent and fly, and is divided into a main area and two smaller compartments, an entry area, and a storage area. The tent floor and fly are made of a saranaex composite material. An airlock allows for decontamination of entering personnel and for purging of chemical agent vapors. The support kit contains a motor/blower assembly that supplies air to the system and flexible ducts that guide the air to the hermetically sealed filter canister and then to the shelter. The hermetically sealed aluminum canister contains a gas filter and a particulate filter (DoD, 1999; U.S. Marine Corps, 1999b).

RDT&E Programs for Collective Protective Systems and Structures

Chemically and Biologically Protected Shelter. The chemically and biologically protected shelter is designed to provide a contamination-free, environmentally controlled work area for a battalion aid station moving up to three times a day or a division clearing station moving once every three days. This system will be a direct replacement for the M51 chemically protected shelter. It consists of a dedicated heavy high mobility multipurpose wheeled vehicle, a lightweight multipurpose shelter mounted on the back of the vehicle, a 300 ft^2 airbeam-supported shelter, and a hydraulically powered environmental support system. A high-mobility trailer is towed by the vehicle to transport the medical equipment and a 10kW tactical quiet generator set for auxiliary power. The chemically and biologically protected shelter can transport a crew of four and can be set up or taken down in 20 minutes in a conventional environment and 40 minutes in a CB contaminated environment. The airbeam-supported soft shelter is fabricated of a fluoropolymer/Kevlar laminate that is CB resistant, capable of being decontaminated, environmentally durable, and flame resistant. The chemically and biologically protected shelter can process 10 litter/ambulatory patients per hour in a CB environment. This system is presently in limited production; fielding is scheduled to begin in the fourth quarter of fiscal year 1999 (DoD, 1999; Siegel, 1998; U.S. Army Soldier Systems Center, 1997).

Joint Transportable Collective Protection System. The joint transportable collective protection system will be a modular shelter system that can process contaminated personnel through a contamination control area into a toxic-free area. The system, which will be expandable to meet changing mission needs, will consist of an environmental control unit, a filter/blower, and a power unit and can be used as a stand-alone structure or within existing structures. The system will protect against all CB threat agents, toxic industrial materials, and nuclear/radiological particulate matter for 30 days after initial agent exposure without a filter change. The development program for this system is scheduled to begin in FY 2000 (U.S. Army Soldier Systems Center, 1999).

Advanced Integrated Collective Protection System. The advanced integrated collective protection system is a fully integrated collective protection system designed for installation on tactical vans and shelters. Major system elements include an NBC survivable enclosure, a turbo-diesel engine/alternator, an advanced air filtration system, an environmental control unit, and a system control unit. It uses a deep-bed carbon vapor filter system for extended gas filter life. The filtration system has a mission life more than twice that of any filtration system currently in use. The combined components provide reductions in overall size, weight, and energy and eliminate the need for additional electrical power from the host system (DoD, 1999; Negron, 1998).

Modular Collective Protection Equipment (100-, 200-, 400-, 600-ft^3/min *Systems).* The modular collective protection equipment system is a family of equipment designed to provide positive-pressure NBC protection for a variety of vans, vehicles, and shelters. It consists of four different sized filter units, three different free-standing protective entrances, three integral protective entrances, a motor controller, and a static frequency converter. The equipment has common parts and mountings and interchangeable connections and accessories (DoD, 1998b, 1999).

ADVANCED FILTERS AND ADSORBENTS

The key to protection against chemical agents is to remove them from the individual's personal environment. Of the several methods that can be used for removal, trapping, and sometimes deactivating, agent(s) on filters and adsorbing materials is the most practical. Filters and adsorbents are used in filter cartridges for masks and in air purifiers for collective protection systems; adsorbents are also used to impregnate liners for the fabric of the JSLIST chemical protective ensemble. Filters can be improved by modifying fiber structures and by improving the integration of filters into protective systems. Improving the adsorbers in current use will be critical for protecting deployed forces in the future. Therefore, substantial R&D is being done to develop advanced adsorbers that will improve the chemical agent filtration capabilities of current single-pass filter systems as well as regenerative filtration systems (that are under development). Future filter systems with advanced adsorbents will be smaller, lighter weight, and less combustible. So far, some candidate materials have been identified, but complete investigations have not been done on the relationships between adsorption performance and adsorbent properties (e.g., pore structure, surface characteristics, and impregnant reactivity).

Filters

Current air-purification devices have two parts: (1) an aerosol/particulate-matter filter, and (2) a gas absorber. Typical specifications for a military air-purification device for individual protection are listed in Table 4-6 (Kuhlmann, 1998).

The aerosol/particulate-matter filter is built up of layers of glass fibers, and the space between the fibers is large in relation to the size of the aerosol/particulate matter in contaminated air streams. Consequently, a filter of this kind functions by attracting and retaining particles rather than by entrapping them. Attraction/retention is an important factor in protecting against some bioaerosols (e.g., the diameter of the bacteriophage 0-X 174 surrogate for the hepatitis C virus has a diameter of only 27 nm) (ASTM, 1993).

Early laboratory studies showed that porous fiber-type filters could remove 99.998 percent of a bacterial aerosol (Zuykova, 1959); tests of a medical field hospital showed that an ambient challenge as high as 100,000 organisms/ft^3 could be reduced to 0.015 organisms/ft^3 (Landsberg, 1964).

TABLE 4-6 Requirements for the C2 Air-Purification Device

Requirement	Specification
Aerosol efficiency	99.99 @ 32 lpm
Cyanogen chloride gas life	30 min @ 4,000 mg/m^3
Dimethyl methylphosphonate gas life	59 min @ 3,000 mg/m^3

Source: Katz, 1999.

Recent tests on a multistage bioaerosol filtration system at a large metropolitan medical facility showed that the filtration media remained effective after a year of continual operation (Fadem and Tsai, 1998). This system incorporated various aspects of Brownian motion, gravitational field, electrical forces, thermal gradients, turbulent diffusion, and inertial impaction. The microorganism genera found in the internal atmosphere of the facility at levels ranging from 100 to 200 colony-forming units/m^3 included acremonium, actionmycetes, aspergillus, bacillus, chysosporium, clasdosporium, micrococcus, mucor, penicillium, phoma, rhieopus, rhodotorula, staphylococcus, streptococcus, and gram-positive and gram-negative bacteria. Initial airborne fungal and bacterial levels of 187 and 40 colony forming unit per cubic meter were reduced to non-detectable levels after 24 hours of filter operation corresponding to 264 air changes in an 819 ft^3-room. Corona-charged, melt-blown polypropylene media (Electret AEM-1, AEM-2 and AFF-200) exceeded the threshold criteria for emery-oil penetration and pressure drop (Kuhlmann, 1998).

Absorbers

A gas absorber follows the particle filter to remove any gaseous toxic materials in the air stream and/or gases volatilized from particulate material retained by the filter. The gas-absorbing component of the air-purification device consists of activated carbon. Other absorbents have been evaluated, but none was found to be superior to activated carbon in removing chemical agents from contaminated air streams.

Activated carbon is produced by heating charcoal with carbon dioxide or steam at 800° to 1,000°C. The activated product contains numerous pores and cavities for trapping toxic gases in the contaminated air stream. The activated carbon used in most air-purification devices has a surface area of several hundred to more than a thousand m^2/g.

Some low molecular mass chemical agents, such as arsine (agent SA), hydrogen cyanide (agent AC), and cyanogen chloride (agent CK), are not strongly absorbed or retained by activated charcoal. Until recently, an activated carbon formulation containing compounds of copper, silver, and chromium (ASC carbon or Whetlerite) was used to physically absorb and chemically decompose these highly volatile chemical agents. Concerns about the potential inhalation of carbon dust containing carcinogenic hexavalent chromium and failure of the canisters to pass an Environmental Protection Agency submersion test, however, prompted a reformulation of the absorbent (Katz, 1990). The current gas absorber used in military air-purification devices is activated carbon treated with copper, silver, zinc, molybdenum, and triethylenediamine.

This type of bonded activated carbon was found to surpass the minimum CK and dimethyl methylphosphate (DMMP) gas life requirements for the C2 air-purification device (Kuhlmann, 1998). A 100-cm^3, 24-mm deep bonded carbon disc showed a 50 percent-longer-than-threshold-criterion CK gas life and nearly a 2.5-times-longer-than-threshold-criterion DMMP gas life. In addition, the pressure drop for the bonded carbon disc was 9.5 mm of water below the threshold criterion of 22.5 mm of water.

Carbon absorbents prepared from fullerene soot have been reported to be superior to charcoal-based absorbents for adsorbing halocarbons from humid gas streams (Bell et al., 1998). The soot, obtained from pyrolyzing a mixture of Carbon-60–Carbon-70 and higher fullerenes, was blended with a polymeric binder and pressed into discs prior to carbonization in an inert atmosphere. Compared to sorbents prepared from commercial carbon black, pellets from fullerenes had larger surface areas, longer breakthrough times, better dynamic capacities, higher adsorption rate coefficients, and greater transverse crush strength.

The absorption capacities of carbon fiber-based absorbents have been found to be greater than those of granulated activated carbons. The advantages of using fiber-based adsorbents in individual protection air-purification devices would be lower pressure drop, smaller volume, and lower mass. Carbon-loaded nanofibers prepared by electrospinlacing have been proposed for filter use but will have to be tested to demonstrate their applicability to the absorption of toxic gas in individual protection air-purification devices (Schreuder-Gibson, 1998).

Service-Life Indicators

Air-purification devices have finite capacities that limit their service life. A means for determining residual filter life after initial use or after prolonged storage has been and continues to be a subject of active research. Color-change indicators (Lielke et al., 1986) and liquid-crystal sensors (Henderson and Novak, 1992) were among the first approaches taken to monitor residual life. More recently, a SAW chemical sensor has been used to monitor the residual absorption capacity of in-service activated carbon air-purification devices (Dominguez et al., 1998). This small, rugged, sensitive sensor had a large, nonspecific dynamic range. Its surface was prepared with a 50-nm film of fluoropolyol prior to evaluating its ability to sense DMMP and thereby indicate exhaustion of its absorption capacity. The sensor successfully monitored DMMP breakthrough in real time without degrading the performance of the air-purification device.

SAW chemical sensors, as well as semiconductor devices and ion-mobility spectrometry, have been evaluated as filter life-indicator systems for air-purification devices in tanks and other armored vehicles

(Nieuwenhuizen et al., 1998). Ion mobility spectrometry was the most promising.

Regeneration

In the absence of a reliable service life indicator system, schedules for replacement have been developed. Pressure and temperature swing absorption is also being investigated as an alternative. The alternative system would have to be completely regenerable so that the absorbents would not have to be replaced, and the time the air-purification device operates in the absorption mode would have to be adjusted to ensure that the mass-transfer front of the most volatile impurity does not endanger personnel.

Activated carbon outperformed polymeric resins and molecular sieves in a pressure-swing absorption system for regenerating air-purification media used to collect chemical agents (Stallings, 1984). Optimal performance was obtained at a purge-to-feed velocity ratio of 1.5 during 40-minute operation cycles. Zeolites outperformed activated carbon when pressure-swing absorption was used in the nonisothermal, adiabatic mode (Chue et al., 1995).

Pressure and temperature-swing absorption has been used for the removal of water that competes with toxic substances for the absorption sites on activated carbon (Coombes et al., 1994). In tests of the pressure-swing system, water from composite air-purification devices consisting of layered Amberlite XAD-4 resin and two commercial activated carbons (Chemviron BPL F3 and Sutcliff Speakman Type 607) was completely recovered. Each two-hour operating cycle consisted of four 30-minute steps:

- absorption at 10 bar and 75 liters per minute
- depressurization to ambient pressure while heating to 125°C with 5 liters per minute countercurrent flow
- cooling to ambient temperature with 10 liters per minute countercurrent flow
- repressurization with 20 liters per minute countercurrent flow

In this study, regeneration appears to have consumed 75 percent of the operation time and nearly half of the purified air.

Catalytic Oxidation

Catalytic oxidation is being developed as an advanced technology for NBC collective protection. Studies have focused on the feasibility of integrating catalytic oxidation/environmental control unit technology into a combat ground vehicle (Cag et al., 1995). Some of the elements of a protection system are: a catalytic reactor; a high-efficiency particulate air filter; an acid gas filter; a heater; volume, mass, and power requirements; cleaning and maintenance systems; waste disposal; and thermal signature.

Activated carbon as a filter for some acid gases (HBr, HF, NO and NO_2) has been evaluated previously (Buettner et al., 1988). Subsequent work with NO-NO_x and 3X catalysts showed that the majority of acid gases were condensed with the water in the environmental control unit, thereby minimizing the need for treatment of the effluent stream (Rossin, 1996). AS-1 and AS-2 NO_x absorbers developed by AlliedSignal's Aerospace Division have been shown to satisfy the post-treatment filter uptake, capacity, and durability requirements of the catalytic oxidation/environmental control unit system (Renneke, 1998).

FINDINGS AND RECOMMENDATIONS

Finding. Current challenges used to evaluate protective equipment do not reflect changes in threat levels.

Recommendation. The Department of Defense should reevaluate its requirements for materiel development to protect against liquid and vapor threats and revise design requirements, if appropriate.

Finding. PPE modules (e.g., masks, garments, gloves) were designed as independent items and then "retrofitted" to create an ensemble. They were also developed without adequate attention to various human factors issues, such as the integration of PPE with weapon systems.

Finding. The most serious risk from most CB agents appears to be from inhalation. Current doctrine allows for Mask-Only protection, but the mask seal could be broken while advancing from Mask-Only to MOPP 4 status.

Recommendation. A total systems analysis, including human factors engineering evaluations, should be part of the development process of the personal protective equipment system to ensure that the equipment can be used with weapon systems and other military equipment. These evaluations should include:

- the performance of individuals and units on different tasks in various realistic scenarios

- the interface of the mask and garments and potential leakage during an "advance" from Mask-Only to MOPP 4 status

Finding. Although researchers have good data from human factors testing that identifies serious performance (cognitive and physical) limitations as a result of wearing PPE, they have been unable to adequately relate these deficiencies to performance on the battlefield.

Recommendation. The Department of Defense should place greater emphasis on testing in macroenvironments and controlled field tests rather than relying mostly on systems evaluations for personal protective equipment.

Finding. Although the seal of the M40 mask is much improved over previous mask models, seal leakage continues to be a critical problem. The leakage can be attributed to (1) problems with the interface between the seal and the face, and (2) improper fit.

Recommendation. Additional research is needed on mask seals and mask fit. The research program should focus on seals, fit, and sealants (adhesives). The duration/severity of leaks, if any, during transitions in protective posture from one MOPP level to another should also be investigated. These data would be useful for future studies on long-term health effects of low-level exposures. In addition, training to fit masks properly should be conducted for all deployed forces equipped with mission-oriented protective posture equipment.

Finding. Although mask fit testing has been shown to improve protection factors 100-fold, the Air Force and Army have only recently begun deploying mask fit testing equipment and providing appropriate training protocols and supportive doctrine.

Recommendation. Doctrine, training, and equipment for mask fit testing should be incorporated into current joint service operations. The Department of Defense should deploy the M41 Mask Fit Test kit more widely.

Finding. Leakage around closures in personal protective equipment remains a problem.

Recommendation. The Department of Defense should continue to invest in research on new technologies to eliminate problems associated with leakage around closures. This research could include the development of a one-piece garment, the use of barrier creams on skin adjacent to closure areas, and other technologies still in the early stages of development.

Finding. Current gloves reduce tactile sensitivity and impair dexterity.

Recommendation. The Department of Defense should evaluate using a combination of barrier creams and lightweight gloves for protection in a chemical and/or biological environment. Multilaminate gloves should also be further explored.

Finding. An impermeable garment system is believed to provide the most comprehensive protection against CB agents. But impermeable barriers cause serious heat stress because they trap bodily moisture vapor inside the system. Permeable systems, which breathe and allow moisture vapor to escape, cannot fully protect against aerosol and liquid agents.

An incremental improvement could be achieved by using a semi-permeable barrier backed with a sorptive layer. This system would allow the moisture vapor from the body to escape and air to penetrate to aid in cooling. The multilayer system would have some disadvantages, however. It would be bulky and heavy; and the sorptive layer is an interstitial space where biological agents could continue to grow because human sweat provides nutrients for growth of biological agents, which could prolong the period of active hazards. Countermeasures should be investigated to mitigate these problems.

Recommendation. The Department of Defense should investigate a selectively permeable barrier system that would be multifunctional, consisting of new, carbon-free barrier materials, a reactive system, and residual-protection indicators.

The carbon-free barrier materials could consist of: (1) smart gel coatings that would allow moisture/vapor transport and would swell up and close the interstices when in contact with liquid; (2) selectively permeable membranes that would allow moisture/vapor transport even in the presence of agents; (3) electrically polarizable materials whose permeability and repellence could be electronically controlled.

The reactive material could be smart, carbon-free clothing with gated membranes capable of self-decontamination. A reactive coating could also be applied to the skin in the form of a detoxifying agent (e.g., agent reactive dendrimers, enzymes, or catalysts capable of self-regeneration).

A residual-protection indicator would eliminate the premature disposal of serviceable garments and might also be able to identify the type of contamination. Conductive polymers could be used with fiber-optic sensors to construct the device.

Finding. Nanofiber technology is still in its infancy, and production capacity for nonfilter applications is not available in the United States or elsewhere.

Recommendation. The Department of Defense should evaluate the potential contributions of nanofiber technology to the development of personal protective equipment. An advanced protective garment should include nanofiber-impregnated yarn fabric or nanofiber/microfiber nonwoven fabrics.

Finding. The Department of Defense does not have enough collective protection units to meet the needs of deployed forces.

Recommendation. The Department of Defense should assess the needs of deployed forces for collective protection units in light of changing threats and the development of new personal protective equipment and provide adequate supplies of such equipment to deployed forces.