9

Personal Protective Equipment for Emergency Response, Decontamination, and Remediation

Know, first, who you are; and then adorn yourself accordingly.

Epictetus

What a strange power there is in clothing.

Isaac Bashevis Singer

Carelessness in dressing is moral suicide.

Honoré de Balzac

I base most of my fashion sense on what doesn't itch.

Gilda Radner

PERSONAL PROTECTIVE EQUIPMENT FOR EMERGENCY RESPONSE

The ultimate purpose of personal protective equipment (PPE) is to shield responders from the chemical, biological, and physical hazards that may

be encountered during operations involving hazardous materials. For any given situation, equipment and clothing can be selected that provide an adequate level of protection (Figure 9.1). It is important that users of PPE appreciate that no single combination of protective equipment and clothing is capable of protecting against all hazards; therefore, PPE should be used in combination with other protective methods. For example, engineering controls (ventilation, barrier emplacement, etc.) to limit chemical contact with personnel should be employed as additional measures for preventing exposure.

Protective clothing must be worn whenever the user may face hazards arising from chemical exposure. In the context of terrorism and WMDs, examples include the following:

- Emergency response to an industrial incident (leak/spill, explosion, fire)
- Terrorist incident (release of chemical, biological, radiological/nuclear, explosive materials)
- Chemical manufacturing and process industries

Figure 9.1 Proper protective equipment (PPE) is essential when working in hazardous conditions.

During an emergency response, the following activities require use of PPE:

Site Reconnaissance. The initial investigation of a hazardous materials incident is often characterized by a high degree of uncertainty, and will require the highest levels of protection.

Search and Rescue. PPE may be required when entering a hazardous materials area to retrieve a victim. Special considerations must be given to how the selected PPE may affect the ability of the wearer to carry out rescue.

Spill Mitigation. Entering a hazardous materials area to prevent a potential spill or to reduce the hazards from an existing spill (i.e., applying a chlorine kit on railroad tank car) will require PPE. Protective clothing must accommodate the required tasks without sacrificing protection.

Monitoring. PPE is needed for personnel who are observing a hazardous materials incident without entry to the affected site.

Decontamination. PPE must be worn by those applying decontamination procedures to personnel or equipment leaving the site. In general, a lower level of protective clothing is used by personnel involved in decon compared with those entering the hot zone.

The use of protective clothing can itself create significant wearer hazards such as heat stress and physical and psychological stress, in addition to impaired vision, mobility, and communication. In general, the greater the level of chemical protective clothing, the greater the associated risks.

RESPIRATORY PROTECTION SYSTEMS

Respiratory protection systems (i.e., respirators) protect the user by preventing inhalation of toxic airborne contaminants and/or by providing oxygen in an oxygen-deficient atmosphere. Many forms of respirators are available; however, the two primary classes are air purifying and supplied atmosphere respirators. We can further divide these classes into type of fit and mode of operation.

Type of Fit

So-called tight-fitting respirators include facemasks composed of flexible molded rubber, neoprene, or other materials. Designs include rubber or woven elastic head straps. Tight-fitting respirators are available in three basic configurations: (1) A quarter-mask covers the mouth and nose, and

the lower sealing surface rests between chin and mouth. (2) The half-mask fits over the nose and under the chin. Half-masks are designed to seal more reliably than quarter-masks, so they are preferred for use against more serious hazards (Figure 9.2). (3) The full-facepiece covers from the hairline to below the chin. The full-facepiece masks provide the greatest protection, usually seal most reliably, and provide eye protection as well (Figure 9.3) (U.S. DOJ, 2002).

Loose-fitting respirators enclose the head at a minimum. A typical configuration includes a hood, that is, a light flexible device covering only

Figure 9.2 Half mask air-purifying respirator.

Figure 9.3 Full-facepiece air-purifying respirator.

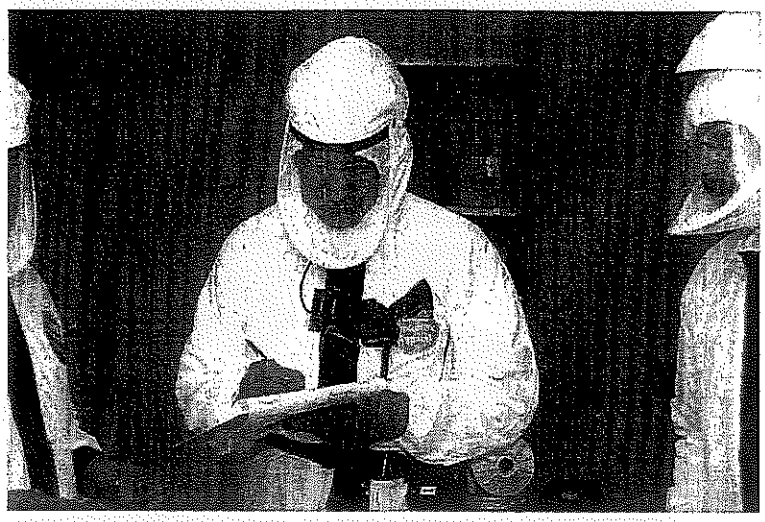

Figure 9.4 Hood respirator. (From U.S. Army Dugway Proving Ground.)

the head and neck (Figure 9.4). Since these respirators are loose fitting it is essential that sufficient air be provided to maintain a slight positive pressure inside the hood relative to the environment immediately outside. In this way contaminants are prevented from entering the wearer's breathing zone.

Air-Purifying Respirators

Air-purifying respirators (APRs) are of the tight-fitting category and contain a replaceable filter, cartridge, or canister that removes a specific contaminant by passing ambient air through purifying media before it is inhaled by the wearer (Figure 9.5). Elements that remove particulates are termed *filters;* those elements that remove vapor or gas are termed *chemical cartridges* or *canisters.* Two critical aspects regarding air-purifying cartridges must be made clear to the user:

1. These respirators do not supply oxygen. They can only be used when the atmosphere of the work zone contains sufficient oxygen to sustain life.
2. The concentration of the air contaminant must be below the concentration limits of the air-purifying element. Otherwise, the cartridge will quickly become saturated and will allow toxic vapors to break through to the user.

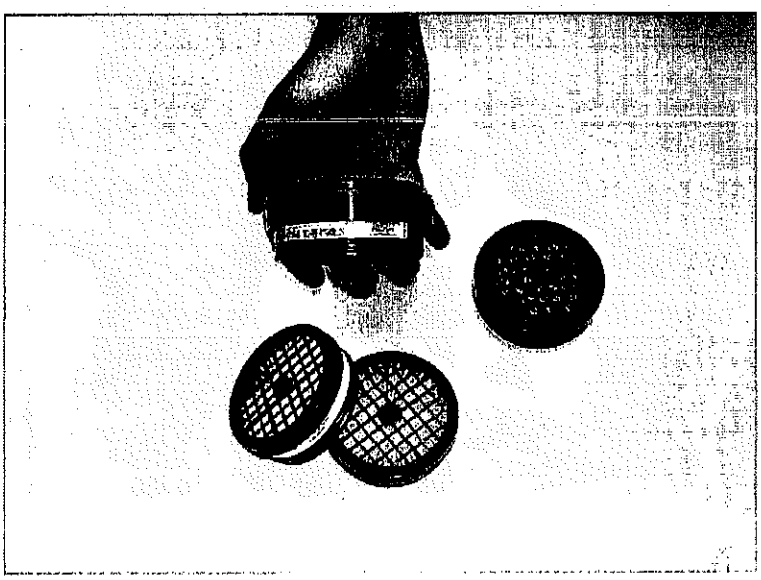

Figure 9.5 Cartridge used in APR. Cartridges can be selected for removal of a particular contaminant (e.g., hydrocarbon vapors, HCl, asbestos, etc.).

Filters and canisters are the key functional portions of APRs, and they can be removed and replaced once their effective life has expired.

APRs are grouped into three functional categories: particulate removing, vapor and gas removing, and combination. These respirators may be nonpowered or powered.

1. Particulate removing respirators are designed to reduce inhaled concentrations of harmful dusts and aerosols by filtering contaminants from inhaled air before they enter the breathing zone of the wearer. Different types of filtration technologies include (1) mechanical filters (high-efficiency particulate air (HEPA) and ultra-low penetration air (ULPA)); (2) electrostatic filters (which incorporate electrostatic charges into the filter medium); and (3) membrane technologies (which physically separate air particles based on their size and geometry). The simplest and least expensive (and least reliable) of the APRs are filtering facepiece respirators, commonly referred to as dust masks, disposable respirators, or single-use respirators (Figure 9.6).
2. Vapor- and gas-removing respirators use sorbent chemicals such as activated charcoal or catalysts to remove (*ad*sorb or *ab*sorb) specific gases and vapors from ambient air before they can enter the breathing zone of the wearer.

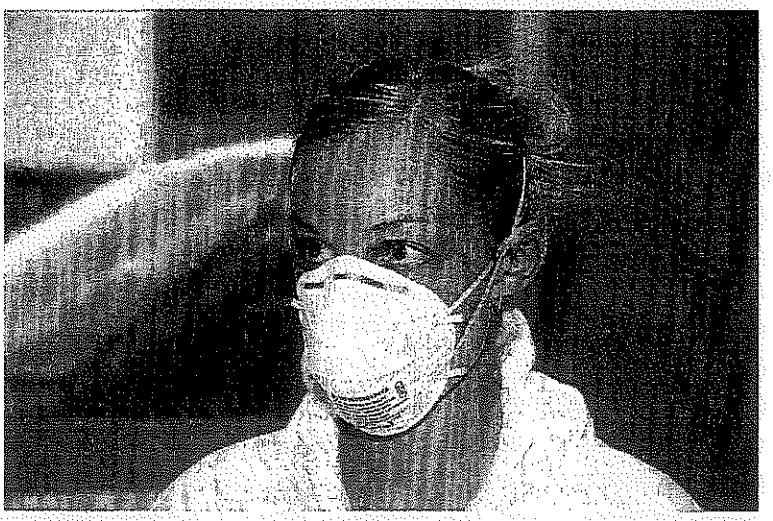

Figure 9.6 A dust mask is the simplest and least costly, but the least effective of all respirator types. (From U.S. Army Dugway Proving Ground.)

3. Combination cartridges and canisters are available to protect against particulates as well as vapors and gases. An example of a combined particulate and vapor removal technology is the C2A1 canister, a component of the M40 protective mask. The C2A1 canister contains a HEPA filter layered with a tetraethylene diamine activated carbon vapor filter.

Filtration Mechanisms

Some particulate filters use simple screening (sieving) to remove particles from the air; that is, they exclude the particles that are larger than the pores. These are termed *absolute filters*. Most respirator filters, however, are nonabsolute, which means they contain pores that are larger than the particles to be removed. Nonabsolute filters rely on a variety of mechanisms to remove particulates, including interception capture, sedimentation capture, inertial impaction capture, diffusion capture, and electrostatic capture. The filtration mechanisms that occur within the media depend upon the flowrate through the filter and particle size.

1. *Interception Capture.* As a stream of air approaches a fiber lying perpendicular to its path, it splits and compresses to flow around the fiber. If a particle in the airstream comes sufficiently close to the fiber surface, it is captured. As particle size increases, the probability of interception capture increases.

2. *Sedimentation Capture.* Only large particles (2 microns and larger) are captured by sedimentation. This type of capture relies on gravity to pull particles from the airstream. Flowrate through the filter must therefore be low.
3. *Inertial Impaction Capture.* As the airstreams split and change direction to pass around the fiber, particles with sufficient inertia cannot change direction sufficiently to avoid the fiber. Thus, they impact on the surface of the fiber. The size, density, speed, and shape of the particle determine its inertia.
4. *Diffusion Capture.* The motion of small particles is affected by air molecules colliding with them. The particles randomly cross the air stream and encounter the fiber as they pass. This random motion is dependent on particle size and air temperature. As particle size decreases and air temperature increases, the diffusive activity of the particle increases, which increases the probability of capture. Lower flow rate through the filter also increases probability of capture because the particle spends more time in the area of the fiber.
5. *Electrostatic Capture.* Target particles have a natural charge and filter fibers can be designed with the opposite charge. Therefore, the particles are attracted to the fiber surfaces. The electrostatic capture mechanism aids the other capture mechanisms, especially interception and diffusion (U.S. DOJ, 2002).

Mechanisms for Removal of Vapors and Gases

Vapors and gases are removed from cartridge respirators by a physico-chemical process termed *sorption.* In the cartridge, contaminant molecules come into contact with a granular, porous sorbent material. In addition to sorption, some respirators use chemical catalysts, which react with the contaminant to produce a less toxic vapor or gas (U.S. DOJ, 2002).

Three mechanisms are responsible for vapor and gas removal.

1. *Adsorption* retains the contaminant molecule on the surface of the sorbent granule by physical attraction. The intensity of the attraction varies with the type of sorbent and the characteristics of the contaminant. Sorbent molecules tend to have extremely large surface areas for reaction with the contaminant of interest.

   Adsorption by physical attraction holds the adsorbed molecules weakly. If chemical forces are involved, the bonds between

contaminant and sorbent granules are much stronger and can be broken only with difficulty.

Granular activated charcoal (GAC) is by far the most common adsorbent used in cartridge respirators. It is used primarily to remove organic vapors. Activated charcoal also can be treated with other substances to make it act selectively against specific gases and vapors. Examples are GAC impregnated with iodine to remove mercury vapor, with metallic oxides to remove acid gases, and with salts of metals to remove ammonia gas. Other sorbents that could be used in vapor- and gas-removing respirators include activated alumina and silica gel (U.S. DOJ, 2002).

2. *Absorption* involves the incorporation of a molecule deep within pores of the sorbing material. This mechanism can remove certain vapors and gases in addition to particulates. Vapor and gas molecules usually penetrate deeply into the molecular spaces throughout the sorbent and are held there chemically. Absorbents do not have as large a specific surface area as do adsorbing media. Furthermore, absorption tends to be slower than adsorption, which occurs instantaneously. Most absorbents are used for protection against acid gases. They include mixtures of sodium or potassium hydroxide with lime and/or caustic silicates.
3. *Catalysts* increase the rate of chemical reaction between substances without themselves changing. One catalyst used in respirator cartridges is hopcalite, a mixture of porous granules of manganese and copper oxides. A common ratio is approximately 3:1 manganese dioxide: copper oxide. Hopcalite speeds the reaction between carbon monoxide and oxygen to form carbon dioxide.

Within the respirator cartridge, vapor and gas removal is essentially 100% efficient until the sorbent's capacity to adsorb vapor and gas or catalyze its reactions is exhausted. Then the contaminant will pass completely through the sorbent and into the facepiece. This is termed **breakthrough**.

Powered Air-Purifying Respirators

Breathing in ambient air through an APR takes effort on the part of the user such that its use may eventually result in user fatigue. A powered air-purifying respirator (PAPR) uses a blower to force ambient air through the cartridge to the inlet. PAPRs reduce the burden caused by drawing air through the filter element, therefore allowing the wearer to breathe easier.

PAPRs have been designed in several different configurations. One design consists of the air-purifying element(s) attached to a small blower that is worn on the belt and is connected to the respiratory inlet covering by a flexible tube. The device is usually powered by a small battery, either mounted separately on the belt or as part of the blower. Some units are powered by an external DC or AC source. Another type of PAPR consists of a helmet or facepiece to which the air-purifying element and blower are attached. The battery is carried on the belt.

Supplied Atmosphere Respirators

Supplied atmosphere respirators provide clean breathing air from an uncontaminated source and separate from the surrounding atmosphere. Such respirators are tight-fitting, and are classified by the method used to supply air and the way in which the air supply is regulated. The principle classes of atmosphere-supplying respirators are self-contained breathing apparatus (SCBA) and supplied air respirators (SAR).

1. The SCBA (Figure 9.7) is quite similar to a SCUBA tank. Air is supplied from a compressed air cylinder through a full-face mask that is worn on the back. This generally allows greater movement than a SAR; however, the air supply is limited, typically to 30–60 minutes. These times may be cut in half if the wearer is subject to moderate to heavy workloads.
2. SAR (also called *airline respirators*) usually involve a facemask or hood connected by a hose to a stationary source of compressed air. The air is delivered continuously in a sufficient volume to meet the wearer's breathing requirements. There are limitations as to the length of the hose connection—most airline hoses extend no farther than 300 feet. There are also dangers of damage to or crimping of the hose.

Open-Circuit versus Closed-Circuit SCBAs

SCBAs are available as open-circuit systems or closed-circuit systems. Open-circuit systems exhaust the exhaled air to the atmosphere instead of recirculating it. The open-circuit SCBA utilizes a cylinder of compressed air that supplies air to a regulator, which reduces the pressure for delivery to the facepiece. The regulator is either mounted directly to the facepiece, or a flexible hose connects the regulator to a facepiece (Figure 9.8).

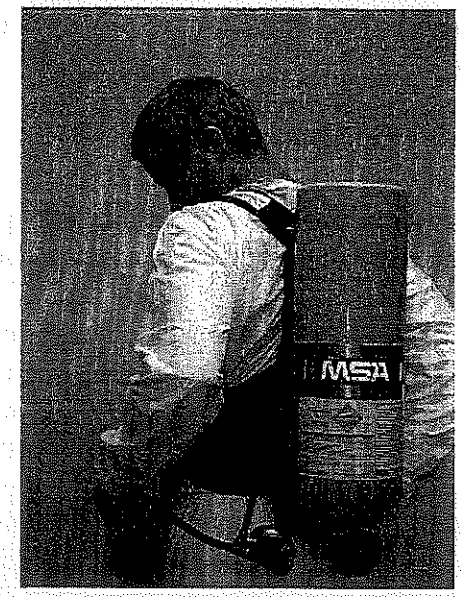

Figure 9.7 Air tank for self-contained breathing apparatus (SCBA).

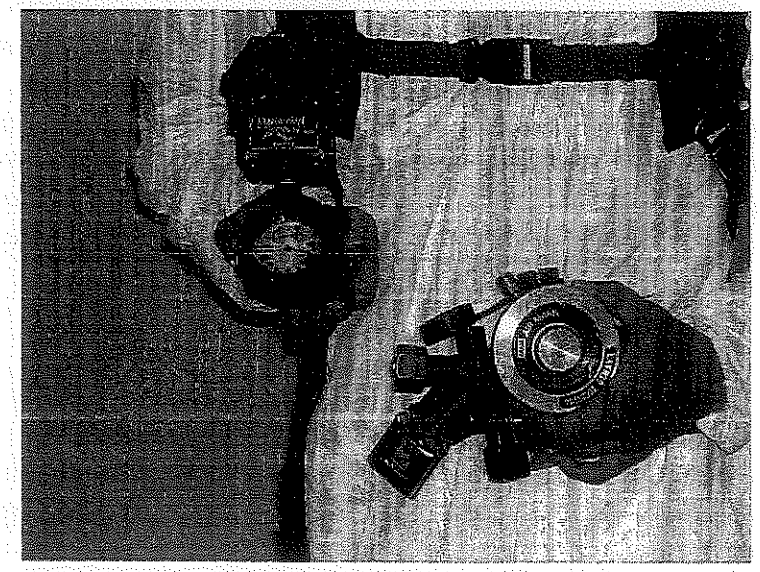

Figure 9.8 Standard regulator for SCBA.

Another name for a closed-circuit SCBA is a rebreather device. The breathing gas is rebreathed after the exhaled carbon dioxide has been removed (scrubbed) and the oxygen content restored by a compressed or liquid oxygen source or an oxygen-generating solid. These devices are

designed for one to four hours use in toxic and/or oxygen-deficient atmospheres (U.S. DOJ, 2002).

Airflow Regulators

Regulators within atmosphere-supplying respirators provide three types of airflow: demand (negative pressure regulator), pressure demand (positive pressure regulator), and continuous flow.

In a demand regulator, the air supply valve stays closed as long as there is positive pressure in the facepiece (during exhalation). Inhalation creates negative pressure in the facepiece, and the supply valve opens, allowing air into the facepiece. In other words, air flows into the facepiece only on "demand" by the wearer.

A pressure-demand or positive pressure regulator is similar to a demand type except for a spring that tends to hold the supply valve slightly open, theoretically allowing continual air flow into the facepiece. A combination of modified regulator and special exhalation valve is designed to maintain positive pressure in the facepiece at all times. Because of the positive pressure, any leakage should be outward; therefore, a pressure-demand system provides very good protection to the wearer.

Continuous-flow regulators maintain airflow at all times, rather than only on demand. By design, either the control valve cannot be closed completely, or a continually open bypass is provided to allow air to flow around the valve, maintaining a positive flow rate. Continuous-flow regulators are used only with SAR, not SCBAs.

THE PPE ENSEMBLE

There is no single "PPE suit," which is appropriate for all situations. Selection of PPE must include an ensemble of clothing and equipment that are integrated to provide both an appropriate level of protection and still allow the responder to carry out response activities involving hazardous materials. The primary components that may comprise the chemical protective ensemble are as follows:

- Protective clothing (suit, coveralls, hoods, gloves, boots)
- Respiratory equipment (SCBA, APR)
- Cooling system (ice vest, air circulation, water circulation)

- Communications device
- Head protection (hardhat)
- Eye protection
- Ear protection
- Inner garment
- Outer protection (overgloves, overboots, flashcover)

Levels of Protection

The U.S. Environmental Protection Agency, in collaboration with the Occupational Health and Safety Administration, has established four levels of protection in an occupational environment that are labeled A, B, C, and D. The levels described below are not strict ensembles and should be used as guidelines only; the levels should be adjusted to meet the needs of the responder and the situation.

Level A

The Level A suit provides the highest level of respiratory, skin, and eye protection from solid, liquid, and gaseous chemicals. The ensemble includes a pressure-demand, full-face SCBA, inner and outer chemical-resistant gloves, and chemical-resistant safety boots (Figure 9.9). Two-way radio communication is strongly recommended for this ensemble, as ordinary verbal communication is extremely difficult through the suit.

Level A is used in situations where the composition of the atmosphere is unknown. Level A is also used when the composition of the atmosphere has been identified and is found to have a high level of hazards to the respiratory system, skin, and eyes. Level A is required for operations

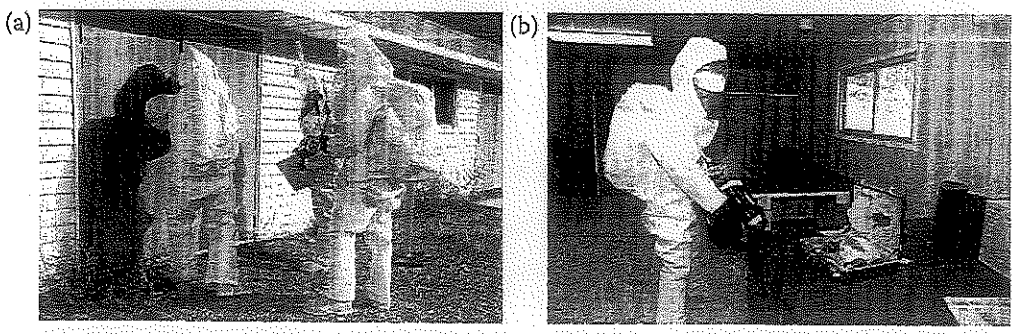

Figure 9.9 Two examples of Level A PPE. (From U.S. Army Dugway Proving Ground.)

conducted in oxygen-deficient locations, for example confined spaces or other poorly ventilated areas.

Optional components for the Level A ensemble may include a cooling system (e.g., an ice vest [Figure 9.10]), outer gloves, and a hard hat.

It is obvious that the Level A suit must resist permeation by the chemicals present at the response site. In addition, ensemble components must allow integration without loss of performance; for example, a respirator must fit within the hood of the Level A suit.

Level B

The Level B suit is used when the chemical(s) in the response zone have been identified and do not require a high degree of skin protection. The primary hazards associated with site entry are from liquid and not vapor contact. Level B provides the same level of respiratory protection as Level A, but less skin protection.

The Level B ensemble includes a liquid splash-protective suit, a pressure-demand, full-facepiece SCBA, inner chemical-resistant gloves, and chemical-resistant safety boots (Figure 9.11). As with the Level A suit, a two-way radio communication system is very useful.

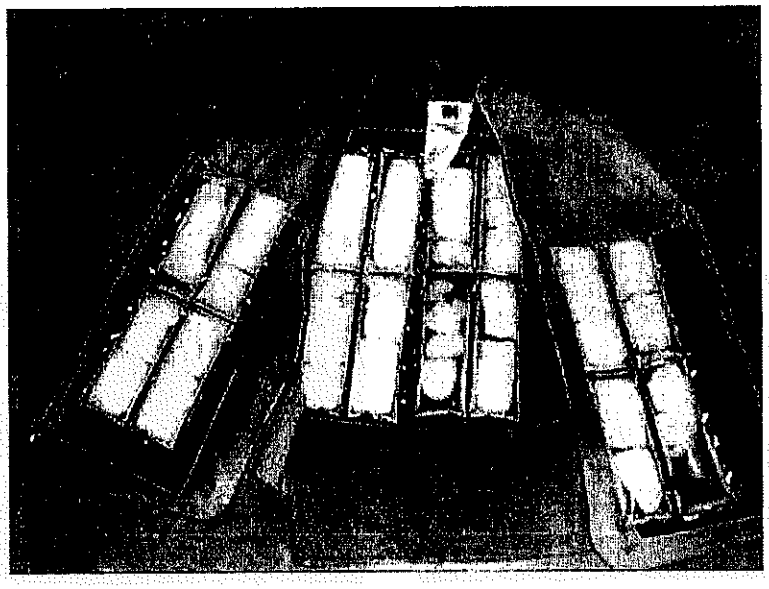

Figure 9.10 Ice vest for PPE ensemble.

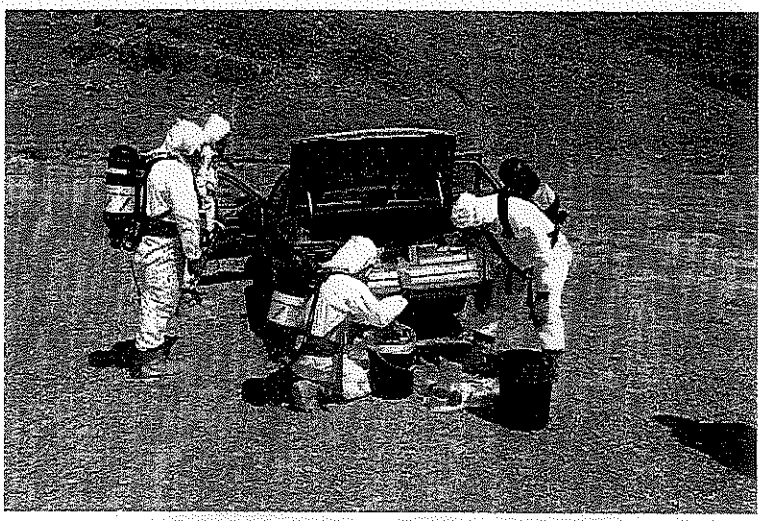

Figure 9.11 Level B PPE. (From U.S. Army Dugway Proving Ground.)

Level C

The Level C ensemble is used when contact with site chemical(s) will not affect the skin. In addition air contaminants have been identified, the concentrations measured, and airborne concentrations are less than immediately-dangerous-to-life-and-health (IDLH) levels. There is sufficient oxygen (at least 19.5% v/v), and an APR must be selected to filter out the specific atmospheric contaminants. The ensemble includes a protective garment (e.g., a lightweight Tyvek™ suit); a full-facepiece, air-purifying, canister-equipped respirator; chemical-resistant gloves; and safety boots (Figure 9.12).

The degree of skin protection provided by the Level C ensemble is the same as Level B; however, a lower level of respiratory protection is provided, via the APR. Level C provides minimal liquid splash protection but no protection against chemical vapors or gases.

Level D

The Level D suit is considered the standard, day-to-day clothing ensemble for responders. Level D is used when the atmosphere contains no known hazard (i.e., the atmosphere must contain at least 19.5% oxygen and concentrations of hazardous constituents are either negligible or below detectable limits). Work functions preclude splashes, immersion,

Figure 9.12 Level C PPE.

potential for inhalation, or direct contact with hazardous chemicals (Figure 9.13).

The Level D ensemble may include coveralls, safety boots/shoes, safety glasses, or chemical splash goggles. This level is not appropriate for emergency response and should not be worn in the hot zone.

Selection of Ensemble Components

What criteria should be used to select a certain level of protection? As we shall see, factors beyond those of the hazardous situation must be considered.

Chemical Hazards. Chemicals present a variety of hazards such as toxicity, corrosiveness, flammability, reactivity, and oxygen deficiency. Depending on the chemicals present, any combination of hazards may exist.

Physical Environment. The response site can occur in industrial or commercial settings, along highways or in residential areas. The environment may be extremely hot or cold. The exposure site may be relatively cluttered, presenting a number of physical hazards; chemical handling

Figure 9.13 Level D personal protective equipment.

activities may involve entering confined spaces, heavy lifting, climbing a ladder, or crawling along the ground. The choice of ensemble components must account for these conditions.

Duration of Exposure. The protective qualities of ensemble components may be limited to certain exposure levels. The decision for ensemble use time must be made assuming the worst case exposure.

Protective Clothing or Equipment Available. Ideally, an array of different clothing or equipment is available to responders meet all intended applications. Reliance on one particular clothing or equipment item may severely limit an agency's ability to handle a broad range of exposures. In purchasing PPE, the agency should attempt to provide a high degree of flexibility, while choosing protective clothing and equipment that is easily integrated and provides protection against most potential hazards.

Ease of Decontamination. The degree of difficulty in decontaminating protective clothing may dictate whether disposable or reusable clothing is used, or a combination of both.

Chemical Protective Clothing Standards. Buyers may wish to specify clothing that meets specific standards, such as 1910.120 or the NFPA standards.

Cost. Protective clothing end-users must endeavor to purchase the broadest range of protective equipment with available resources to meet their specific application.

Other factors that affect the selection of ensemble components include how each item accommodates the integration of other ensemble components. Some ensemble components may be incompatible due to how they are worn (e.g., some SCBAs may not fit within a particular chemical protective suit or provide for acceptable mobility when worn). Another example is the ease of interfacing ensemble components without sacrificing required performance (e.g., a poorly fitting overglove may greatly reduce wearer dexterity). Selection of ensemble components also affects donning time and complexity.

Chemical Resistance of PPE

There is no single material used in PPE which is 100% resistant to all hazardous chemicals. When entering the hot zone the chosen material(s) must resist permeation, degradation, and penetration by the contaminant chemicals.

Permeation is the process by which a chemical dissolves in or moves through a PPE material at the molecular level. Typically there is little visible evidence of chemicals permeating a material. Permeation breakthrough time is used to assess material compatibility with chemicals. The rate of permeation is a function of several factors, including chemical concentration, material thickness, humidity, and temperature. Most material testing is carried out using a concentrated form of a chemical over an extended exposure period. The time it takes the test chemical to permeate through the material is termed the **breakthrough time.** A material is considered acceptable when the breakthrough time exceeds the expected period of PPE use. However, the effects of temperature and pressure may accelerate permeation and reduce the safety factor. For example, small increases in ambient temperature can significantly shorten breakthrough time and the protective properties of PPE material.

Penetration is the movement of chemicals through zippers, seams, or imperfections in PPE material.

Degradation is the result of a chemical reaction between the contaminant and the protective material. Degradation involves physical changes in a material as the result of a chemical exposure, use, or ambient

conditions (e.g., sunlight). The most common observations of material degradation are discoloration, swelling, loss of physical strength, or deterioration. Degradation can cause the PPE material to shrink or swell, become brittle or very soft, or completely change its chemical and physical structure. Such changes may enhance permeation or allow penetration of the contaminant.

Tables are available indicating relative effectiveness of various protective materials against generic classes of chemicals (Table 9.1). Most tables only reflect the ability to resist degradation. Such tables are useful when used with discretion and when the degree of hazard is properly evaluated.

PPE Material Types

Decades of research have been devoted to engineering materials that can withstand chemicals ranging from simple industrial products to complex mixtures to highly destructive chemical weapons.

Table 9.1 lists the names of some commercial products that are used in the manufacture of certain personal protective clothing (e.g., gloves, suits). The list in Table 9.1 is not intended to be comprehensive.

Limitations with PPE Use

Wearing PPE is not without some inherent drawbacks. A number of practical factors must be considered when choosing PPE for a response activity.

Communication. Talking to team members while wearing PPE is difficult. This problem is especially apparent in the Level A ensemble, when the responder's face is covered with at least two layers, that is, the respirator mask and the encapsulating suit. Suitable communications systems (i.e., push-to-talk radios) are extremely useful in such situations. Otherwise, hand and arm signals are imperative. All signals must be agreed upon (and practiced) before site entry.

Recognition of Team Members. During a response problems may arise with recognition of support personnel; for example, when the entry team is suited up, how to recognize who is in charge? Also, multiple entry teams will want to recognize each member. To alleviate this problem, duct tape of a specific color or labeled using a marker can identify team

Table 9.1 Selected Commercial Products Used in Manufacturing PPE

Trade Name	Manufacturer	Description
4H™	Safety 4, Inc.	Multilayer laminate of polyethylene and ethylene-vinyl alcohol. Offers protection against exposure to many chemicals and mixtures
Barricade™	DuPont	A chemical barrier fabric (multilayer laminate) that provides excellent chemical resistance
Chemrel™	Chemron UK	Multilayered film barrier composites, laminated onto a soft polypropylene substrate; encapsulated suits made from different Chemrel (TM) fabrics are available providing protection against different chemicals and gases
Kevlar™	DuPont	Aramid (aromatic polyamide) fiber—tough textile fiber used in protective clothing where resistance to cuts, heat, bullets, or flying fragments is needed
Nomex™	DuPont	High-temperature-resistant aramid (aromatic polyamide) fiber; resistant to a wide range of industrial chemicals and solvents
Responder™	Life-Guard	Multifilm material designed to offer a high degree of permeation resistance to a broad range of chemicals; also used in level A protective suits
Saranex™	Dow Chemical Company	Multilayer coextruded film made from polyethylene, polyvinylidene chloride, and ethylene-vinyl acetate. Used as a coating for protective clothing
Silver Shield™	Siebe North Inc.	A laminate material that offers excellent protection against a wide range of chemicals and solvents but does not have good cut resistance. Can be used as an inner glove to enhance protection where cuts/mechanical damage are likely
Teflon™	DuPont	Fluorocarbon polymers made from tetrafluoroethylene or from a mixture of tetrafluoroethylene and hexafluoropropylene. Has excellent chemical and thermal resistance but poor physical strength properties; is combined with other materials in protective clothing

Table 9.1 Selected Commercial Products Used in Manufacturing PPE (continued)

Trade Name	Manufacturer	Description
Trellchem™	Trelleborg Protective Products AB	Trade name of a range of chemical protective suits. All are made with a polyamide fabric coated with different materials for the outside and inside layers offering protection against exposure to wide range of chemicals; some suits meet NFPA flammability test criteria. Examples of Trellchem materials: Trellchem HPS (High Performance Suit)™—Viton and butyl rubber outside, and a polymer barrier laminate inside Trellchem VPS (Vapor Barrier Suit)™—chloroprene rubber outside and a polymer barrier laminate inside Trellchem Super™—Viton™ and butyl rubber outside and butyl rubber inside Trellchem Butyl™—butyl rubber outside and inside Trellchem Light™—polyvinyl chloride outside and inside Trellchem TLU™—polymer barrier laminate outside and inside Trellchem TLU-A™—ensemble comprising an aluminized fiberglass fabric cover and a Trellchem TLUsuit
Tychem™	DuPont	Offers protection against exposure to wide range of chemicals and is more tear- and puncture-resistant than Barricade™ material
Viton™	DuPont Dow Elastomers	Series of synthetic fluororubbers, elastomers based on polymers made from hexafluoro-propylene and vinylidene fluoride or vinyl fluoride; other fluorocarbons may be used in some Viton™ products
Zetex™	Newtex	Clothing products are woven from highly texturized silica yarns—an alternative to asbestos for gloves, etc., for protection against heat, flames and sparks

Source: Canadian Centre for Occupational Health & Safety. 2005. Personal protective clothing—trade names, manufacturers. http://www.ccohs.ca/oshanswers/prevention/ppe/trade_name.html.

members. The Team leader may have a separate label on his/her shoulder or hood.

Other Practical Considerations

Donning. Properly donning PPE takes time. It is useful, if not essential, to have a team member (a "buddy") to assist in donning PPE.

Dexterity. Dexterity is greatly impaired by donning multiple pairs of gloves. It is therefore imperative for responders to prepare as much of their supplies and equipment as possible before entry into the hot zone. For example, fill in spaces on forms; have evidence labels clearly marked; peel back the outer layer of selected packaging.

Mobility. When wearing PPE movements are slow and sometimes difficult.

Impaired Vision. Due to the often narrow facepiece, peripheral vision is impaired.

Beyond the above practical difficulties are several significant risks associated with PPE use. Heat stress can occur even when working in an extremely cold environment. Level A and B ensembles do not allow for loss of perspiration (and hence cooling of the body). It is important to monitor core body temperature and blood pressure of all entry team members, both before and after response work. Team members must be sure to watch their buddies for any sign of heat stress. Psychological stress may also come into play during a response. Heavy, multiple-layer PPE can trigger a claustrophobic reaction in some. In others there is the simple fear of not being able to get out of their suits without assistance.

DECONTAMINATION

Decontamination may be defined as the reduction or removal of chemical or biological agents so they are no longer hazardous. Agents may be removed by physical means, they may be neutralized chemically, or they may be detoxified. Decontamination processes may be labeled based upon who or what is being treated:

- Oneself—personal decon
- Victims—casualty decon
- Responders—personnel decon
- Equipment and structures

In the event of a mass casualty incident (e.g., CBRNE attack or accidental industrial release), decontamination should be performed before victims are transported to a hospital. Hospitals should not accept patients who have not been thoroughly decontaminated, as they could possibly introduce hazardous substances to the facility.

Many hospitals and hazmat response teams have limited experience in handling large numbers of persons exposed to hazardous chemicals. A typical hazmat team will not possess the necessary numbers of personnel and will rapidly deplete the equipment needed to handle a CBRNE event, which may include hundreds of victims or more. At a mass casualty incident persons of all ages and both sexes will be affected. Victims may show symptoms of exposure to CBRNE materials and have traumatic injuries. In addition victims may have preexisting medical conditions, be untrained in emergency response, multilingual, or under extreme emotional stress, all of which will complicate a decontamination process.

TYPES OF DECONTAMINATION

Several decontamination approaches are available, depending on the incident and the persons or items exposed. The types of decontamination to be discussed in this section include mass, emergency, secondary, technical, and equipment.

Mass Decontamination

Mass decontamination refers to the rapid physical removal of agent from the skin of a number of contaminated victims, typically including the general public only (i.e., not responders) (Figure 9.14). Other terms associated with mass decontamination are emergency, gross, and immediate. The mass decon procedure must be performed as quickly as possible. A low-pressure, high-volume water system is recommended. High-pressure water systems are discouraged because contaminants may be forced into the victim's skin or spread further over the victim. High-pressure sprays can also spread contamination into the local environment.

One of the most effective methods for providing mass decontamination for large numbers of contaminated persons is the use of elevated master streams, using fog nozzles operating at low pressure to shower

Figure 9.14 Mass decontamination. (Used with kind permission of Santa Clara [CA] County Fire Department.)

Figure 9.15 Mass decontamination of civilians using ladder-pipe system. (Reproduced with kind permission from Globalsecurity.org.)

the victims. The ladder-pipe decontamination system has been shown to be highly effective for mass decontamination (Figure 9.15). A decon line using multiple hoses allows for a long corridor for decontamination that can accommodate numerous victims.

Other effective mass decontamination methods make use of facilities such as chlorinated swimming pools, school shower facilities, car washes, or other locally available facilities for rapid decontamination of a large number of victims (U.S. DHS, 2007).

Secondary Decontamination

Secondary decontamination is performed following mass decon and is performed on an as-needed basis. If a victim has received proper decontamination treatment and continues to display symptoms of contamination, a secondary decon may be necessary. This procedure may be applied only to limited areas of the body and is more thorough than mass decontamination (Figure 9.16).

Secondary decon can consist of one to several stations, depending on the degree of hazard. A decontamination team must be present to assist in the handling of victims and to supervise the operation. To control the spread of contaminants, low-pressure water should be used and overspraying and splashing should be kept to a minimum. The decontamination corridor should be established in a location where runoff can be contained and controlled.

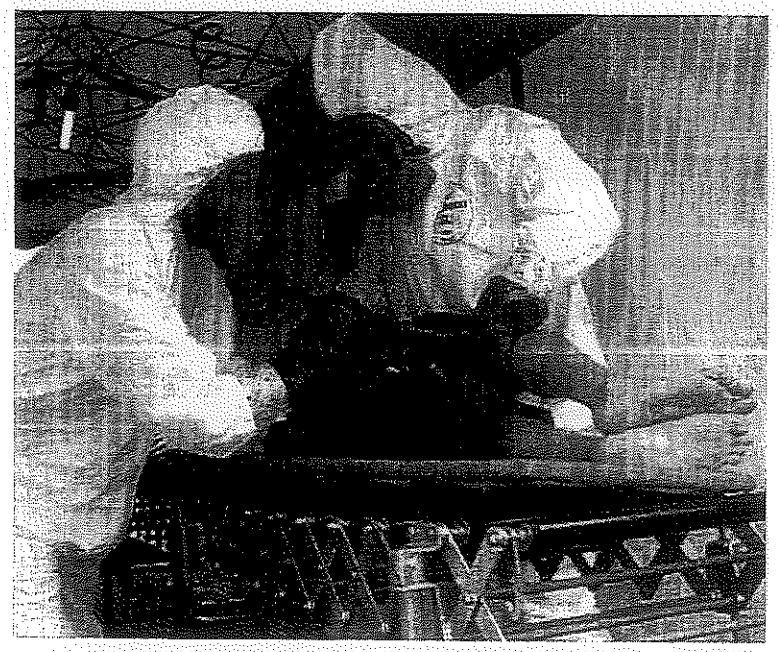

Figure 9.16 Secondary decon of a victim. (http://www.dec.state.ak.us/SPAR/perp/gallery/MassDeconJune2007/images/MassDecon_June2007_p009.jpg.)

Emergency Decontamination

Emergency decontamination can occur at any time during an incident response. Should an emergency occur during a response action (e.g., a responder collapses while carrying out assigned duties), immediate steps must be taken to manage the emergency, while practicing contamination avoidance. Speed is crucial in emergency decon.

Technical Decontamination

Technical, or definitive decontamination, refers to the carefully planned cleaning of response personnel and their equipment after they have completed their assigned duties. The goal of technical decon is to completely remove the agent from a responder's PPE. Responders are carefully and thoroughly cleaned using brushes, hoses, water and soap, and so on. (Figure 9.17). Technical decontamination should be performed on responders with their arms out and their legs apart (i.e., the "star configuration") (Figure 9.18). The responder should be washed from the top down; hence, elevated wash systems such as overhead showers are useful. Technical decontamination is not time-constrained, that is, there is no need to rush through the process. Technical decontamination should be conducted in a location separated visually from victim decontamination—this will avoid psychological stress to the latter.

Figure 9.17 Technical decontamination of emergency responders. (www.usarmy.vo.llnwd.net.)

Figure 9.18 "Star" configuration used in emergency decon.

Equipment Decontamination

Decontamination is not limited to victims and responders; all equipment that had entered the hot zone must also be decontaminated. Many such items pose practical problems.

Air monitoring and sampling equipment are often fragile and extremely sensitive to environmental conditions; for example, an atmosphere rich in hydrocarbon or acid vapors may permanently damage sensors and render the equipment inoperable. Such equipment are also difficult to clean without damaging, once they have been contaminated. Therefore, before entering the hot zone, personnel should carefully wrap sensitive instrumentation in plastic such that they will operate correctly (Figure 9.19). Trucks, bulldozers, backhoes, or other heavy machinery may require decontamination in certain situations. Such equipment is decontaminated using a high-pressure water wash, steam cleaning, and/or hand scrubbing with a decontamination solution (Figure 9.20). Runoff from the area must be captured by the prior installation of plastic in the decon zone. In addition, a sump system may be installed. Wipe tests of equipment are recommended to determine success of decontamination.

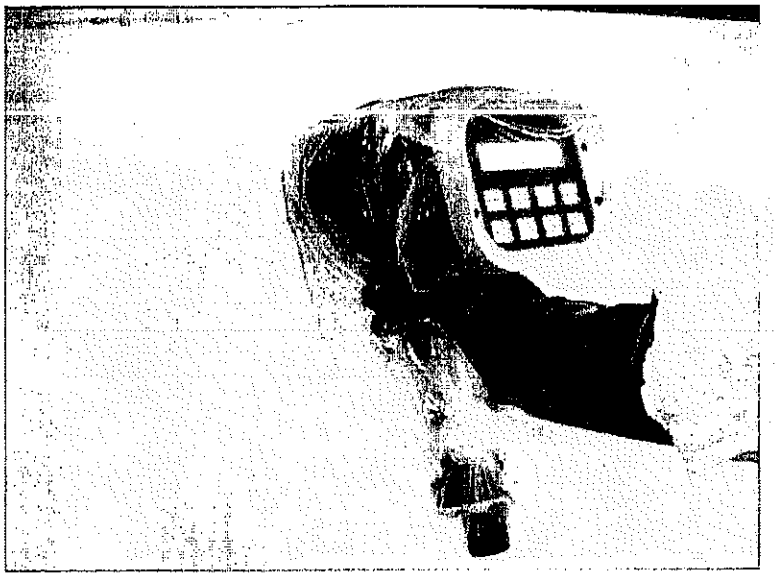

Figure 9.19 Wrapping sensitive air monitoring equipment in plastic will ensure that the instrument is not damaged in a hazardous atmosphere.

Figure 9.20 Equipment decontamination. (From DNR.WI.gov.)

Area Decontamination

Structures may only be slightly contaminated on a limited number of surfaces (e.g., pavement and building walls). In the case of surficial contamination, site cleanup may take the form of high-pressure spray-washing using specialized cleaning agents, to loosen contaminants for collection and treatment (Figure 9.21).

A series of stringent decontamination procedures were used at the Reston, VA, Primate Facility where 450 monkeys were destroyed when the ebola virus was discovered (Peters and Olshaker, 1997; U.S. DHS, 1995). The monkeys were disposed and supplies were incinerated, and all particulate matter was scraped from surfaces. Surfaces and drains were subsequently drenched with bleach. Thirty-nine electric frying pans were placed on timers and filled with paraformaldehyde mixed with water. Every seam in the building was taped and the paraformaldehyde was boiled off with a target atmospheric concentration of 10,000 ppm. The building was put up for sale but eventually demolished (Muller Vogt and Sorensen, 2002).

Decontaminating the fecal matter of the monkeys was a difficult problem. The U.S. Army Medical Research Institute of Infectious Diseases (USAMRID) proposed to soak the fecal matter in Clorox® and dump it in the sewer. However, Virginia environmental officials objected to putting the disinfectant down the sewer. Permission was finally given to proceed with the disposal when the Army informed the state that they would leave it for the state to dispose (Muller Vogt and Sorensen, 2002).

Figure 9.21 Decontamination of cars of the Tokyo Metro after the 1995 sarin attacks. (http://ehp.niehs.nih.gov/docs/2001/109-11/gas.jpg.)

DECONTAMINATION MEDIA

An ideal decontaminant will rapidly and completely remove or detoxify all known chemical and biological warfare agents (Baker, 1985; Chang, 1984; Hurst, 1997). Desirable traits of a skin decontaminant are listed in Table 9.2. A range of substances, many of which are commercially available, have been evaluated for possible use in decontamination of both PPE and skin. Household products have been investigated for decontamination of civilians and soldiers; for example, timely use of water, soap and water, or baking flour followed by wet tissue wipes have shown promising results.

Decontaminants should be acquired and stocked long before an incident. They must be accessible, clearly labeled, and routinely tested for viability (i.e., strength). Responder training must stress the importance of decontaminants, application methods, and possible risks of use (e.g., skin irritation). Several effective decontamination solutions and materials are discussed below.

Soap and Water

Both freshwater and seawater physically remove chemical agents from the body and from PPE; additionally, they serve to both dilute the contaminant

Table 9.2 Desirable Aspects of a Skin Decontaminant

Neutralizes all chemical and biological agents
Is safe, i.e., nontoxic and noncorrosive
Applied easily by hand
Readily available
Acts rapidly
Produces no toxic end-products
Stable in long-term storage
Stable in the short-term (i.e., after application)
Inexpensive
Does not enhance agent absorption through skin
Is non-irritating
Is hypoallergenic
Easily disposed with no hazardous residues

Source: Chang, A.M.H., *A Survey and Evaluation of Chemical Warfare Agent Contaminants and Decontamination.* AD-202525. Defense Technical Information Center. Dugway Proving Ground, UT, 1984.

and initiate hydrolysis of toxins. Unfortunately, however, chemical warfare agents tend to be of low solubility; therefore, water alone tends to limit agent hydrolysis rate (Chang and Ciegler, 1986).

When soap, particularly an alkaline soap, is used with water, the rate of chemical hydrolysis reactions increases. Soap and water serves as an effective and inexpensive decon solution. Whereas some personal decontamination solutions irritate the skin, are toxic and/or costly, soap and water pose no such problems for decontamination. According to the U.S. Army Medical Research Institute of Chemical Defense, timely use of soap and water followed by wet tissue wipes produced results equal, or, in some instances better than, those produced by the use of Fuller's Earth, Dutch Powder, and other decontamination compounds (U.S. DHS, 2007).

Sodium Hypochlorite

Sodium hypochlorite, the active ingredient in household bleach, is highly favored for disinfecting tools, equipment, and structures. Dilute hypochlorite solution should be made fresh daily with a pH in the alkaline range (pH 10–11). Plastic bottles containing calcium hypochlorite crystals are currently used by the military for this purpose.

Although dilute hypochlorite (0.5%) is an effective skin decontaminant, most responders have recently discontinued the use of bleach due to skin irritation. This effect is attributed to the oxidizing and corrosive properties of the hypochlorite ion. Concentrated mixtures may cause corneal injuries. Hypochlorite is not recommended for brain and spinal cord injuries (Hurst, 1997). Emergency responders must abide by jurisdictional requirements and consult with medical personnel to determine whether to employ bleach in patient decontamination operations.

Absorbents

Commercially available materials may be used to remove gross chemical contamination from surfaces. Several nonaqueous (i.e., without water) materials provide for contaminant removal; these are available in dry, gelled, or powdered forms. Common absorbents include soil, flour, Fuller's earth, baking powder, sawdust, charcoal, ash, activated carbon, silica gels, and clays. The effectiveness of these materials in removing contaminants varies substantially. Contamination transferred to the

absorbent material must be treated as contaminated waste and disposed appropriately.

The U.S. Department of Defense uses the M-291 and M-295 Skin Decontamination Kits, which employ a charcoal-based resin absorbent. The M-291 kit is considered highly effective as a dry decontaminant for skin (see Box 9.1). Both the M-291 and M-295 kits are typically effective in removing localized spots of liquid chemical agent; in other words, they may not be suitable for treating mass casualties. The small size of the decontamination pad and the time needed to clean large amounts of contamination from a victim may also limit its utility in the field.

Dry Powder Decontaminant

Some decontaminants incorporate dry powders for the absorption of toxins; for example, FAST-ACT®, a powder developed by NanoScale Materials, is designed to provide protection against and treatment for toxic chemical hazards. FAST-ACT is proven to remove more than 99.6% of VX, GD (soman), and HD (sulfur mustard) from surfaces in less

BOX 9.1 M-291 RESIN KIT

The M-291 Skin Decontamination Kit consists of a wallet-like carrying pouch containing six individual tear-open decontamination packets. This is sufficient to carry out three complete skin decontaminations. Each packet includes an applicator pad filled with a non-toxic/non-irritating decontaminating compound, Ambergard XE-555 resin (Rohm and Haas Co, Philadelphia, PA). The M-291 Kit is designed to completely decontaminate the skin through physical removal, absorption, and neutralization of toxic agents (Figure 9.22).

Each pad has a loop that fits over the hand. Holding the pad in one hand, the user scrubs the pad over contaminated skin. The chemical agent is rapidly transferred into and trapped in the interior of the resin particles. The presence of acidic and basic groups in the resin promotes the destruction of trapped chemical agents by acid and base hydrolysis. Given that the resin particles are black, it is easy to observe which areas have been decontaminated (Braue et al., 1997).

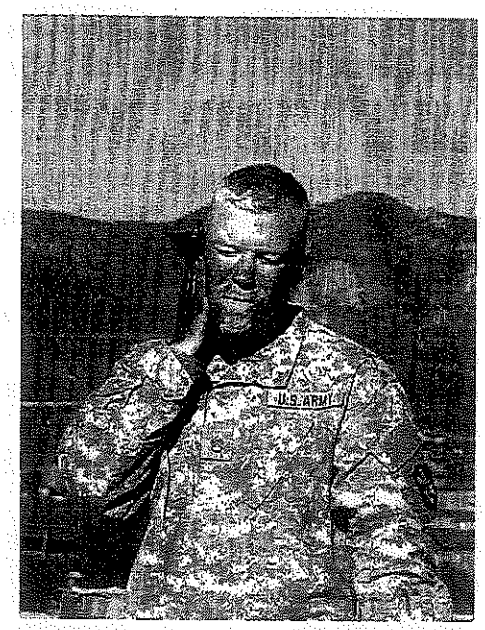

Figure 9.22 The M-291 Resin. (From Army.mil.)

than 90 seconds, converting the agents to relatively safe byproducts. FAST-ACT has also been demonstrated to neutralize acids and other TICs such as caustic gases, phosphorus compounds, and some organics (U.S. DHS, 2007).

It should be noted that natural processes may enhance decontamination. For example, high temperatures tend to increase the rate of chemical degradation. Agents may become dispersed by the wind, thus reducing concentrations on skin and PPE. Moisture (rain, etc.) tends to dissolve and sometimes break down chemical agents. In contrast, biological agents dehydrate in low humidity. The ultraviolet light occurring in sunlight may also serve to inactivate microbial pathogens and decompose certain toxins.

DECONTAMINATION CORRIDOR

Site control is an essential component of any hazardous response. Site control includes designation of work zones, for example, hot, warm, and cold. The primary purpose of the warm zone is to reduce contamination, thereby

allowing victims, responders, and equipment safe access from the hot zone out to the cold zone. The warm zone contains the decontamination corridor and any access control points through which personnel and equipment enter and exit the hot zone.

The size and design of the warm zone are based on conditions specific to the incident and the discretion of the Incident Commander.

Key variables include

- Physical conditions of the site (topography, drainage, buildings, obstructions, etc.)
- Physical, chemical, and toxicological characteristics of the chemical(s) present
- Contaminant concentrations measured in the field
- Weather conditions including wind direction
- Possible atmospheric dispersion of toxic chemicals as predicted by air dispersion models
- Potential for fire or explosion
- Adequate roads, power sources, and water

Additional factors regarding the site and the equipment to be considered include the following:

- Availability of decontamination facilities
- How will nonambulatory persons (handicapped, elderly) be accommodated
- Handling of animals, that is, are animals contained until after victims are decontaminated
- Visibility, that is, can all activity within the warm zone be observed
- Runoff of decontaminants and management of solid and hazardous wastes

A sample decon corridor is shown in Figure 9.23.

The decon corridor must be designed to provide adequate protection for the treatment of large numbers of victims as well as facilities for the technical decontamination of responders and their equipment.

The decon corridor should be of sufficient size within the warm zone and be placed upwind, uphill, and upstream of the hot zone.

Access control points must be established for the warm zone and the decon corridor. To limit the spread of contaminants, personnel and equipment should only move through these access control points.

Responders should make use of readily available materials and equipment for their setup. Examples include mobile trailers designed for mass

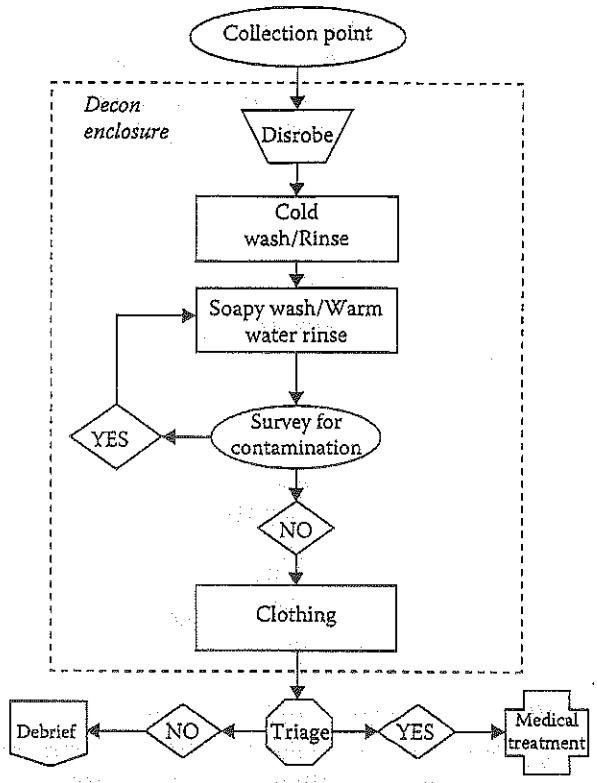

Figure 9.23 Example of a decontamination corridor. (From DHS.ODP.gov.)

decontamination, portable showers, and children's wading pools. Hoses can be set up overhead in corridors to provide a fine spray for victims to walk through. If a school or community center shower or pool (or even car wash) are accessible, these may be used for decontamination, using low-pressure, high-volume water. Equipment has been specifically designed for mass decontamination in which low-pressure, high-volume water sprays, or fog nozzles with low pressure can be sprayed on to victims.

DISPOSAL OF CONTAMINATED MATERIAL

All materials and equipment used for decontamination must be properly disposed. Nondisposable clothing (e.g., respirators, boots, gloves) must be completely decontaminated before removal from the warm zone. In many incidents responders will use disposable clothing. Such items must be bagged and labeled, and secured in drums or other stable containers.

These items are to be disposed with other contaminated substances from the site. Other items used at the incident such as brushes, tools, wash, and rinse solutions, which cannot be decontaminated must be secured in drums, labeled and disposed with substances having similar chemical contamination.

Environmental Concerns

Section 107 (d)(1) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), is often known as the "Good Samaritan" provision:

> No person shall be liable under this subchapter for costs or damages as a result of actions taken or omitted in the course of rendering care, assistance, or advice in accordance with the National Contingency Plan (NCP) or at the direction of an on-scene coordinator (OSC) appointed under such plan, with respect to an incident creating a danger to public health or welfare or the environment as a result of any releases of a hazardous substance or the threat thereof.

The above provision, however, does not preclude costs for damages caused by "gross negligence or intentional misconduct by the state or local government." Therefore, once all threats to human health or life are managed, responders should immediately make every reasonable effort to contain contamination and to mitigate environmental consequences. During decontamination, the obvious priority is to ensure that all victims are decontaminated. The second priority should be to contain runoff so that it does not contaminate the local environment. The IC should check with the state environmental agency or the EPA OSC for guidance regarding disposal options. All areas that had been contaminated should be marked for remediation.

SITE REMEDIATION

Previous chapters have addressed the effects of chemical, biological, radiological/nuclear, or explosive (CBRNE) attacks and/or industrial releases on human health, and, in the case of nuclear and explosive releases, on structures. At this point it is necessary to address how to decontaminate a site affected by CBRNE weapons or industrial chemicals. Residual chemicals may pose both short- and long-term effects on human populations and the environment, and must be removed and/or stabilized quickly to prevent harm.

As mentioned above, structures may only be slightly contaminated on a limited number of surfaces. In more extreme cases, however, contamination may be extensive—chemicals or other toxins may saturate soil and may percolate to significant depths and ultimately contaminate groundwater. Surface water bodies and vegetation may become saturated with chemicals as well.

Such sites are contaminated to a point that intensive cleanup (**remediation**) practices are necessary to restore it to a safe and usable condition.

Environmental Site Assessment

The first key step involved in complete and efficient site remediation is assessment of the degree of hazard. Specifically, this involves identification of site contaminants along with the location of contamination (both aerial and with depth). In the case of actual or suspected long-term industrial releases the conventional procedure is to conduct a Phase I Environmental Site Assessment (ESA) followed by a Phase II and finally site remediation. The Phase I ESA is a study of the historical use of the site and the materials used, generated, and stored on-site. Such information will provide a guideline for eventual sampling and chemical analysis of environmental materials. The Phase II ESA involves detailed sampling of soil, sediments, surface water, groundwater, building materials, and other relevant site attributes to provide an accurate picture of where the chemicals of interest are occurring at the affected site.

In the case of a single significant release of an agent by a terrorist group or industry, the Phase I ESA can be omitted, as historical information about the site may not be relevant. The Phase II, however, will provide scientists, engineers, and planners with a detailed snapshot of the site regarding soil and geologic attributes, where the contaminants are occurring, and, ultimately, how to remove them. The Phase II will provide recommendations as to how to address site cleanup (Figure 9.24). On the basis of soil, landscape, geologic, hydrologic, and numerous other practical considerations, decisions can be made as to how to best address cleanup goals.

Remediation Process

Techniques for removal of a hazardous agent from soil and ground water have evolved greatly over the past two decades; gone are the days when simple soil removal is considered appropriate in all cases. Innovative

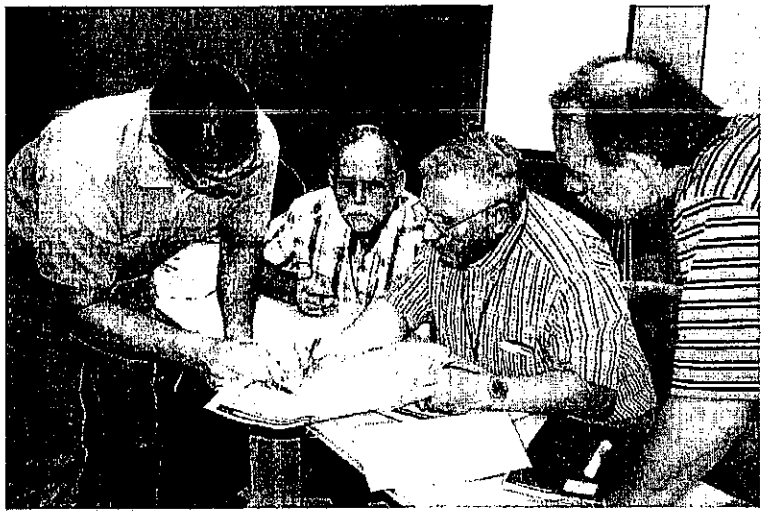

Figure 9.24 Substantial planning among scientists, engineers, planners, and other stakeholders may be required before conducting a remediation activity. (From FEMA.gov.)

technologies employ the use of sophisticated engineering systems, use of exotic chemicals or extremely high temperatures; however, others rely on natural solutions, for example, the use of microorganisms and/or plants to clean a site. This section provides a very brief overview of some selected remediation technologies for sites affected by CBRNE agents. The published literature, plus web sites offered by the U.S. EPA, state environmental agencies, and private environmental firms provide many more options.

Basics

Soil Removal

Among the most straightforward methods to remedy a site affected by hazardous substances is to excavate and relocate the contaminated soil. Backhoes, bulldozers, and other conventional earth-moving equipment remove the soil (Figure 9.25) and transfer it to a secure disposal facility, that is, an engineered landfill equipped with impermeable liners and leak detection systems. Drawbacks to this method are that it is expensive and may actually create new hazards, by causing soil and dust to disperse into the air and be carried significant distances. Ultimately, the contaminant is not being destroyed; rather, it is simply being relocated from one place to another.

Figure 9.25 Soil excavation and removal is often considered a last resort for site remediation. (From EPA.gov.)

Soil/Sediment Incineration

In cases of contamination with highly toxic yet combustible chemicals (e.g., chemical warfare agents) and biological agents (cultures, spores, etc.), excavated soils can undergo controlled incineration. Incineration units can be stationary facilities, or mobile units can be transported to an affected site. The contaminated media may need to be sieved or otherwise cleaned of large debris (logs, tires, etc.) before charging and loading into the unit. The incineration chamber is designed to operate at temperatures sufficiently high to destroy most hydrocarbon compounds (approximately 1800–2000°F, higher for some halogenated substances). It is essential that flue (waste) gases be captured and treated, as necessary, to remove toxins such as halogenated gases, mercury, and other volatile wastes. The residual ash will also need to be tested for potential toxicity and disposed of accordingly.

Pump-and-Treat

Should groundwater and/or surface water be contaminated by the toxin, the water can be extracted via wells and pumps and transported via pipeline to a designated treatment area. The water is chemically and/or biologically treated to destroy the contaminants of concern. Treatment

may be as simple as applying pulverized limestone (e.g., to neutralize acids) or addition of microbial cultures and oxygen (to destroy certain explosive residues, nerve gases, or other carbon-containing toxins). More complex and/or **recalcitrant** (resistant) compounds can be removed from water by passage through a large bed of absorbent material such as activated charcoal or synthetic resin. A key disadvantage of pump-and-treat technologies is that the process may take years for removal of significant contamination from groundwater. Furthermore only a portion of the contaminant will be removed; much will remain attached (adsorbed) to soil materials such as clay, organic matter, and hydrous iron oxides. These latter contaminant phases require more rigorous treatment technologies for removal.

Chemical Treatment

Hazardous chemicals can be extracted from the site, or they can be fixed in place. The decision depends in part on the toxicity of the contaminants. In the case of VX, a highly toxic nerve agent, which is also highly persistent, it is critical to remove and/or destroy the contaminant. In contrast, if a single "hot spot" of a radionuclide occurs in soil, the optimal procedure may be to immobilize it in place.

Soil Washing/Flushing. Soils contaminated with toxins can literally be washed; in other words, a solution of appropriate chemical formulation is applied to a site to flood it. The goal is for the contaminant to dissolve in the washing solution and percolate downward, where it is collected in strategically placed wells and underdrains (Figure 9.26). This technology

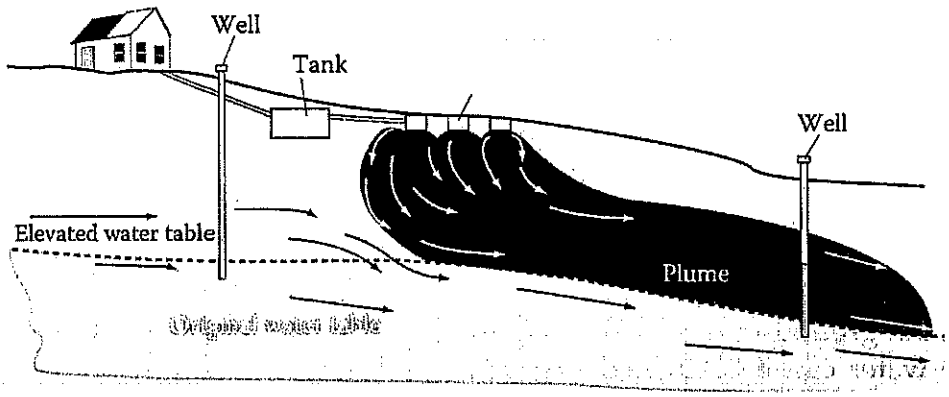

Figure 9.26 Basic soil washing technology. (From EPA.gov.)

is subject to interferences and complications; for example, the contaminant of concern may adsorb tightly to soil and not be readily solubilized by the washing solution; in addition, improper placement of recovery wells may actually cause the contaminant to migrate off site.

Destruction in place. Certain contaminants, particularly hydrocarbon-based substances such as explosive residues and nerve gas, may be destroyed by the addition of selected chemicals to the soil. Oxidizing or reducing chemicals can be pumped underground directly into the contaminant plume. Ozone (O_3) and concentrated hydrogen peroxide (H_2O_2) are extremely effective for hydrocarbon destruction by the process of oxidation, that is, addition of oxygen to the contaminant of concern. Once these compounds react with the plume, ideal products would include carbon dioxide and water (plus heat). However, not all contaminants will decompose completely in the presence of oxidizing agents; in some unusual cases, the contaminant will react with an oxidizing agent to generate even more resistant and hazardous chemical forms.

Fixation in Place

For certain compounds that occur in relatively small areas and may be highly toxic (e.g., an accumulation of VX nerve gas or high-level radioactive debris), it may be best to "fix" the contaminant in place. Depending on chemical composition of the contaminant, solidification/stabilization can take place using fixative materials as simple as Portland cement (for aqueous-based contaminants) or asphalt or polyethylene (for hydrocarbon-based contaminants) (Figure 9.27).

For situations in which the contaminant is extremely toxic and thereby precludes the possibility of removal (for example soil affected by plutonium debris), soil can be **vitrified** by heating to extremely high temperatures. A series of electrodes are placed into the ground and a voltage passed between them. The soil heats to the point that it fuses to a bright viscous orange mass (typical temperatures of 2900–3600°F) (Pichtel, 2007). Carbon-based contaminants (e.g., chemical weapons, biological agents, explosives) are destroyed in the melt by thermal processes. Potentially hazardous gases that may be released (e.g., fluorine from sarin destruction) are captured in a fume hood. The voltage is subsequently shut off, allowing the mass to cool and harden to a glassy material (Figure 9.28). Those contaminants that are noncombustible (e.g., radioactives) are securely retained in the glass. Given the very high cost of the technology, its application is limited to situations of contamination by highly toxic substances.

Figure 9.27 Solidification of contaminated soils using Portland cement is highly effective for fixing toxic materials in place. (From EPA.gov.)

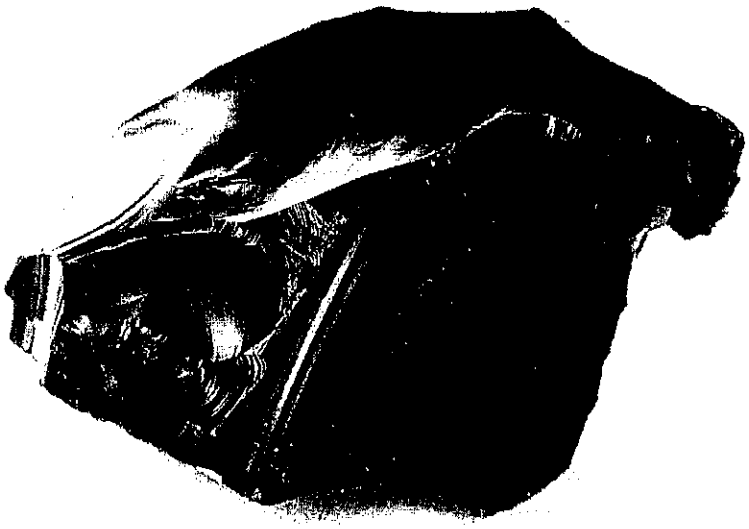

Figure 9.28 Following in situ vitrification, the affected soil is converted to a solid block of glass-like material after cooling. (http://srnl.doe.gov/images/vitrification.jpg.)

Biological Treatment

Microbial Remediation

Microorganisms that occur naturally in soils, sediments, and water can be employed to decompose hydrocarbon-based contaminants. Soil bacteria and fungi are particularly well suited to degradation of carbonaceous substrates; the energy and carbon extracted are used for the benefit of the microbial cell. So-called bioremediation processes have been in use for decades to treat sites contaminated with crude oil, fuels, solvent wastes, pesticides, and other toxic and recalcitrant compounds; additionally, bioremediation has shown success in the decomposition of explosives and their residues. It is also feasible to apply bioremediation to soils affected by chemical weapons such as nerve agents and blister agents.

Engineered bioremediation processes may be relatively simple and involve the injection of nutrients and oxygen to indigenous populations of soil microorganisms occurring at the site of contamination. Additives may be applied to a substantial depth below the land surface (Figure 9.29) or directly at the surface. The ultimate goal is for the microbial populations to use the hydrocarbon contaminant (explosive, VX, sulfur mustard, etc.) as sole carbon source, leaving behind simpler, less toxic compounds such as carbon dioxide and water. A simplified reaction showing the bacterially catalyzed decomposition of TNT is shown in Figure 9.30.

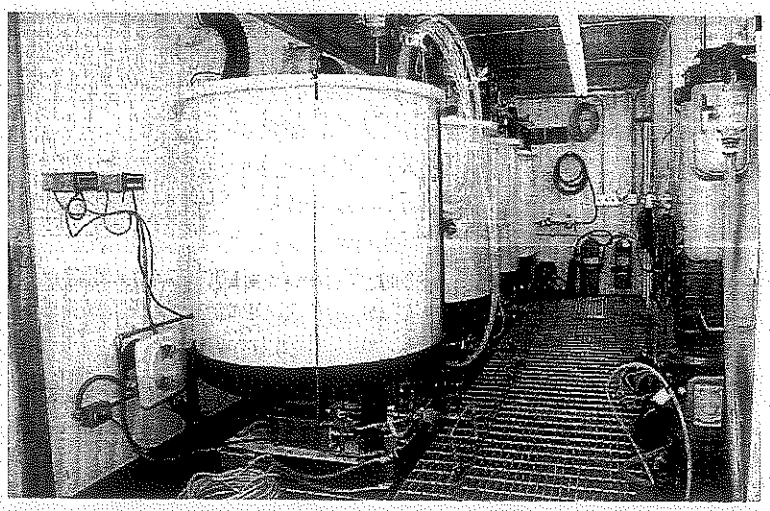

Figure 9.29 Nutrient injection tanks, pumps, and related equipment in a process trailer for an in situ bioremediation program. (From Battelle/Pacific Northwest National Laboratories [pnl.gov].)

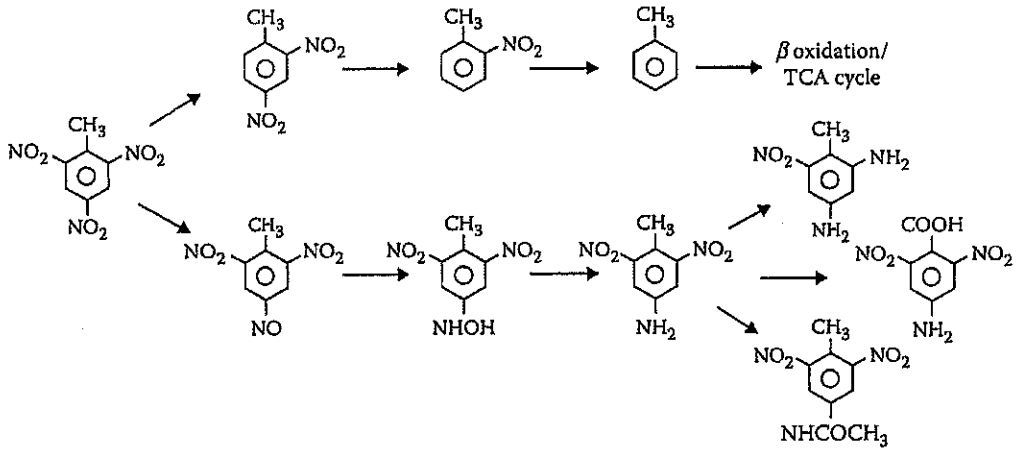

Figure 9.30 Reaction showing the bacterially catalyzed decomposition of TNT.

Current research in biodegradation of chemicals is focusing on identification of organisms or mixed microbial populations with broad degradation capabilities. Much work is devoted to genetic engineering of bacteria and fungi to provide them with the capability of accelerated decomposition of target compounds.

Phytoremediation

Plant-based remediation (phytoremediation) involves the use of green plants, selected for a specific capability, to remove and/or destroy hazardous compounds in place.

Phytoextraction. Certain plants have been identified with the ability to hyperaccumulate metals such as lead and mercury (both of which occur in primary explosives) (see Chapter 6). Others can hyperaccumulate radioactive metals from soil. Hyperaccumulation is defined as the extraction, uptake, and storage of soil metals in plant tissue in extremely high concentrations (Figure 9.31). The metal- or nuclide-enriched plant tissue must be harvested at the end of the growing season and chemically or physically treated to remove the metals. Treatment may involve ashing followed by acid extraction of the metals, or smelting in a furnace to recover the contaminant of concern. Alternatively, the metal or nuclide-enriched plant tissue can be compacted and disposed as a hazardous waste.

Rhizosphere-Enhanced Degradation. Green plants possess highly active microbial populations within the **rhizosphere** (i.e., root zone). In addition, the rhizosphere harbors a much greater microbial diversity (i.e., more microbial types and physiologic processes) compared with nonvegetated

Figure 9.31 Phytoremediation is a very promising, low-cost technology that can be used for the destruction and/or removal of soil contaminants.

soil. In many cases the microbes present in the root zone carry on the identical reactions listed above for bioremediation (dehalogenation, breakdown of complex organic compounds, etc.); however, rhizosphere microbes proliferate due to the abundance of compounds exuded from the plant root. Microbial reactions may be more rapid and efficient and result in more complete decomposition of the target contaminants as compared to processes in nonvegetated soil. The combined decomposition processes carried out by green plants in concert with soil microbes is termed **rhizosphere-enhanced degradation**.

Obviously, success of phytoremediation is limited by depth—the process will work only where roots can effectively reach the contaminant.

Other Innovative Technologies

Extensive research at laboratory-, pilot-, and field-scale continue to offer more effective, efficient, and rapid technologies for the destruction of highly toxic compounds, including various weapons and their debris, in soil, sediments, and groundwater.

Plasma Incineration

Conventional incineration typically works at operational temperatures of 1800–2000°F; however, there are situations in which a highly toxic and/or

recalcitrant chemical may require significantly higher temperatures to ensure complete destruction.

A plasma torch produces an arc that directly contacts a conducting portion of a specialized reactor vessel. The heat generated by the plasma torch brings the feed material to temperatures sufficient to melt soil (typically about 3000°F; however, temperatures as high as 50,000°F have been documented). This intense heat melts contaminated soil, incorporating any inorganic and metal components into a stable material. Organic components are volatilized by the heat of the plasma and oxidized by the air. Oxygen may also be added in the plasma chamber to enhance combustion of organics (U.S. EPA, 1992). As with conventional incineration, there is still a need to capture waste gases and ash, as these may themselves pose toxicity hazards.

QUESTIONS

1. Explain how permeation of a hazardous chemical into PPE differs from degradation and penetration. Provide examples of each.
2. A wide range of material types are available for PPE, depending in part upon the chemicals a responder may encounter. What suit materials are appropriate for exposure to HCl vapors, vinyl chloride vapors, asbestos particles, and CCl_4? Check the web site of several vendors of PPE to support your response.
3. Complete the table given here. Which level of PPE would be appropriate for the following hazardous situations?

Contaminant in Atmosphere	PPE Level
Unknown	
Nerve agent (sarin)	
Blister agent (sulfur mustard)	
Blood agent (HCN)	
Choking agent (chlorine)	
Biological agent (anthrax spores)	
Radiological particulates	
No contaminant; $[O_2]$ = 14.5%	

4. Compare and contrast the following decontamination modes: mass, emergency, and technical. How do they differ in terms of persons treated (i.e., citizens/responders)? Time constraints?

5. Describe the operation of the M-291 skin decontamination kit. What is the active ingredient, and how does it work?
6. In the mass decon of a large group of males and females, how could you set up a decon system allowing for maximal privacy with minimal availability of supplies? Draw an example of the decon train.
7. Identify three things you should do when checking a vehicle and its cargo for contamination before transitioning from a contaminated zone to an uncontaminated zone.

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