A. Design Philosophy

Through the years, the safety-design philosophy for hazardous radionuclides has evolved into the central theme "containment and concentration." Contain the process to ensure a barrier exists between the worker and the toxic substance. Then, if the barrier breaks down, concentrate or confine the released material to a limited area. This philosophy implies the need for multiple barriers. The containment protects the worker from the hazards of the material. A source enclosed in a capsule would be a simple means of containing or enclosing the material. Sometimes, both the substance and the process need to be contained, and enclosures such as gloved-hoods, gloveboxes, hot cells, and other structures are used.1-6

In Figure 16.1, a train of glovebox systems is shown. Transfer of hazardous material between modules is carried out through transfer ports, so that the worker remains in a different environment from the hazardous radionuclide. In the case of pyrophoric (spontaneous ignition) materials, such as finely dispersed plutonium or uranium, the glovebox atmosphere is an inert gas such as nitrogen. The gloves are usually made of neoprene or butyl rubber, which may have special coatings (hypalon) for acid protection or may contain lead for shielding purposes.6

Depending upon the degree and type of hazard, one may require a completely enclosed compartment as shown in Figure 16.1, or, for low hazard applications (i.e.-low radiotoxicity, non-pyrophoric and low external radiation), an open hood with no shielding.2,3 When the radiation hazard from the material becomes great enough, gloveboxes, even when shielded, may not be adequate. In this case, recourse is made to large, heavily shielded enclosures, called hot cells or caves, which are often supplied with thick concrete walls and lead-glass shielded viewing windows. Operations are performed with the use of manipulators, see Figure 16.2, which allow the operator to perform the necessary operations on the highly radioactive substance. In some cases, in-cell gloveboxes may be used,3 for highly radioactive α material such as occurring in trans-plutonium element research.
Figure 16.2 Manipulators on a hot cell.
Containment refers to the barriers for preventing the release of the radioactive substance. However, a release should not result in the discharge of a hazardous amount of the contained substance from the facility. This requires the presence of other systems to concentrate any release of contained material when an accident occurs. Proper design of airflow patterns and tandem exhaust high efficiency filtering provide a multiple barrier to releases. Airflow patterns are directed from clean areas toward those in which hazards may develop, as shown in Figure 16.3. Air in these areas flows from offices through corridors into the laboratory to pass through the enclosed system. The enclosure (hood, glovebox, etc.) atmosphere is discharged through the filter system. The flow pattern is always into the enclosure, which reduces the chance of material escaping. The room, the airflow, and the filter system provide the concentration or confinement of the released material.

Figure 16.3 Concentration (Confinement) and Containment for a Plutonium Laboratory.
For the more hazardous radionuclide materials, such as plutonium or the trans-plutonium elements, at least two lines of defense are required. The primary line of defense is containment. This is the enclosure, shown as a glovebox in Figure 16.3. Other lines of defense are provided by the confinement or concentration systems. These are the airflow pattern, the room or laboratory itself and the tandem high efficiency filters (HEPA) used.

Various designs of safety systems have been employed over the years. The purpose of the safety design in all cases is to achieve these goals:

1. Ensure that personnel radiation exposure is kept as low as reasonably achievable (ALARA) under normal operations.

2. Control effluent release to ensure no increase in present environmental background levels occurs. Ensure that any radiation exposure to nearby population groups is kept as low as reasonably achievable. Design systems to prevent the release of hazardous levels of material in the event of accidents.

3. Include features that will prevent or reduce the severity of incidents. The impact of the event in regard to personnel injury and threat to life should be the prime concern. Damage to property and program delays should also receive some thought.

The special features of plutonium and certain other radionuclides that increase their utility require that these substances be handled most carefully. This need for safety arises from four main features of the materials. First, they are unstable substances, whose decay results in the release of radiation. This radiation may present a hazard, even if one is distant from the source. Second, these elements are toxic. Intake into the body may result in long-term deposition in bone and other organs with severe local damage at these sites. Third, the substances are fissile. When enough of such material is present in the proper setting, a fission
chain reaction can occur. Such an event would release large amounts of energy and radiation (see 15.1.1.2). Fourth, some forms of these substances are pyrophoric; that is, they ignite spontaneously. Once started, a fire could spread rapidly and result in great damage. To reduce the hazard potential and to achieve safety in handling these substances, control of these features is required.

Because of the special hazards that are present in work with certain radionuclides, many design features must be treated. The type of functions to be carried out will affect the degree of safety needed. Basic studies of the site, plant layout, ventilation patterns, waste-handling needs, fire control approach, radiation safety problems, and nuclear-safety aspects will dictate many design goals. Structure design, process flow, confinement, and containment through gloveboxes or other devices will also call for a certain level of engineered safety. The form, amount, and composition of the radionuclide handled are also factors. These aspects modify the extent of hazards expected from the radiative, biological, nuclear, and ignition properties of the radionuclide.

The need for enclosures then, is basically tied to these conditions: the use of large amounts of long half life, highly radiotoxic substances which require frequent processing in operations exhibiting a high release potential.

If one uses small amounts of short half life, low hazard radionuclides in infrequent processes of low release potential, then one may allow the worker and material to be in the same environment.

B. Control Procedures - Gloveboxes

The type and extent of control measures used in radioactive work will vary. Many factors enter in, and only some of these were briefly mentioned above. For example, in some cases, plutonium is handled in open-faced hoods, but in most instances, it is handled in semiremote units (glove boxes) or remote enclosures (hot cells). The features of a particular handling operation may dictate special control measures, as
does the state of the plutonium being used. Low levels (< 37 kBq - approximately 1 μCi) of nondusty plutonium samples do not require the degree of control that higher levels do. Sealed or clad plutonium, regardless of amount, may be handled in hoods rather than gloveboxes for certain steps in a process. Several reports and articles deal with both the hazards and control measures of certain programs. 6, 9, 16-19, 21

The laboratory handling of plutonium often differs from that found in a plant or production facility. 4 In general, up to 0.2 GBq (~ 5 mCi) of plutonium may be handled in open hoods; gloveboxes are used for larger amounts. In plants in which gram or kilogram amounts are used, gloveboxes are used almost exclusively. For dusty operations or for plutonium in other pyrophoric forms, these call for gloveboxes with inert atmospheres. In processes involving irradiated plutonium samples that have not been separated from fission products, hot cells are used to provide shielding. In the future, glovebox handling of plutonium may be precluded because of the high radiation level produced by Pu isotopes in recycled plutonium. The following discussion will treat aspects of control procedures for enclosures (primarily glovebox systems).

1. Worker Procedures

Transfer of items into and out of the enclosure must be done so as to preserve the barrier integrity. For a closed system, such as a glove box, the design often includes plastic-bag ports or sphincter valves which allow such transfers. 1 Procedures for changing gloves, as well as windows, while maintaining barrier integrity, must also be developed.

The probability of accidents such as spills, unexpected chemical reactions, small fires, or explosions should be considered. 9, 12 Safety design will attempt to overcome or minimize the effects of such incidents. However, since these events may still occur, it is extremely important that personnel be trained in methods of combating such episodes. Needless to say, plans must be formed that treat the problems arising out of such accidents.
Regardless of the design excellence, the worker must also follow certain approved, albeit regimented, practices, which should be spelled out in written work instructions. These measures should include such things as:

(1) Remove all unnecessary equipment from the enclosure before starting a new project.

(2) Use absorbent matter or strippable paint on the surface to avoid contaminating the floor of the enclosure.

(3) Limit or avoid the use of pointed tools, wire, or sharp objects, and quickly report any punctures, wounds, or scratches obtained while performing work with radionuclides.

(4) Follow good housekeeping practices: Clean interior surfaces often, clean spilled matter at once, remove solid waste promptly, limit amount of solvents and other combustible material, and segregate pyrophoric matter.\(^1\) Do not let dust pile up!

(5) Inspect gloves often for signs of rupture, wear, pin holes or deterioration. Be aware that acids and other mixtures attack the gloves. Also, gloves fail rapidly in work with oxides of high specific activity.\(^{22}\) Change gloves frequently to avoid mishaps (preventive measure).

(6) Remember that stored vessels that are not vented can result in pressure buildup leading to rupture and spillage. Also, the storage of high specific-activity \(\alpha\) emitters in solution may result in heat evaporation of the liquid. This process may occur in conjunction with breakdown of the liquid (radiolysis) in the solution, causing gas buildup. For a very high specific activity, such as for \(^{238}\text{Pu}\), gas bubbles rising to the surface may burst and form a very fine oxide dust, which can grossly contaminate the enclosed system.\(^{22}\)
(7) Avoid splashing of liquids or spraying them during enclosure operations and keep liquid containers in a secondary container.

(8) Use latex or surgeon's gloves in addition to those that are part of the enclosure. This ensures a second line of defense if enclosure gloves fail.

(9) Do not perform radioactive work with open wounds or scratches unless you have obtained prior approval from medical authority.

(10) Know what your responsibilities are in regard to work performance and safety procedures.

The above listing is not meant to be complete, nor should it be taken as such. It is provided as a guide to point out some areas of safe practice and perhaps serve as a stimulant to enable the reader to reflect upon other pertinent safety practices. For each facility, other suitable practices may also be recommended.

The toxic nature of α emitters requires that these substances be kept out of the body. For some of these α emitting substances, exposure to air tends to form a finely divided, loosely held oxide. There is a danger of this material being dispersed into air and remaining airborne. The presence of such oxide in air creates an inhalation hazard. To prevent this, the substance is contained. However, the enclosure then becomes highly contaminated with the loose matter, so that a negative pressure must exist in the enclosure to avoid contamination leaks. Then, the airflow in the area will pass through the enclosed system and out through the filters in the exhaust system. This arrangement prevents the spread of contamination. However, since no system is perfect, leaks may still occur.

Since one must have access to the α emitter in gloveboxes, rubber or neoprene gloves, which are attached and sealed to glove ports on the box, are provided. These gloves protect the worker from contamination, but are subject to deterioration. Thus, surgical gloves are also worn to provide another means of protecting the individual from contamination. In
the event of a slight breakdown of the rubber gloves, the individual may not know this merely from appearance. Some other means must then be used to detect the spread of contamination, such as surveying each time hands are withdrawn from the glovebox.

Besides the two examples given above, loss of control may also occur as the result of operator error. Then again, an incident may be due to some unforeseen reason or unknown cause, but loss of control will still be the result.

In hood work, surgical gloves are worn to protect the worker's hands from contamination. If at all possible, one should not handle objects within the hood with the gloves directly. Something else, such as tissues, should be used. Then, the tissue becomes contaminated first, and the gloves act as a second line of defense. Hands should not be pulled out of the hood unless gloves are removed, since this may cause a loss of control. Also, if the gloves pick up significant contamination, they should be changed and disposed of as waste. The use of highly contaminated gloves only disperses the material throughout the hood and increases the chance of hand contamination if the glove fails.

2. Facility Layout

The goal of any contamination-control program is to limit the spread of contamination to as small an area as possible. This aids in reducing the exposure potential of the incident, eases the task of controlling the extent of the event (spill), and enhances cleanup of the area. Prudent facility layout can help to achieve these goals. One common approach is shown in Figure 16.4:

(1) Set up zones or areas to isolate the more hazardous processes. Allow work with radioactive materials only in the laboratory area.

(2) Control access. Set up a security guard (G) at the entrance, or require a special badge to actuate the door lock.
Figure 16.4 Facility design for contamination control.

(3) Direct traffic patterns. Permit access to the laboratory area only through the door at the end of the area (E) and past monitoring stations (M).

(4) Set up monitoring (M) and/or decontamination stations (D) at zone interfaces. Contamination monitors should also be located at selected locations along glovebox lines.

(5) Use protective clothing that is limited to the zone. Leave clothing worn in the laboratory area in the change room (CR) when leaving the laboratory area.

(6) Insist that anything leaving the hazardous zone be surveyed for radiation.

The above scheme provides a means to detect and limit contamination that might otherwise be tracked or transferred to other areas. The
entrance may also be marked with instructions for use of monitoring devices and special protective clothing and equipment while in the radiation zone. Such devices or equipment may be provided there or in the change room. In some cases, decontamination stations located at the zone boundary may be desirable. All these features may be set up, but depend upon the good will of the workers if they are to succeed. That is, unless the workers, and the visitors to the area, realize the necessity for checking everything that leaves the hazardous area, the contamination-control concept will fail. The scheme to contain any contamination within the laboratory area in Figure 16.4 works well only if the total cooperation of all personnel involved is obtained. When cooperation breaks down and exceptions to the control procedures begin to increase in frequency, then the probability of losing control is greatly increased. On the other hand, with strict adherence to the control procedures, the extent of any contamination can be limited to the hazardous zone alone. In addition, if frequent surveys of the laboratory area are performed, contamination incidents are picked up more quickly. This also aids in reducing the size of the area involved in a contamination incident.

3. **Area Contamination Control Practices**

In addition to the practices discussed in 16.B.1 above, personnel should observe other control measures. These measures seek to reduce the hazard potential at the area level as well as prevent intake of contamination. The use of shoe covers, laboratory coats, and surgical gloves that are not worn out of the area will help contain the spread of contamination. Survey of surgical gloves for radiation each time the hands are removed from the glovebox permits early detection of loss of control. The forbidding of smoking, eating, or drinking in the radiation area will reduce chances of radioactive matter being inhaled or ingested. Hands should always be washed following work with radioactive materials. When leaving a radiation area, one should monitor his hands, shoes, and any equipment being removed to further prevent the chance of spreading any contamination. Wounds or punctures should always be monitored for radiation and promptly treated by a doctor.
Fissile material storage practice involves nuclear safety aspects that require special attention. For this reason, storage must be strictly controlled. Large amounts of fissile material are often stored in areas or vaults of special design, and under the control of a responsible individual. This individual must keep records of the amount on hand and be responsible for proper storage and movement of fissile material. For safety purposes, access to these areas should be restricted.

For smaller amounts, the user should submit a material-handling plan that should include storage plans. He is responsible for the movement and storage of this material in his area. This plan should be reviewed for approval in regard to nuclear safety. For amounts below an established minimum the threat of a criticality is no longer a concern. However, depending upon the physical form of the fissile material, special storage precautions may need to be taken. Such factors as the proper type of container or storage in an inert atmosphere will warrant some thought.

4. Control Problems

The previous discussion was concerned with the general design features and administrative aspects of contamination control. However, the problems in the degree of control are specific to the material which is involved. For example, refer to Table 16.1. This table groups together a number of radionuclides which are presently in use. Included in the Table are the ICRP 30\textsuperscript{24} values for the most restrictive DAC and the ALI, in both Bq and $\mu$g, for each of the radionuclides. If one compares only DAC values, the relative control problem appears to be roughly the same

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>DAC $\text{Bq/m}^3(\mu\text{Ci/cc})$</th>
<th>ALI $\text{Bq(\mu\text{Ci})}$</th>
<th>$\mu$g</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>$0.08(2\times10^{-12})$</td>
<td>$200 (5.4\times10^{-2})$</td>
<td>$8.7\times10^{-2}$</td>
</tr>
<tr>
<td>$^{238}\text{Pu}$</td>
<td>$0.09(2\times10^{-12})$</td>
<td>$200 (5.4\times10^{-3})$</td>
<td>$3.2\times10^{-4}$</td>
</tr>
<tr>
<td>$^{252}\text{Cf}$</td>
<td>$0.4 (1\times10^{-11})$</td>
<td>$1000 (2.7\times10^{-2})$</td>
<td>$5\times10^{-5}$</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>$10 (3\times10^{10})$</td>
<td>$2\times10^{4}(5.4\times10^{-1})$</td>
<td>$1.2\times10^{-4}$</td>
</tr>
<tr>
<td>Nor. U</td>
<td>$0.7(2\times10^{-11})$</td>
<td>$2000 (5.4\times10^{-2})$</td>
<td>$7.8\times10^{4}$</td>
</tr>
</tbody>
</table>
(within a factor approximately 9) for all radionuclides, except $^{210}$Po. If we compare ALI values, in Bq, the result is roughly the same (within a factor of 10, except for $^{210}$Po). On the basis of both the DAC and ALI (in Bq) comparison, $^{210}$Po appears to be less hazardous than $^{239}$Pu by a factor of 100-125, whereas for the other radionuclides, the relative hazard is roughly equal. From a control standpoint; however, the degree of control required will be based upon consideration of mass loss, not activity. It is a certain mass of material which will escape the enclosure in a loss-of-control incident. If we look at the ALI expressed in $\mu$g, the relative hazard of a release for a given degree of control will differ greatly depending upon which of the radionuclides in the table is involved.

For example, assume that a system is 99.9% efficient in controlling releases. One would then expect 0.1% to be released. If the sample were 87 $\mu$g of $^{239}$Pu, the release would be $8.7 \times 10^{-2}$ $\mu$G or 1 ALI. The same system employed for 87 $\mu$g of normal uranium would result in a release of $8.7 \times 10^{-2}/7.8 \times 10^{4} = 1.1 \times 10^{-6}$ ALI, too small to be even detected. However, if the incident involved 87 $\mu$g of $^{252}$Cf, then the release would represent $8.7 \times 10^{-2}/5 \times 10^{-5} = 1740$ ALI! Clearly, the degree of control necessary in each case is vastly different. With respect to control design then, one must be aware of the additional containment which may be needed on the basis of mass considerations.

5. **Health Physics Control Measures**

To supplement the efforts of the worker, as well as maintain the control achieved by the safety-design features, requires a program that can evaluate the effectiveness of the control mechanisms. This latter need is supplied by the health physics program. Even though highly sophisticated control devices are used, and techniques are refined to the utmost detail, events that result in the loss of control will still occur. To mitigate the impact of these events by limiting the extent of the loss of control quickly is a function also supplied by the health physics program.
The features of such a program in regard to a high hazard material, such as plutonium, will be discussed. Note that practices at different facilities will not be identical and will depend upon a host of factors. In addition, this discussion is not intended to be all inclusive, since with time, procedures, equipment, processes and even the type and form of the radionuclides used will change thus requiring adjustments in control procedures.

Health Physics control measures may be grouped into two classes: (1) provide fixed monitors for detection of hand, shoe, clothing, or air contamination; and (2) provide portable instrument surveys and monitoring service on a routine basis to maintain contamination control. A survey is the process of monitoring for ionizing radiation, analyzing the results in regard to established protection standards, and defining, or evaluating, any radiation hazard which may exist.

a. Fixed Monitors

A fixed monitor may be used to trigger an alarm when the measured radiation field exceeds a preset level. In this sense, the device indicates that the loss of control is significant. A fixed monitor may also be used to check the contamination status of an item. In this application, the device may indicate either no contamination or some level of contamination. Both types of devices may be used for certain operations.

(1) Personnel Monitor

A personnel monitor is an ac-operated device used to survey hands, shoes, and portable objects (see Section 12). One type features a chamber in the form of a flat plate-type probe of large area through which the counting gas passes. Another type uses a non-flow air probe. Alpha particles enter the chamber through a thin Mylar window and ionize the chamber gas. The chamber output, which is proportional to the alpha activity, is displayed on a count-rate meter and indicated by
audible clicking from an attached speaker. The same device may be used for \( \beta \) monitoring if the operating voltage is changed.

This type of monitor can be placed both at the enclosure and at exits to the work areas. When a hand is withdrawn from the enclosed system, it can be surveyed immediately without the risk of spreading any contamination. Upon leaving the work area, a worker is also able to survey his hands, clothing, and shoes. By making frequent surveys, he will quickly detect the presence of contamination. This action will limit the spread of any contamination.

Another type of personnel monitor, the hand and shoe counter is also used at the entrance to radiation areas. Such units may be designed to monitor both hands and shoes during the same counting period without requiring the use of a probe.\(^\text{28}\) At the end of a fixed counting time, an indication of contamination or no contamination is given. When contamination is indicated, the level can then be measured with portable health physics instruments. These monitors are useful when a large number of people require hand and shoe surveys.

(2) **Continuous Air Monitors**

Continuous air monitors are used to maintain a watch on the level of air activity in the work area. These instruments consist of some air-collecting device and a suitable detector for the radiation. For gases, a flow-through chamber may be used to collect and detect the presence of the radioactive gas. For particulates or dust, filters are often used to collect the material, and the type of radiation emitted will dictate a choice of detector. The device is often provided with an alarm, since the presence of an airborne toxic substance may represent a severe inhalation hazard. Commercially designed units are also available and can provide monitoring of several radiation characteristics.

The presence of natural airborne radioactivity affects the ability of an air monitor to detect airborne plutonium. These radioactive products give rise to short-lived \( \alpha \) and \( \beta \) activities that tend to mask out any activity due to plutonium in an air sample. In
the past, the detection limit of air monitors has suffered because of this feature. This can somewhat be overcome by the use of an air monitor which contains a silicon surface barrier detector. This type can be used in conjunction with a single channel analyzer to count the α particles of a particular energy emitted by the specific radionuclide. In the case of $^{239}\text{Pu}$, the analyzer is set to measure the 5.15 MeV α particles. Air is drawn through a millipore filter which is "seen" by the surface barrier detector. Counts will be recorded for alpha particles in the energy window, which is centered about 5.15 MeV and generally ±.5 MeV to either side. Some interference is still noted because radon daughters produce some α particles of energy greater than this range. Counts occur in the window when these alphas are degraded in energy before interacting in the detector. However, this background is greatly reduced in magnitude and can be approximately accounted for.

An improved alpha spectrometry method has been developed which utilizes alpha counting in a vacuum. In this device, air is drawn through a filter which is viewed in-line by a surface barrier detector. If a release occurs, the detector senses the increased activity and actuates an alarm. The filter may then be advanced to an off-line vacuum chamber to be counted under vacuum. The increased resolution obtained for the vacuum count results in decreased interference from radon daughter products in the plutonium channel.

(3) Stack Monitors

This type of fixed monitor is used to estimate levels of radioactive substances which are released to the environs. In case of an accident, it also serves to denote if control by the filter system has been breached and what the extent of the release may be. These types of monitors are often devices that are designed and assembled for specific jobs, based upon the characteristics of the radiation and the process.

b. Monitoring Services

The monitoring services provided by an active health
physics program include routine instrument and smear surveys for surface contamination, personnel and item contamination surveys, and continuous monitoring. Air sampling of the general work area, as well as special samples during certain operations, are also carried out.

(1) Surface-contamination Surveys

Routine surface surveys should include both instrument and smear surveys. The frequency of these surveys will depend upon the form of the radionuclide and the type of operation carried out. In most cases, because of the degree of containment used for radionuclides such as plutonium, a positive survey result is cause for concern. That is, even a rather low level of contamination should warrant both cleanup and further investigation. For this reason, surface-contamination guides or levels are not readily found for plutonium. At any rate, the toxic nature of plutonium is such that any loss of control should mandate followup surveys. In some cases, certain contamination levels may be tolerated on the basis that proven control techniques are able to maintain contamination at or below these levels.

A number of portable, or survey, instruments are used to perform routine surface surveys (see Section 12). Normally, alpha survey instruments are used for surface surveys when plutonium is involved. If the sample contains fission products, a $\beta\gamma$ survey instrument may be useful. Gas-flow proportional probes are used for all types of $\alpha$ monitoring. When humidity may vary greatly, these are preferred over air probes. However, $\alpha$ air probes have been used successfully in other climates. The counting rate displayed on the instrument meter is proportional to the activity of the $\alpha$ source. Because of the short range of $\alpha$ particles, the probe window must be used very near to the surface being surveyed (< 6 mm). Earphones should be used with the counter to increase detection sensitivity. The lower limit of detection is about 100 dis/min in the area (0.01 m$^2$) under the probe.
This type of counter may be modified so that low-energy beta particles can be detected. This latter capability is useful in monitoring for some of the transplutonic radionuclides. Alpha scintillation counters using ZnS crystals are also used for α surveying. Gas-flow and scintillation counters both respond to neutron fields, so that extra care is needed when surveying for α surface contamination.

The smear survey consists of wiping a filter medium or other suitable material across a surface that is suspected of being contaminated. Sometimes, wet smears are obtained by using alcohol or acetone on the smear. The smear can be surveyed for activity with a portable instrument or counted for activity in a laboratory counter. This technique is easy to apply and allows quick spot-checking of areas for loose contamination. In many cases, one is concerned more about the presence of the contamination rather than its level. The qualitative results obtained in smear surveys are most useful in these instances. The method is also used to check the integrity of clad or sealed sources to ensure that no leakage has occurred.

(2) Personnel and Item Surveys

In addition to the fixed monitors used for surveys in the work area, many other surveys of both personnel and items are made utilizing portable survey instruments. These surveys are required when transfers into and out of enclosures are made. Surveys are also required for such things as skin punctures or wounds, glove changes on enclosures, decontamination of personnel or items, and repair work on potentially contaminated objects. Surveys are always needed by personnel at the end of their work period. These surveys should be complete surveys of the personnel's hands, shoes and clothing, even though surveys of his surgical gloves show no contamination. Cases have occurred in which pinhole leaks have led to clothing contamination higher up on the arm without the surgical gloves indicating activity.
(3) **Continuous Monitoring**

In some cases, the nature of the work may be hazardous enough to require the presence of a health physicist during the entire process. This is called continuous monitoring. This type of monitoring is also good practice each time a new technique is being used. The advantage here is that the worker can devote full concentration to the job and the health physicist will take care of the necessary monitoring. Also, the worker has the benefit of health physics advice at each step of the job. This type of monitoring is also desirable if the operation requires frequent movement of materials and items into, and out of, the glovebox system. The presence of the health physics monitor there will facilitate the necessary surveying and preclude delays in the operation.

(4) **Air Sampling**

Air sampling is carried out to assess the condition of the work-area environment. It also allows a check on the effectiveness of the control design and/or work practices in regard to contamination control. Since internal dosimetry is difficult to perform, common practice has been to limit the concentration of radionuclides in air. Although the DAC values are used as standards that should not be exceeded, the goal is to keep airborne levels ALARA. The DAC value (refer to DOE Order 5480.11)\(^{31}\) is used as an index of control, and airborne concentrations well below this level imply satisfactory control. To confirm that this is the case, routine air samples are collected. When air samples reveal increased levels of airborne activity, this is viewed as a potential breakdown of the control system. Levels above allowable values for short periods do not constitute a severe hazard themselves, but such levels over extended periods would be of concern. In the former case, it is not so much the level but the apparent loss of control that should be the major concern. Once control is lost, levels may go even higher as more material is released. Air sampling methods, as discussed in Section 14, are used
for routine air samples. These may be supplemented by an in-place monitor, utilizing a surface barrier detector to detect specific energy \( \alpha \) emissions, as discussed in 16.B.5.a.(2).

Samplers may be located in the general work area to routinely monitor the overall operation. In other cases, samplers may be positioned close to a source of potential air contamination, such as hoods or gloveboxes. Personal air samplers have also been used to obtain air samples in the breathing zone of the individual. Thought must be directed to the type of sample needed in regard to sampler placement. Large differences have been obtained in the results of some of these methods for sampling a given atmosphere (see Section 14.D). The frequency of air sampling in an area will depend upon the form of the radionuclides, the nature of the work, and the presence or absence of fixed air monitors.

C. Internal Exposure Control

1. Personnel Monitoring Measures

There are many problems in assessing the uptake, distribution, and retention of radionuclides (particularly plutonium) and the subsequent internal exposure that results.\(^{9,32-36}\) To estimate the internal-exposure rate, a measure of relevant organ burden is needed. Given the organ burdens and excretion data, the total dose equivalent may be estimated. The control methods discussed above attempt to exclude the entry of radioactive matter. Nevertheless, such entry may occur, so that methods are needed to estimate the burden and subsequent radiation-dose equivalent.

A common method used to appraise internal exposures is a bioassay program. Routine urine and/or fecal samples are collected at some frequency, reduced chemically, and counted for the radionuclide content. In general, soluble radionuclides retained in the body are excreted mainly through the urine, whereas insoluble radionuclides are found mostly in the feces. Data obtained from a number of samples can be used to estimate
organ burdens. In the event of a suspected intake, it may be necessary to collect all excreta for the first few days following an accident.  

Chest counting of individuals by whole-body counters is used to estimate lung deposition for radionuclides which emit photons of sufficient energy to be detected despite absorption by body tissue. In recent years, whole-body counters of special design have been used to detect plutonium in the body. These devices are able to detect the average 17 keV x rays from $^{239}$Pu and the 60 keV $\gamma$ rays from $^{241}$Am. Since these photons are easily absorbed in dense substances, the method is useful for lung-burden determinations, but not for bone burdens. To correctly assess the Pu lung burden by this method, for an intake equal to a few ALI values, requires that the $^{239}$Pu/$^{241}$Am ratio be known. This technique, used in conjunction with other bioassay samples, has improved the estimate of intake in the case of inhalation events. Multiple Ge detectors, operated in series, show promise of being able to measure plutonium in lung directly.

Wound monitors have been developed that can be used to estimate the amount of radioactivity in wounds. These instruments also count the low-energy x rays from the plutonium. These devices are useful for cases in which plutonium may be embedded in the tissue. Then, alpha radiation will be totally absorbed and not detectable, whereas the x rays can still be detected. These monitors aid the physician treating the wound since the plutonium should be removed and may have to be excised. Normal skin contamination by radionuclides, such as plutonium, can usually be detected by portable $\alpha$ survey meters.

On occasion, other samples such as nose swabs, sputum, or blood may be needed in order to help in assessing the intake.

2. **Therapeutic Measures**

A number of substances have been found useful for increasing the urinary elimination of metals from the body. Of these,
diethylene-triamine-penta-acetic acid (DTPA) has proven the most effective agent.\textsuperscript{38} However, treatment with this substance is most effective only in the early stages following intake. It is presumed that once the heavy metal is bound in an organ, DTPA will have little effect.\textsuperscript{29} In the early stages, when the level of soluble heavy metal in the blood is high, DTPA is able to increase the excretion rate. For a heavy metal, such as plutonium, this results in a loss of deposited plutonium. When plutonium is removed, the subsequent total dose may be greatly reduced. This feature is most important since soluble plutonium is so tightly bound in bone, ensuring long, continuous irradiation.

In recent years, pulmonary lavage (lung irrigation) has been tried as a means of removing inhaled matter from lungs.\textsuperscript{29} In one application of this method to humans, three lavages removed about 1/8 of the estimated initial lung burden.\textsuperscript{40} Since there are risks in this procedure; namely, administration of anesthesia and potential adverse reaction in the individual, the use of this technique requires careful assessment.\textsuperscript{29}

3. \textbf{Protective Equipment}

Protective equipment should be supplied to the worker to increase the degree of protection afforded by other safety measures.\textsuperscript{3, 41-45} Its purpose is to protect the worker from contamination and to aid in the control of contamination. The use of such equipment guards against pickup of external contamination on the worker’s person or clothing and intake of contamination into the body. Also, the equipment is removed by the individual in the given area so that the contamination can be confined to that area.

Types of protective clothing generally used are laboratory coats, coveralls, plastic suits, pants and shirts. Coveralls or pants and shirt are preferred, since these call for a change of personal clothing. This precludes loss of personal clothing in a contamination incident or spill. Gloves and safety shoes may also be provided to round out the basic scheme. In some cases, one may provide laboratory coats and shoe covers at
the zone entry for use by observers or those not normally working in the area. Any handling operation with radioactive material, particularly plutonium, should be done with protective gloves on. Other more elaborate types of clothing may be used.\textsuperscript{41,42}

Other necessary protective devices include respiratory equipment. These may be needed for special operations, such as repair work or modifications, as well as for an emergency. The use of these devices on a continuing basis in place of proper source control of the radioactive work is undesirable.\textsuperscript{45} One class of respirators, the full facepiece type, processes the air the worker breathes in from his surroundings.\textsuperscript{41} These are suitable for particulate matter, and some may provide protection up to 100 times the allowable concentration in air.\textsuperscript{46} In the other class of respirators, which includes self-contained breathing units, the worker does not breathe the air from his surroundings. This type is suitable for both gases and particulate matter and should be used for particulate concentrations greater than 100 times the DAC in air. Here again, the function performed and the form of the radioactive material used will affect the type and required use of the above protective equipment.

Utilizing a respirator fit-testing program, one may be able to demonstrate a greater protection factor than that stated above. This requires that the individual be tested, wearing his respirator, in an enclosed chamber where the penetration of the test aerosol can be measured.\textsuperscript{6,45} In this case, the protection factor is actually measured and documented. Even in these cases though, prudent practice has been to use the more conservative factor found in Reference 43.

D. External Exposure Control

The external dose rates from some materials used in enclosures can be significant. In particular, \textsuperscript{239}Pu, with large percentages of \textsuperscript{240}Pu, \textsuperscript{241}Pu and \textsuperscript{242}Pu can exhibit relatively high external radiation fields. The external radiation field is a sensitive function of the isotopic composition.\textsuperscript{9} For plutonium that contains less than 5\% on a
weight basis of isotopes other than $^{239}$Pu, the external field is not a
great problem. Above this weight percent, the external exposure hazards
increase and eventually require special controls, such as reduced work
time, shielding, or semiremote handling.\textsuperscript{18,47,48} Of course, recently
irradiated uranium capsules may contain fission products in amounts
comparable to the plutonium content. These would present very serious
external exposure hazards that would require extensive shielding and
totally remote handling, such as in hot cells. This latter consideration
also applies to handling large amounts of transplutonium matter.

In the case of a plutonium sample, the external field is comprised of
low-energy $\text{x}$ rays, low- and high-energy $\gamma$ rays, and fast neutrons.
Beta radiation is absorbed either by the enclosure itself or by the
enclosure gloves. X rays and $\gamma$ rays are reduced to some extent by the
enclosure and by using leaded gloves. However, the photon dose rate
increases with surface area of the plutonium. Thus, a thin layer of
plutonium on the floor area of the enclosure may increase the photon dose
rate. The presence of $^{241}$Pu will mean a $\gamma$-dose-rate ($> 40$ keV)
increase for years due to $^{241}$Am buildup. Neutron dose rates depend
upon the mass of the sample in the case of spontaneous fission. The dose
rate from neutrons may also be significantly increased if low-$Z$ number
substances are present as impurities.\textsuperscript{9}

In the early handling of plutonium, extremity exposures were of
little concern. With the advent of high-exposure plutonium, hand
exposures, as well as whole-body exposures, became important, and methods
of reducing such exposures had to be provided.\textsuperscript{47,48} For transplutonium
substances, dose rates are such that whole-body doses must be greatly
reduced for all but small amounts of these substances.\textsuperscript{49}

1. \textbf{Exposure Control Practice}

Among the practices that may be used to limit the external
exposure received by the worker are:\textsuperscript{48,49}
Limit the amount of material in the enclosed system.

- Reduce the total worktime allowed in handling radionuclides.
- Process the material as soon as possible after chemical separation.
- Remove waste matter as quickly as possible so that surface deposits do not build up.
- Use remote handling devices, such as tongs, forceps, etc., as much as possible.²
- Rotate personnel for those jobs having the higher exposure rates.

2. Shielding

A number of substances have been used as shields to reduce the external radiation dose. Initially, the normal thickness of material on the enclosure provided enough shielding to reduce the low-energy x rays to low enough levels. As the plutonium isotopic composition shifted, the use of leaded gloves became common practice. These gloves were used to limit hand exposure, but their thickness, in lead equivalents, was restricted since at some point handling operations became too difficult. Common practice has been to limit thickness to .8 mm (30 mil) leaded gloves (0.1 mm lead equivalent). As both γ and neutron dose rates became larger, it was necessary to go to more potent shielding to achieve the needed dose reduction. In the case of gloveboxes, only so much shielding can be included or added (approximately .15 m) and still allow ease of manual handling. Therefore, at some point, hot cells and remote handling devices must be used.

In the case of x and γ rays, high-Z-number substances are most useful as shields. However, a shield material does not absorb equally for all energies of the incoming photons. The transmission expresses the fraction of the incoming photons of a certain energy that pass through a shield of given thickness. Table 16.2 gives photon-transmission values for some common materials used in gloveboxes.
Table 16.2 Transmission of X and Gamma Rays in Selected Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>17 keV</th>
<th>43 keV</th>
<th>60 keV</th>
<th>100 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2-in. Lucite (Plexiglas)</td>
<td>0.28</td>
<td>0.74</td>
<td>0.81</td>
<td>0.82</td>
</tr>
<tr>
<td>30 mil lead gloves (0.1 mm lead equivalent)</td>
<td>0</td>
<td>0.38</td>
<td>0.67</td>
<td>0.54</td>
</tr>
<tr>
<td>1/4-in. aluminum</td>
<td>0</td>
<td>0.45</td>
<td>0.59</td>
<td>0.78</td>
</tr>
<tr>
<td>1/8-in. steel</td>
<td>0</td>
<td>0</td>
<td>0.046</td>
<td>0.43</td>
</tr>
</tbody>
</table>

As may be noted from the table, as photon energy increases, the shield thickness must also be increased to retain the same shield transmission factor. For transplutonic isotopes, which have more photons in the range above 100 keV than plutonium, the photon shielding problem becomes more troublesome.\textsuperscript{16} Attenuation factors for PuO\textsubscript{2} sources in several materials can be found in Reference 9.

In the case of neutron shields, the choice of a proper shield substance is more complex. For a fast-neutron spectrum, the shield must quickly remove the neutrons, yet be thick enough to absorb photons produced in radiative capture.\textsuperscript{50} In very thick shields, the neutrons will be removed and still enough matter will be available to reduce the capture gamma ray hazard. In thin shields, one may reduce the neutron hazard but increase the $\gamma$ hazard.

For fast neutrons, low-Z number substances, such as hydrogen, are most useful as shield materials.\textsuperscript{6} One may compare neutron shielding substances on the basis of their hydrogen content. On this basis, polyethylene and water are among the better neutron shields, while concrete is adequate if the water content is approximately 7%. Reference 51 contains data on the shielding ability for some of these materials for fast neutrons. Transmission factors for thin neutron shields are difficult to
obtain, since one must deal with a spectrum of neutron energies (see Section 8.E.1). In thin shields, the spectrum changes rapidly over short penetrations, so that the shield effect may depend upon the initial spectrum assumed. In thick shields, removal theory for neutrons may be applied. Reference 52 contains shielding information useful for transplutonium material ($^{282}$Cf).

3. Health Physics Services

Health Physics provides advice, recommendations, consultations, computations, hazard analysis and safety review and approval of operations and designs in an effort to reduce exposures to ALARA. In addition, presentation of indoctrination lectures to new personnel, refresher training of long-term personnel, and discussions and review of procedures with operations personnel help to foster an ALARA approach to carrying out operations. Frequent observation of the radiation handling practices in a given area lead to ideas for performance improvement which help to reduce personnel exposure.

Other health physics control measures cover monitoring services with survey instruments to define the radiation field and personnel monitoring programs to assess exposure. In addition to these features, fixed monitors that respond to external radiation fields above certain preset levels may be used. The response may include visual and audible alarms to indicate accident situations requiring prompt action.

a. Monitoring Services

A number of survey instruments (see Section 12) are used to estimate the external radiation field. For photons, beta-gamma survey meters (Geiger counters) or ion chamber devices are most often used. Neutron fields may be evaluated by devices that measure the neutron fluence rate (such as the PNC or long counter) or approximate the dose equivalent rate (such as the neutron rem meter). Fluence rate units may be
related to the estimated dose equivalent rate by means of the relationships in Table 4.3. These values have been adapted from Reference 51.

For a fast neutron spectrum, such as in fission or \((\alpha, n)\) processes, an average value for the neutron energy is estimated, and the corresponding allowable fluence rate from Table 4.3 for that energy is used for the spectrum. In practice, the allowable fluence rate value for a mean energy of 1 MeV is often used to estimate the dose equivalent rate. Any moderation of fast neutrons then provides a safety factor. This is particularly true when the field is measured after passing through hydrogen-rich shields.

Estimates of the total dose rate from neutrons and gamma rays can be used to assess the hazard. If the dose rates greatly exceed the allowed standards, a severe hazard may exist. In these instances, actions that will greatly limit exposure during handling will have to be taken. For not so severe hazards, only minor changes may be called for.

b. Personnel Monitoring Devices

In the past, the most common device to monitor exposure was the film badge. These devices could be supplied with separate films that responded to beta and photons, and neutrons, respectively. In Section 13, we discussed several alternate devices which are replacing film as the method of choice. These included TL, RFL and Exoelectron devices for photons and beta, and albedo and track etch devices for neutrons. In particular, TL dosimeters are now extensively used and are recommended for plutonium monitoring. A pocket dosimeter (see Section 13.C) is often used with the film badge or other monitoring device to allow visual checking of the exposure while it is being received. These devices can be read and recharged during stages of an operation to pinpoint the steps which result in the highest doses. Alternatively, they may be used to determine daily \(\beta\gamma\) exposure, and the readings recorded. In some cases, audible dosimeters, which give off intermittent chirp-like sounds
and light flashes, may be worn. These devices respond with increasing signal rate as the exposure rate increases.

Finger rings and wrist bands containing TL dosimeters are used for monitoring extremity exposures. Film has been replaced in ring devices to avoid the problem of light leaks, which produce erroneous response. This is not a concern with TL substances.

A problem in the use of film for neutron monitoring by track counting has been poor response in the intermediate energy region (see Section 13.8.a.(1)). The NTA film in common use will not respond to neutrons below about 0.5 MeV. For moderated neutrons, this film may miss a large portion of the neutron dose.

Since much work with plutonium or transplutonic radionuclides leads to moderated neutrons coming through the shielding, personnel neutron monitoring presents a problem. The use of a simple ratio of $n/\gamma$ doses to estimate the neutron dose is undesirable, unless this ratio is evaluated for each specific process. Albedo neutron dosimeters may be used, but since these are severely energy dependent, one must calibrate their response for the spectrum of interest. Track etch recorders using the plastic recorder CR-39 show promise of covering the energy range of 0.1-18 MeV.

E. **Nuclear Safety**

Much of the work done in gloveboxes and hot cells involves plutonium and transplutonic radionuclides. Because of the fissionable nature of many of these materials, both with respect to thermal and fast fission, a nuclear safety program is also required. Many of the principles and protective measures discussed in Section 15.1 will be applied in achieving such a program.

F. **Waste Removal Practices**

Waste removal practices set up for different forms of contaminated
waste should be observed. Dry waste is often put in metal containers (sphincter cans), sealed in plastic bags, and removed through bag ports. This waste may then be placed in large, covered, metal drums, which can be sealed when filled, and removed for disposal (see Section 16.J.). Liquid waste is handled by piping to waste tanks or containers, by use of small bottles or other containers, and by treatment (evaporation and absorption in vermiculite) that changes the liquid waste to solid waste. Gaseous waste is often planned for in the design features of the exhaust system.\(^1\)\(^4\) Pyrophoric wastes are often burned within an enclosure (passivated) before being disposed of.

Waste handling rules should specify the correct method of disposal for items that do not fit standard containers. Also, the correct use of waste containers as well as proper waste segregation should be explained (see Section 16.J.3).

G. \textit{Emergency Procedures}

Much has been said in regard to preventing certain incidents, yet they still seem to occur. A number of causes can be assigned or postulated in each case, but the cogent feature is that, despite all that can be done, accidents still occur. For this reason, one must accept the premise that certain accidents are going to occur. To properly deal with these situations at any level requires both a well-thought-out plan and trained individuals to execute the details.\(^5\)\(^4\) As one might expect, the more complex the incident, the more detailed will be the plan and the more substantial will be the group involved.

The philosophy that should apply in an emergency situation will reflect these goals:\(^4\)

1. Protect personnel from injury and hazards, and quickly identify exposed personnel.
2. Avoid actions that might create greater hazards.
3. Bring the emergency under control and limit the extent of environmental releases.
4. Prevent property damage.
5. Limit the extent of any contamination.

To deal with an event and form a plan of action will require an initial analysis of the accident potential. Thought should be given to the type and nature of events likely to occur. These may include criticality accidents, contamination release in fires or explosions, or high-radiation fields. At this stage, extra precautions should be taken to reduce the likelihood of the event, if possible. One should ponder the extent of the area and estimate the number of people involved. Key areas should be identified, and photographs of the suspected trouble spots may be prepared. Other building data and plans to aid emergency response groups unfamiliar with the area may also be included.

Once the events are defined, written procedures for immediate actions in these emergency situations can be prepared. There may be many facets to the plan, depending upon the nature of the event. However, at every level these plans should (1) be easy to understand, (2) specify actions to be taken, (3) detail responsibilities, (4) define communication lines, and (5) denote sites of emergency equipment. The plans should cover such aspects as evacuation plans, reporting emergencies, and the types and meaning of alarm systems. Assembly points and decontamination centers, and the proper routes to these areas, should be detailed. Drills and training of personnel should be carried out to test response and familiarize workers with their part in these plans. Review of these drills should be carried out to point out weak spots in the scheme so that these may be corrected.

When immediate local actions are not able to cope with an event, a major emergency plan is needed. This will require the response or assistance of many groups; medical people, health physicists, communications personnel, security forces, firemen, utility men, and others. The major plan designates a director whose function is to coordinate the actions to ensure a team effort. He should be assisted by other designated personnel whose responsibility is to provide expertise in certain aspects
of emergency control. This group should include someone who is familiar with the area in which the emergency has taken place.

Among the functions that must be carried out in the event of a major radiation incident are:

1. Evaluation of the situation in regard to degree of hazard.
2. Assistance in the evacuation or recovery of personnel.
3. Surveying of persons for contamination and/or radiation.
4. Accounting of personnel who may have been involved in the incident.
5. Planning of actions or procedures to bring the emergency under control.
6. Treatment and decontamination of any injured workers.
7. Provision of instruments, clothing, portable decontamination units, and other specialized equipment.

Following any incident, a review of the sequence of events during the emergency response should be conducted with a view toward improving performance and attaining greater safety in the future. An evaluation of the emergency measures and response of emergency groups may indicate ways of improving the handling of future emergencies.

Since facilities may be vastly different, specific details of an emergency plan must be worked out on an individual basis. The intent here is to simply point out some of the aspects that must be treated in an actual plan. References 54 and 55 discuss several aspects in regard to emergency planning.
H. Hot Cells

Many operations involving radioactive substances must be carried out in shielded enclosures called "hot cells" or "caves." Hot cells protect workers from intake of these substances and from exposure to penetrating radiation. The main parts of a cell are the shielding walls, cell liner, services, ventilation system, and, in some cases, a drainage system. Special-purpose cells may also include viewing windows, remote-handling devices (manipulators), hoists or cranes, and access ports. Figure 16.5 shows the layout of a multicell facility.

To keep the working areas free of airborne activity, cells may be hermetically sealed or maintained under a negative pressure. The latter method is generally desired for large multipurpose cells. An air flow prevents the buildup of troublesome vapors and removes heat from equipment and lights.

The containment required is related to the state and toxicity of the substance being handled. Gases may be trapped or, if the amounts are small or the half life is short, they can be dispersed via tall stacks.

The surfaces of some solids may oxidize and produce fine airborne particles. Some of the more toxic substances are also pyrophoric, and a fire would produce radioactive smoke. Alpha emitters, being highly toxic, require good containment. However, these substances can be handled in thin-walled, in-cell gloveboxes. For processes involving large amounts of both alpha and gamma emitters, remote handling must be done in cells that provide adequate shielding and a high degree of containment. In these cases, an in-cell glovebox may still be used, in which the hot cell manipulators, sealed in vinyl plastic which also forms the roof of the glovebox, are used to perform the operations.

1. Shielding

Materials used for hot cell walls include concrete, steel, lead, and water. Concrete is by far the most commonly used material, mainly because of the low cost. It can be obtained in a range of densities-from
2.2 to 5.9 Mg/m³. The higher-density concretes are used, in most cases, for monolithic shielding structures. The added cost is justified by reduced space requirements and smaller remote handling devices.

The choice and thickness of shielding material for a given high-level gamma cell are often based upon a certain amount of \( \gamma \) activity. For example, a megacurie hot cell is designed to provide sufficient shielding so that \( 10^6 \) Curies (37 PBq) of a 1 MeV \( \gamma \) emitter can be handled safely with respect to exposure. The activity may be assumed to be at a point. This is a conservative approach since a finite source is always less intense. The unshielded dose rate \( D_o \) at the position of the worker is approximated by

\[
\hat{D}_o = \frac{1.264 \times 10^{-13} \text{ n C E}}{r^2} \gamma \text{ Gy/h},
\]

16.1
where \( n_\gamma C \) is the \( \gamma \) activity in \( \gamma/s \), \( C \) is the source activity in Bq, \( E \) is the energy in MeV/\( \gamma \), and \( r \) is the distance between the source and the worker in meters.

In passing through the shield, the gammas undergo absorption and scattering processes. This requires the use of a buildup factor, \( b \), in the shielding calculations.\(^{56,58}\) The value of \( b \) varies with \( \gamma \) energy, shield material, source and shield geometry, and depth of shield penetration. The attenuation of monoenergetic gamma rays by a given substance is then obtained from the simplified expression.

\[
D = D_0 b e^{-\mu x},
\]

where \( D \) is the reading at a point outside the shield, \( D_0 \) is the reading at the same point without the shield, \( \mu \) is the attenuation coefficient, \( x \) is the shield thickness, and \( b \) is the buildup factor for a given value of \( \mu x \) (see Section 8.D.2).

Buildup factors for point isotropic sources for common shielding substances are given in the references.\(^{59,60}\)

A further complication is introduced for cells designed to handle transplutonic radionuclides. For these materials, the neutron emission is significant enough to warrant attention. For these radionuclides, it is generally sufficient to assume a neutron energy spectrum similar to a fission spectrum. One is then concerned with fast neutrons, thermal neutron capture gammas, and activation of the shield itself. Sometimes, in high-level \( \gamma \) cells, the concrete is thick enough (1-2 m) to adequately attenuate the neutrons, but other components of the cell, such as steel doors or the windows may offer inadequate shielding.\(^{49}\)

The walls of a hot cell should always be checked for leakage prior to initial use.\(^{56}\) A high-energy \( \gamma \) source is often used for this purpose. It should be placed in all possible future source positions. The leakage survey can be made with rate meters, dosimeters, or film. Large x ray films have been used to conveniently map large areas during the leakage survey. If neutrons are expected, one will need to perform neutron leakage measurements also.
2. Ventilation

Ventilating systems control the temperature and limit the spread of contamination both inside and outside hot cells. Cells are maintained at negative pressure relative to the working area to prevent the escape of contamination.\(^3,9\) When possible, airflow patterns are set up so that air is carried to a cleaning system. This exhaust air may contain contaminants and must be cleaned before release.

Air cleaning can be achieved with filters (for particulate matter), with scrubbers (for particulates and gases), or by adsorption (for gases).\(^{15}\) Prefilters are often used to extend the life of the more costly final filters. The use of filters on air inlets may offer some protection—for example, if the airflow is momentarily reversed due to an explosion or fire.\(^{15}\)

When doors or access ports are opened, the air exchange should increase to keep the inlet velocity above a minimum value. A second fan is often used for this purpose. This fan turns on automatically when the cell is opened.\(^{57}\)

An airflow can be maintained in completely sealed cells. The cell air is pulled through a filter system and recirculated back into the cell.\(^{15}\)

3. Viewing Facilities

Windows, periscopes, mirrors, and television are some of the means employed for viewing remote operations. The choice of viewing method depends upon the process to be performed, the information required and the skill and desires of the operator.\(^{56}\)

a. Windows

A solution of about 78% zinc bromide in water has been used widely for liquid windows.\(^{3,56,57}\) The ZnBr\(_2\) solution (\(\rho = 2.5\) Mg/m\(^3\)) is highly transparent, rather stable under irradiation, and
relatively cheap. If the solution is exposed to air or radiation, coloration occurs with a corresponding decrease in light transmission. This type of window can receive a total dose of about $10^5$ Gy ($10^7$ rad) before discoloring enough to require a reducing agent or replacement of the zinc bromide.

Lead glass ($\rho = 3.27-6.22$ Mg/m$^3$) can be used with zinc bromide. This combination can produce a window having a shielding capacity for $\gamma$ equivalent to that of the cell wall.

b. Periscopes, Mirrors and Television

Periscopes are often used for detailed examination of the work within a hot cell. A periscope is a lens system that conveys images from the objective end of the system (inside the cell) to the eye of the worker. Mirror systems can augment direct viewing and permit one to follow the progress of simple operations with fairly low activity substances in open-top cells.

Closed-circuit television is useful for performing widely spaced operations, for viewing inaccessible areas, and for viewing by more than one person. It is hampered, however, by the lack of depth perception and the small field of view.$^{2,3,56}$

4. Remote Handling Devices

In many cases, handling radioactive substances with the bare hands is unwise. Therefore, many operations are carried out with remote handling devices (manipulators). Many such devices have been developed, the particular design depending upon the process to be performed.$^3$

Tongs can be used for simple operations with substances of low activity. They have only one motion, that of grasping, and provide distance as protection for the worker.

The ball-joint manipulator is often used in small hot cells.$^{3,56}$ A rod having a handle at one end and tongs at the other, moves through a ball joint to adjust the reach. This shielding ball joint
is mounted in the cell wall. The rod axis can also be moved, but is confined to a cone-shaped volume having an apex angle of about 70-90°. This device is useful for radiochemical or simple mechanical functions.

The more complex processes performed in many large hot cells require the use of general-purpose manipulator systems, often called master-slave manipulators. These manipulators have a master arm (control arm) outside the shielding wall and a slave arm (working arm) within the cell (see Figure 16.6). The arms are connected (with remote control linkages) so that motion applied to the handle drives the slave arm in a like manner. These master-slave units have at least seven independent motions-three along the x, y, and z coordinates, three rotational, and one for gripping objects. They may be obtained with arms having unequal lengths and also different distances between the two arms. Snap-in type tongs (or fingers) can be changed remotely. The slave arms

Figure 16.6  Section through a hot cell wall.
may be obtained with or without sealed boots (flexible rubber or plastic bags which are sealed to the wrist of the device at one end and sealed by a glove ring mechanism at the wall penetration).

Some of the many types of remote-handling devices are further discussed in the literature.¹,⁵⁶

5. **Monitoring Hot Cell Operations**

Hot cell operations require monitoring services because of the radiation exposure problems that may be encountered in handling the high-level sources used in these facilities. Monitoring services (radiation protection surveys) are provided on a routine basis and/or upon request. They can be provided while an experiment is in progress, or during cell transfers, decontamination, filter changes, etc. These services include measurements of radiation fields to set working time limits or to check the adequacy of shielding walls, and the collection of air samples plus direct and smear surveys of surfaces to detect and/or control environmental contamination. Samples of the cell exhaust can be checked to determine and control releases to the atmosphere.

Some of the various cell operations that may require monitoring services are briefly discussed below.

a. **Cell Transfers**

Movement of items into or out of a cell (transfers) can be accomplished with pouches or bags, transfer drawers, map tubes, shielded casks, etc. Items brought out of a cell may be covered with loose activity. Therefore, these items are normally surveyed before complete removal from the transfer system. Gamma-emitting objects are generally checked remotely with a survey meter in the cell before they are withdrawn. The meter reading shows whether the object should be extracted directly into a shielded carrier.

Highly toxic substances are often placed in pouches that are sealed upon removal. The sealed end is a likely spot for contamination
and therefore should be surveyed. This bagging technique is also useful for cells that must be maintained under an inert atmosphere.61

b. Decontamination Operations

Hot cells may need to be decontaminated to install new equipment when the nature of the experimental work changes, to make repairs that cannot be done remotely, or to prevent the activity from reaching unmanageably high levels.3 This cleanup process may require consideration of such things as personnel exposure to radiation, contamination control, criticality, and the handling and disposal of active wastes, as in the case of glovebox systems.

c. Filter Changes

Air cleaning filters used in hot cell exhaust systems must be changed periodically. This changing operation can present a contamination or personnel exposure problem because of the accumulated waste matter.56 Push-through filter-exchange systems, with or without shielding, have been developed to overcome some of these problems. In some facilities, the first of a series of filters can be changed remotely with the cell manipulators. However, these protective measures are not available for many of the filter exchange operations; therefore, these operations are usually covered by radiation surveys. In some cases, respirators may be required.

6. Control Measures

Many of the health physics control measures and services discussed in 16.B.5, 16.C, 16.D and 16.E also apply in the case of hot cells or shielded facilities. That is, a program of routine checks and surveys needs to be performed to continually evaluate the effectiveness of the control program.
I. Decontamination

As has been discussed earlier, operations in gloveboxes and hot cells lead to the accumulation of high levels of loose radioactivity, which is contained in the enclosure. In addition, the use of certain forms of radioactivity in hoods will also lead to levels of loose activity on the inside hood surfaces. The levels which can be tolerated will be related to the containment and protection which the enclosure provides. Depending upon the quality, nature and form of the radionuclide used, and the operations involved, the degree of necessary containment varies. Even for adequate containment, at some point, the buildup of activity in the enclosure reaches an undesirable level and cleanup is indicated. In other cases, the operation and/or the radionuclides used may change so that one may desire to clean up the old radioactivity in the system so as not to affect the result of experiments with the new radionuclide. In some instances, loss of control occurs leading to a release of radioactivity from the enclosure into the worker’s environment (often referred to as a "spill"). This requires location of the source of leakage, re-establishment of the required degree of containment, and cleanup of released radioactive material. The cleanup phase may also involve equipment, clothing and personnel which were involved in the release of material.

The general term used for the radioactivity in the above situations is contamination. The term contamination is generally used to refer to the presence of unwanted radioactivity in any place where it may present the potential to harm personnel, spoil experiments, or render products and equipment unsuitable, or unsafe, for further use. Loose contamination is usually surface contamination which can be easily removed, or rubbed off the surface to which it clings, and transferred to other sites. The term "fixed contamination" is a relative term used to describe contamination which is not easily removed. Since it is not really fixed to the surface, in time, this type of contamination may also become loose contamination.

The control of contamination at the source is a prime objective of a radiation protection program. This action limits the spread of contamination and helps to reduce cleanup time and costs, as well as loss of
equipment and facilities, due to decontamination. Many features of contamination control have already been discussed in this section. When such actions fail, or incidents occur, or even when certain modifications are being made to a facility, the need for decontamination may arise.

If undetected or not properly removed, radioactive substances may enter the body, be taken home on contaminated clothing and shoes, be spread to other parts of the facility, or interfere with, or spoil, sensitive equipment or experiments. For these reasons, contamination should be promptly removed as soon as it is discovered. This reduces the chance of dispersal to other areas. The proper response in finding and removing contamination represents a prominent part of effective contamination control.

1. Principles of Decontamination

Although it is desirable to remove all contamination, there may be situations in which only a degree of decontamination is required.\textsuperscript{42,43} Certainly all loose contamination should be removed, but sometimes the cost and effort required to remove the relatively fixed contamination can be considerable.\textsuperscript{42} In some cases, it may be more costly to decontaminate an article than to simply replace it. In other cases, a certain level of contamination may be acceptable since the item or piece of equipment will be used inside a contaminated enclosure.\textsuperscript{3} It may be more economical to just transfer the contaminated item from enclosure to enclosure without cleaning it. If the item is to be released, the criterion for release may allow certain limits of contamination based upon the specific radionuclide involved.\textsuperscript{31,64} If a laboratory is contaminated in a spill though, the objective may be to remove all contamination since it may represent a hazard to personnel. However, in skin contamination cases, contamination levels below allowable levels may be tolerated if drastic removal methods would result in skin damage.\textsuperscript{42}

The approach to decontamination is often complex because of the many available elements which have radioactive isotopes, as well as the form of the contamination: solid, in solution, or carried by a gas or vapor. In addition to the chemical, physical and radiochemical nature of
the contaminant, the material and surface characteristics of the substrate affect decontamination. Generally, radioactive materials are held on a surface by physical adsorption (most fission products and all heavy natural radionuclides), or adsorbed from suspensions and deposited on substrate (pores and indentations). To remove the contamination will often require the use of a specific chemical to dissolve the particular contaminant.

For a given choice of surface material, the ease of decontamination will be related to the manner in which the surface is contaminated and the particular decontaminating chemical agent chosen. For metallic surfaces, the contamination tends to become incorporated in the metal making removal difficult. Organic surfaces (paints, plastics and textiles) and vitreous surfaces (glass, porcelain) have a capacity for ion-exchange which is probably the most important contamination mechanism. All porous surfaces are easily contaminated and difficult to decontaminate. When metal and porous materials are used, strippable coatings are usually employed to seal the surface. During decontamination, the coating is often removed with the contaminant so that a new strippable coating must be applied.

In order to provide ease of decontamination, an ideal surface should have these features:

1. Be non-absorbent since porous materials are very difficult to decontaminate;
2. Contain as few acidic groups as possible since these groups are chemically reactive;
3. Have a low moisture content;
4. Be protected from exposure to solvents or chemicals which attack the material;
5. Possess sufficient chemical resistance to withstand decontaminating agents;
6. Be capable of withstanding abrasive action;
7. Be smooth with no cracks and ledges;
8. Be resistant to heat and radiation.
Since no one material exhibits all these features, compromises have to be made with respect to use of materials which have deficiencies with respect to decontamination. As mentioned above, often the permanent surface will be covered by a temporary surface which can be easily removed for decontamination purposes. Among the more frequently used strippable coatings are latex paint, PVC or PVA sheet, coated paper or polyethylene.63

With respect to the choice of decontaminating agent, almost all detergents will do the job.42,63 The constituents of a detergent which aid in the decontamination process are:63 a wetting agent to emulsify oils and grease, a suspending agent to capture dirt and prevent redeposition, and complexing agents to react with the contaminants to form compounds. These agents have the virtue of cleaning the surface without damaging the integrity of the surface. However, repeated applications can cause damage in polyethylene and PVC.63 Acids and other aggressive chemical agents, such as chromic, sulfuric, nitric, phosphoric and citric acid and sodium hydroxide, aqua regia and acetone may be used on various surfaces, but these remove some of the surface material with the contaminant.42 This approach may be undesirable for equipment that must be reused. Once damaged, these surfaces then tend to collect contamination easily. If acid or other chemicals are not effective, then sandblasting with a fine sand may be tried. This latter method may result in contamination of the sandblaster as well as the abrasive agent.

A number of commercially available decontamination agents are available on the market under various trade names. Summaries of decontamination approaches can also be found in the literature.66,67

2. Decontamination Approaches

a. Working Areas

Initial decontamination efforts should be directed toward removal of loose contamination. In the case of floors or other horizontal surfaces, the surface may be dry vacuumed with special vacuum cleaners equipped with HEPA filtering of the exhaust. This procedure will eliminate
a lot of the easily removed contamination. Then the surface may be wet mopped first with soap and water or detergent, and vacuumed up. For smaller contaminated areas, swabbing may be used. The use of swabs (detergent-soaked rags) should be with a wiping motion, not rubbing, and the wet rags should be frequently discarded as radioactive waste. Following this, the area should be resurveyed and remaining contaminated areas marked. If fixed contamination is indicated by the survey results, the area should be washed with a solution containing complexing agents. If contamination remains after several attempts, then removal may be undertaken with abrasive material (metal polish, abrasive creams, steel wool, etc.). If the contamination persists, the surface may need to be removed by scabbling. However, an alternative is that the level may be low enough that a seal may be used (paint, concrete, or other material) over the radioactivity. Application of any specific procedure, and the decontaminating agent used, depends upon surface characteristics.

b. Equipment

Wash all glassware with chromic acid cleaning solution or with concentrated nitric acid as a routine procedure following use. If these leave the glassware still contaminated, mineral acids or solutions of ammonium citrate, trisodium phosphate, or ammonium bifluoride may be tried. If decontamination is difficult, it is usually more convenient to replace the items. In order to prevent accidental return to stock or to other use, break discarded glass equipment before disposal.

Metal objects may sometimes be decontaminated with dilute mineral acids, a 10% solution of sodium citrate, or ammonium bifluoride. The use of strong acids on metal tools may corrode them, thereby causing greater difficulty in future decontamination procedures. If other procedures fail, hydrochloric acid may be used on stainless steel. Since this will remove some of the surface, use it only as a last resort, unless the equipment is to be discarded as decontaminated scrap. Brass polish is an excellent decontaminant for brass. Oxalic acid generally is satisfactory for rusty surfaces. Titanium dioxide paste is a good agent
for removing fission products from metallic surfaces; do not let the paste harden, for it is then extremely difficult to remove.

Plastics may be decontaminated with ammonium citrate, dilute acids, or organic solvents.

c. Clothing

Generally, clothing used during decontamination operations consists of plastic garments and/or paper suits (Tyvek) which are discarded at the end of the operation when the worker leaves the contaminated area. Figure 16.7 shows a worker, involved in volume reduction of highly-contaminated plutonium gloveboxes, dressed in a plastic suit which is worn over paper coveralls. In this case, plastic garments, paper suit, gloves and shoe covers will all be discarded.

For regular protective clothing, if the contamination levels are not too high, the garment may be washed in a washing machine, utilizing soaps or chemical agents (detergents with certain additives, such as citrus acid) to attempt decontamination. For very high levels of contamination and/or involving highly hazardous radionuclides, it is generally more advantageous to discard the clothing, rather than to try to clean it.

For operations involving high hazard material, the clothing which is supplied is usually restricted to that specific control area. This helps in the control of contamination since the individual is required to change into other clothes before exiting the area.

d. Personnel

With respect to personnel decontamination, one should follow this guidance: if a few decontamination efforts do not work, call in a physician and/or decontamination efforts should be discontinued when the skin starts to become thin and reddened. If the integrity of the skin is damaged, then absorption of radioactive material may occur leading to potential internal deposition of radioactive material. All personnel decontamination procedures should be reviewed and approved by the plant physician.
Figure 16.7  Worker dressed for tent entry.
(1) Hand Washing

One procedure for washing contaminated skin and hands is the following:

(a) Wash thoroughly for two to three minutes by the clock. Use tepid (not hot) water and a mild soap or detergent, such as Tide or Phisoderm or Radiacwash. Cover the entire surface of the contaminated area with a good lather. Rinse off completely with water. Repeat the process at least three times. Do not use abrasive or highly alkaline soaps or powders.

(b) Eight-minute surgical scrub. If the above procedure is not enough to remove all dirt and contamination, scrub the hands for a period of at least eight minutes by the clock with a liquid or cake soap, hand brush, and tepid water, being sure to brush the entire surface of the hands, especially around the nails and between the fingers. Light pressure should be exerted on the brush - do not press so hard that the bristles are bent out of shape. Eight minutes is usually a sufficient time to allow three complete changes of tepid water and soap. Each one of these three washings should be so thorough that the brush will cover all areas a minimum of four strokes. A convenient routine is to start by scrubbing one thumb, being sure to brush all surfaces, proceed to the space between the thumb and first (index) finger and similarly to each finger and the webs between the finger.

Give attention to the palm and the back of the hand and, finally, scrub the nails and cuticles before proceeding in the same manner with the other hand.

(c) Use an appropriate radiation survey instrument to verify the removal of contamination from the dried area, then use lanolin cream to soften the hands and prevent chapping.
(d) Discard the hand brush and towels after they have been used for the removal of contaminated material (use an active waste can).

(2) Titanium Dioxide to Remove Fission Products

Titanium oxide (TiO₂) may be used as a paste or slurry made by shaking the powder into the wet palm of the hand until a good paste is formed. Run tap water over the hands continually so that the paste is kept wet, and apply this later thoroughly to all hand surfaces, especially around the finger nails, for a minimum time of two minutes.

Rinse off thoroughly with luke-warm water and follow by a thorough washing with soap and water and a hand brush. If any of the paste is left under the nails after washing, it will form a rather hard cake which is difficult to remove.

(3) Potassium Permanganate to Remove Plutonium

(a) Mix an equal volume of a saturated solution of potassium permanganate (KMnO₄) with 1% sulfuric acid solution (0.2 N). Pour this weak acid solution over the wet hands, covering the nails and cuticles thoroughly. Rub the entire surface lightly with a hand brush without applying enough pressure to bend the bristles out of shape.

Use running water ( tepid, not hot), and rinse off after the application has thoroughly covered the hands. Do not continue this procedure for more than two minutes. This process will stain the skin a deep brown.  

(b) Use a freshly prepared 5% sodium acid sulfite solution in the same manner as above, using the hand brush and tepid running water for a two-minute period. This solution will remove the brown stain on the skin. (It is convenient to keep labelled packages containing 10 g NaHSO₃ on hand and dissolve this amount in 200 ml of water.)
The complete procedure above may be repeated several times without appreciable harm to the skin if each washing is limited to two minutes.

An abundance of water is essential. To wash other skin surfaces such as neck, face, ears, etc., the solutions may be applied with absorbent cotton. If another person is manipulating the solution, rubber gloves should be worn as protection from both contamination and permanganate staining.

Recommendations for a skin decontamination kit with respect to supplies needed can be found in Reference 59.

e. Glovebox Approach - General

The initial decontamination step is to remove all items within the box, either for separate treatment or for disposal as active waste. This usually requires that these items be bagged in plastic and removed from the enclosure through a glove port or transfer area, if available. Following this procedure, sweeping or vacuuming of the box surface takes place. The debris collected by these procedures is then also bagged out. Swabbing of the walls and floor of the glovebox is then performed. Alternatively, a water spray may be used in some cases to wash down the walls if criticality safety considerations permit. Liquid from this separation is often collected by siphoning into a liquid waste container. The remainder is then wiped up with rags, and, if feasible, these rags are allowed to dry by evaporation, before being bagged out in a long pouch which is attached to one of the glove ports. Several such washings may be required in order to reduce the contamination levels sufficiently. Radiation surveys of the glovebox surfaces following each washing determine the effectiveness of the decontamination effort. Since the glovebox system is re-used for radioactive material, it is not necessary to clean the box down to very low activity levels. In some cases, as shown in Figure 16.8, it may be necessary to construct a temporary enclosure in order to remove the equipment from a glovebox without creating a loss of control situation which will contaminate the area. In this operation, in
order to dismantle a fairly large piece of equipment, an enclosure was constructed on the front face of the glovebox to insure that airflow was into the enclosure. The face of the glovebox was then removed to dismantle the large piece of contaminated equipment.

f. Hot Cell Approach - General

Hot cells may need to be decontaminated to install new equipment when the nature of the experimental work changes, to make repairs that cannot be done remotely, or to prevent the activity from reaching unmanageably high levels.\textsuperscript{3,56} This cleanup process may require consideration of such things as personnel exposure to radiation, contamination control, criticality, and the handling and disposal of active wastes. The first phase, general cell cleanup, is usually carried out by remote means. Protective coatings, active scrap, small tools, loose debris, etc., can be placed in waste-disposal drums or picked up with a vacuum cleaner. This can be followed by the wiping of machinery and any remaining "hot spots." Liquid wastes are often absorbed in vermiculite or other inorganic substances and discarded along with the solid waste. This first phase is more effective if the work is guided by a high-range survey meter. The high-level waste is removed before direct decontamination takes place.

Cell entries require the wearing of protective clothing (coveralls, caps, shoe covers, and gloves) and respiratory devices. Disposable suits and shoe bags made of paper or plastic film are often worn over the above items if the cell contamination is severe. They are removed and discarded as waste when the person leaves the cell.

Respirators are often worn for short work periods. However, an air-supplied head hood offers more comfort as well as a higher degree of protection for an extended work period. One-piece suits may be used in handling more toxic substances. The suit is also removed and discarded as radioactive waste when the worker leaves the cell. Health Physics surveys of the worker as he discards potentially contaminated clothing, help to control the spread of contamination by discovering
Figure 16.8 Separate temporary contamination control enclosure attached to a glovebox.
contaminated items prior to the worker leaving the cell. There is usually more than one worker in the cell at a given time, and this allows each to assist the other in removal of potentially contaminated garments. The Health Physics person is used to check each worker before he exits from the transition zone (between contaminated areas and clean areas).

Direct decontamination is often guided by in-cell radiation surveys. Items or areas of highest intensity are removed or cleaned first. This lowers the radiation field, which, in turn, reduces the exposure to the decontamination crew and health physics surveyor. The remaining tools and equipment can now be removed to an adjacent room or cell where they are further wiped down. Disposition of these items depends upon the success in cleaning, which is determined through surveys. The items may be sent to a "hot lab" equipment storage area pending future use, or dismantled and cleaned again using more effective methods and equipment.

In-cell containment boxes are often used within the cell for operations which have a high potential for spreading contamination. These units generally have such high levels of activity that discarding the entire box upon completion of the experiment may turn out to be more economical than decontamination.\(^3\) Since these units may need to be somewhat dismantled, monitoring service is also required for this operation.

Communication between the crew in the cell and those on the outside of the cell is hindered by the protective equipment and the surroundings. Respirators, coveralls, plastic suits, the noise of supplied air, shielding walls, and distance all act to preclude effective communication. For this reason, it is important that the crew have some means, such as radio contact, of communicating with personnel outside the cell.

J. Waste Disposal

A consequence of using radioactive material is that ultimately one must consider what must be done to dispose of this material safely. Of all the possible radionuclides in use, many of these have sufficiently long half lives so that the material will still be around long after a given experiment has been completed. This poses a problem since there is no way
to treat, or process, the material in order to alter the half life of the radionuclide. When the half life is relatively short, one may retain the material in storage until the activity decays away. When the waste contains highly radioactive, long-lived radionuclides, special disposal methods are required. The proper disposal of radioactive waste is a matter of concern and is regulated by federal and state regulatory agencies.

1. Types and Sources of Wastes

Radioactive wastes may be classified according to their physical state as solid, liquid and gaseous. Practically all operations with radioactive materials produce small amounts of solid waste in the form of contamination of the materials or equipment used in the operation. In certain chemical studies and other experiments, solutions of radionuclides are used which result in the production of liquid waste. In these studies, exchange reactions may produce solid radioactive waste in the form of precipitates or treatment columns (ion exchange resins). Certain chemical reactions or thermal reactions can lead to the production of radioactive waste when their useful life is over. Decontamination of enclosures may often produce both solid and liquid radioactive wastes to be dealt with. Certain experiments may result in the release of radioactive gases followed by the production of both solid and liquid radioactive waste. Sometimes, large pieces of contaminated equipment may need to be disposed of following the shutdown of an experiment or facility.

Considering the three basic forms of radioactive waste, other categories or classifications may also affect the method of disposal: soluble or insoluble, combustible or noncombustible, with respect to solids. The radionuclide content with respect to the half lives and radiotoxicity of the constituents will be important factors in the treatment of the radioactive waste. In addition, the activity levels will also dictate the potential disposal mechanism which can be used.

There are four main activities which are the basic sources of radioactive waste production. The first is the mining, milling, feed preparation and fuel manufacturing activities, called the "front end" of the nuclear fuel cycle. Wastes from these activities generally result in
small amounts of natural radioactivity (\(^{238}\)U, \(^{235}\)U) products -
\(^{230}\)Th and \(^{226}\)Ra in tailings being of most concern.\(^70\) Second, the
largest source of radioactive waste in the sense of contained activity, is
the fuel irradiation and processing activities. The chemical processing of
the irradiated fuel results in highly radioactive waste containing fission
products, activated reactor materials, corrosion products and chemicals.
The third source is activation of non-fuel materials in reactors or and
accelerator components. This includes samples inserted into reactors or
accelerators, as well as reactor and accelerator structural materials and
impurities in coolants. The fourth source is the use of radionuclides in
medical, radiopharmaceutical, industrial and scientific research applica-
tions. It should be noted that an operating power reactor is a potent
source of radiation and that release of some of this radioactivity occurs
under normal operating conditions.\(^70\) To minimize those releases, certain
cleanup systems are utilized which remove radioactive material from the
effluents so that the discharge of radioactive effluents is ALARA.
References 70-72 discuss some of these systems for PWR and BWR units. In
the removal of the radioactive products by these systems, residues and
resins containing the removed radioactivity become solid radioactive waste
which must be dealt with.

2. Disposal Philosophy

The objectives of a radioactive waste management program are to
determine the steps necessary for the safe disposal of radioactive waste
and to see that these steps are followed. The necessary control mechanisms
may be quite complex and there may be many types of waste to deal with.
However, there are two basic approaches which have been generally applied,
in the case of radionuclides which do not have short half lives; these
are:\(^42\)

(1) Concentrate and Contain - Reduce the volume of the
radioactive waste to concentrate the radionuclide and then safely store
the waste in a controlled area (contained). For very highly radioactive
material, the waste may be solidified for long-term storage. This approach
is generally applied in the case of high levels of long-lived activity for which indefinite storage is indicated. By reducing the volume of contaminated material, one lessens the cost of disposal. These wastes are generally stored in isolated areas to minimize the chance of contact with humans or ecological systems.

(2) Dilute and Disperse - Use air or water to dilute the given concentration so that when released it will be within the release criterion. This requires that the initial concentration be of low activity to begin with. By dispersing the diluted concentration into the atmosphere or into a waterway, a further reduction in the concentration is achieved. Disposal by this method is regulated by federal standards (for example, the DAC values for allowable offsite concentrations in DOE Order 5480.xx) which also require that one consider possible ways to keep releases well below these limits (ALARA).

3. Solid Waste Disposal

A variety of radioactive waste products which vary in half life and activity may be encountered when dealing with solid radioactive wastes. This includes such materials as paper, rubber gloves, glassware, metal tools, animal carcasses, plastics and large equipment items. The cost of disposal will depend directly on the volume and weight of the radioactive waste produced. To minimize the waste volumes requires advanced planning, facility and equipment design and control of work methods. It is essential to separate ordinary nonradioactive trash from solid radioactive waste, at the point of origin. For this reason, solid radioactive waste containers should be clearly identified with the radiation symbol and easily distinguishable from ordinary trash containers. A number of suitable containers should be distributed through a work area. Figure 16.9a shows some solid radioactive waste containers. The basic collectors are a 28.3 l (1 ft³) fiber drum and an 18.9 l (5-gallon) pail. A stainless steel secondary container (Blickman can) is generally supplied with the containers. The cover of the secondary is opened by stepping on a treadle. The sliding cover is supplied with a
mechanical spring to ensure the return of the cover to the closed position. For cases in which larger quantities of solid waste may be produced, a 127.4 l (4.5 ft³) cardboard carton (see TV carton in Figure 16.9b) may be used. For waste expected to produce readings > 2 mGy/h (200 mrad/h) at the receptacle surface, a shielded secondary container (approximately .05 m lead equivalent) can be supplied (see Figure 16.10). Larger shielded containers are also available.

The waste producer is required to provide documentation of the identity and estimated quantity of radioactivity and see that the waste is properly labeled and contained. Because disposal is governed by the most restrictive limit for radionuclides in a mixture, and waste acceptance criteria state that some materials are prohibited from the waste, and waste volumes should be kept to a minimum to reduce waste handling costs, radioactive wastes are segregated at the source. Solid waste is segregated into combustible and noncombustible, as well as compressible and non-compressible. One further segregation of solid wastes is made. If the waste consists of a emitting material of $^{233}$U or radionuclides with $Z≥93$, of half life $>20$ y, it is designated transuranic (TRU) waste if the radionuclide concentration is $> 3.7 \times 10^6$ Bq/kg (100 nCi/g). Secondaries are labeled to indicate the category of waste permitted in the container (see Figure 16.8).

By segregating compressible waste from noncompressible, one is then able to compact the waste to achieve a volume reduction and a subsequent cost saving. Combustible waste in some cases may be effectively treated by incineration to greatly reduce the waste volume. It is necessary to separate TRU and non-TRU waste since these will be disposed of differently. At present, TRU waste is sent to an above-ground interim storage site for subsequent shipment to the Waste Isolation Pilot Plant (WIPP).

Special requirements must be met for certain solid waste such as biological materials (animal carcasses, other biological material). These materials tend to form gases or produce liquids as they decompose. No liquid is permitted as free liquid (not absorbed in a host material) in solid waste and there are limits on the allowable pressure in a container ($< 7$ psig). To prevent bacterial action which could cause gas buildup
Figure 16.9a Solid radioactive waste containers.
Figure 16.9b  TV carton secondary container.
Figure 16.10  Shielded SRW container.
and/or the formation of liquids, preservatives such as slaked lime and
dessicants or absorbents should be used and the wastes sealed in plastic
bags prior to being placed in the container.

Bagged waste, such as that from gloveboxes or hot cells, is often TRU waste. These are generally handled in metal containers, either
the 18.9 l (5-gallon) pails or paint cans, which can be sealed, or 208 l
(55-gallon) drums which are sealed at the time of pickup (see Figure
16.11). Not shown in the figure are 114 l (40-gallon) drums which are also
used. These wastes are generally highly radioactive and/or radiotoxic
α wastes (Pu, Am, etc.), which require more care in their handling.
All wastes reading > 0.2 mGy/h (200 mrad/h) are sealed in such metal pails
or metal drums.

When containers are full, or when the reading on a container
approaches the limit, health physics surveys the container for both the
external radiation reading and for possible surface contamination (by
smear survey). If survey results are within the limits, the waste
container can be picked up. Pickup consists of removing the fiber drum
insert, sealing the lid of the drum and removing it from the area to a
waste storage area. In the case of pails or metal drums, the metal
container cover is sealed when the waste is picked up.

Several treatment methods are available for solid radioactive
waste disposal. The most widely used method is burial. This may be at a
commercial burial site, at a designated DOE contractor site or sometimes
on the facility site. Fiber drums and other containers which are brought
to the waste storage area are transferred to bins for shipment out to a
DOE-owned burial site. Figure 16.12 shows a number of such bins loaded on
a truck, prior to leaving for the burial site. These bins are low-level
radioactive waste and do not require shielding of the bins.

For compressible waste, the material may first be put into a
baler to reduce the volume (average reduction factor of about 4) before
the material is put into the bin. Baling is not done if the material reads
> 0.2 mGy/h (200 mrad/h), and/or contains α activity and other than
normal uranium and/or contains biological material.

Incineration can also achieve a dramatic volume reduction and
is often used for low level radioactive wastes. One must exercise care in
Figure 16.11 TRU solid radioactive waste container.
the use of incineration when volatile radionuclides (such as $^{125}$I) may be involved. This could result in airborne $^{125}$I being carried off during incineration. A further problem may occur when incinerating vials of liquid scintillation samples. Sometimes, the combination of the plastic vial and the scintillation cocktail results in incomplete combustion.⁶⁹

Finally, for some radionuclides, the half lives will allow storage of the waste until sufficient decay of the radionuclides occurs so that the waste can be considered trash. Then, such waste can be disposed of as trash in a landfill.

TRU wastes are put into bins similar to those shown in Figure 16.12, except that the bin is painted white to indicate TRU waste. These bins are not buried but are stored above ground. One further refinement for TRU waste is that the waste must be packaged in rigid containment. This may be accomplished for bins by using plywood liners. Non-TRU wastes are packaged in the regular bins and shipped out for burial.

4. Liquid Waste Disposal

The treatment of liquid wastes is generally more expensive than that of solid wastes. So, it is desirable to keep liquid waste to a minimum. Moreover, the treatment of liquid waste ultimately leads to residues which are converted to solid wastes since disposal sites are reluctant to accept waste in liquid form. The basic approach in control of liquid wastes is also segregation at the source, collection of concentrated wastes in containers, and treatment by various methods to remove radioactivity from the waste. The nature of the waste needs to be identified at the source. If the waste is acidic, it should not be mixed with alkaline wastes.⁶⁹ Precipitation may occur and the heat from the chemical reaction could result in the release of active aerosols. Non-aqueous wastes should be kept separate from aqueous solutions or this could cause problems later in the treatment of these wastes. Liquids containing organic compounds must not be mixed with those containing inorganic compounds.

Collection of the waste is generally by polyethylene carboys. These are usually protected by a steel secondary container to provide a
Figure 16.12  Shipment of Low Specific Activity (LSA) bins.
second line of defense in case of leakage. Because of the possible breakage factor, glass is often avoided. However, some non-aqueous solutions may chemically attack polyethylene, so these should not be used for non-aqueous solutions. Liquid waste containers should be kept closed to prevent evaporation.

The experimenter is supplied with these radioactive liquid waste containers (see Figure 16.13). These can be unshielded with a stainless steel secondary as shown in the figure. Or, the containers can be supplied with a shielded secondary. The user is expected to supply information with respect to the content of the liquid wastes. In particular, the identity and quantity of the radionuclides and volume of each entry, are to be recorded, as well as any other pertinent information regarding the potential chemical activity or hazards of the solution. When the containers are full, they are surveyed by health physics to determine radiation level and potential surface contamination. The containers are then collected and processed by various means (discussed later) and the effluent discarded via a waste treatment plant.

A second system which is used consists of retention tanks (see Figure 16.14), which are connected to the sink drains in all areas in which radioactivity is used. These are 5.7 m³ (1500 gallon) capacity glass-lined tanks, which are generally operated in pairs. No radioactivity is permitted in laboratory drains, so this system provides a positive backup control to guard against mistakes. When one tank fills up, flow is diverted to the other tank. A sample from the full tank is obtained and measured for radioactivity. If the radioactive content is less than the allowable discharge level, the tank is directly discharged to the waste treatment plant. If above the permitted level, the contents of the tank are pumped out into a tank truck and taken to be processed as liquid radioactive waste. The effluent is then discarded via the waste treatment plant. This consists of essentially four 265 m³ (70,000 gallon) hold-up tanks, where the pH is adjusted and final discharge control is maintained. That is, a radioactivity check is made before final discharge to ensure that the radioactivity level is within the limits for discharge.
Figure 16.13  Liquid radioactive waste (LRW) containers.
Figure 16.14 Typical retention tank system.
The treatment of liquid radioactive wastes may be by chemical methods, ion exchange, evaporation, incineration in the case of organic solvents (scintillation counting samples), and storage and decay (applicable to short half life radionuclides). Chemical methods are suitable for the case in which the required reduction in activity is not too large (approximately 90% removal can be achieved). Chemical methods include coagulation and precipitation. In each of these processes, the residue or sludge which is formed is converted to solid waste, generally by solidification in concrete or cement. In the ion exchange process, the liquid is passed through a resin which concentrates the contaminant in the bed or column. The resin can then be treated as solid active waste. Evaporation is useful when the liquid has a low content of dissolved solids. In the evaporation process, the liquid is boiled off and the resultant concentrate, which will contain almost the entire radioactive content can then be converted to a solid waste by absorption in a porous material, such as vermiculite. Incineration is mainly of use in the case of vials containing organic solvents, such as are produced during medical tests (radio-immunoassay) or during other liquid scintillation applications. The successful use of the incineration method requires that careful design of the incinerator be undertaken.

A number of the above treatment methods are used in order to obtain the most economical means of treatment of the liquid radioactive waste. However, if incineration is not available, scintillation liquids are normally packaged and stored until shipped to a hazardous waste disposal facility to be incinerated. Many scintillation cocktail fluids are classified as hazardous waste as defined by 40 CFR 261, Subparts C and D. These fluids must not be absorbed in vermiculite. When liquid immobilization by absorbents, such as vermiculite, is used, at least twice as much absorbent as is actually needed for complete absorption is added.

5. Gaseous Waste Disposal

Gaseous wastes include radioactive gases, vapors or fumes produced during an experiment, the leakage of a particular radioactive gas being used in an operation, fission product gases or particulates which
are carried by air from a reactor, activation products produced in an accelerator which are entrained in the exhaust, and particulates arising from surface abrasion in machining. In mines, the release of radon occurs during the operations involved in mining uranium ore. In the latter case, control can usually be obtained by proper design of ventilation to the mine to reduce the radon concentrations. The exhausted radon gas is vented to the area outside of the mine and is quickly dispersed so that it adds little to the concentration in that area. Moreover, the short half life of the radon daughter chain assures that most of these products have completely decayed within a few hours.

Control of airborne particulates is often accomplished either by providing local exhaust ventilation or by individually hooding or enclosing the operation. Local exhaust ventilation is accomplished by the use of flexible exhaust tubing (called elephant trunks) in the immediate vicinity of the operation to catch the particulates as they are formed and direct the particles into the exhaust system. The exhaust stream may then be passed through a filtering system before discharge. Local exhaust ventilation is used when the activity level and the radiotoxicity of the material is low. When large amounts of radioactivity, and/or highly hazardous materials are involved, the process is usually performed in an enclosure, which will then be followed by tandem high efficiency filtration (HEPA filters) of the exhaust prior to discharge. One should note, that when the filters are changed, the replaced filter, itself, becomes solid radioactive waste because of the trapped radioactive particulates.

For radioactive gases, special systems need to be supplied to remove these before discharge. Activated charcoal filters have proven successful for removal of radiiodines. Silica gel and other adsorbing materials have been used for tritium water vapor removal. For some processes, one may need to use caustic scrubbers or adsorbers to remove chemical fumes and gases.

In some applications, such as in reactors, it is possible to design a holdup system which delays the release of effluents. For those radioactive gases with short half lives, this approach results in a significant reduction in the radioactive content. Following holdup, the
effluent is then passed through filters to trap particulates before being exhausted through tall stacks. The tall stacks utilize the dispersion characteristics of the atmosphere to achieve the desired concentration reduction at the site boundary.

For many applications, the required dilution and dispersion may be achieved by controlled release of the radioactive gas. That is, a quantity of radioactive gas is slowly released over a period of time such that the concentration at the site boundary or the point of potential exposure of the population is well within allowable limits. This method takes advantage of the initial dilution in the exhaust volume and the dispersion in the atmosphere.

K. Transportation of Radionuclides

In addition to shipment of radioactive wastes by certain commercial carriers, a large number of shipments involving radioactive materials for various uses also takes place. A major portion of these shipments involve small or intermediate quantities of radionuclides in relatively small packages. Many of these radionuclides are used for medical applications—either diagnosis or therapy. However, others are used by schools, laboratories and industry. Many of these radionuclides are shipped by rapid delivery services, air freight or air express.

Prior to 1966, the Interstate Commerce Commission was charged with regulating the transportation of hazardous materials between the states. In 1966, the Department of Transportation (DOT) was created and given the regulatory responsibility for safety in the transportation of all hazardous materials. This responsibility includes shipments by all modes of transport, except for postal shipments. Since that time, the regulations governing packaging and shipment of radioactive materials from the safety standpoint can be found in 49 CFR Parts 100-199. Amendments appear in the Federal Register as they are implemented. The Department of Energy requirements for packaging and shipment of fissile and other radioactive materials are contained in DOE Order 5480.1, Chapter III. In addition, the U.S. Nuclear Regulatory Commission, which has responsibility for safety in the possession, use and transport of byproduct,
source, and special nuclear material, have requirements for their licensees regarding transportation of radionuclides in 10 CFR 71.\textsuperscript{77} Table 16.3 which has been taken from Reference 78, summarizes the federal regulations with respect to the transportation of radioactive materials.

**TABLE 16.3**

**SOURCES OF FEDERAL REGULATIONS**

<table>
<thead>
<tr>
<th>U.S. Department of Transportation's Hazardous Materials Regulations</th>
<th>Title 49, Parts 100-177 and 178-199</th>
</tr>
</thead>
<tbody>
<tr>
<td>49 CFR 106</td>
<td>Rulemaking Procedures</td>
</tr>
<tr>
<td>49 CFR 107</td>
<td>Hazardous Materials Program Procedures</td>
</tr>
<tr>
<td>49 CFR 171</td>
<td>General Information, Regulations and Definitions</td>
</tr>
<tr>
<td>49 CFR 173</td>
<td>Shippers - General Requirements for Shipments and Packagings</td>
</tr>
<tr>
<td>49 CFR 174</td>
<td>Carriage by Rail</td>
</tr>
<tr>
<td>49 CFR 175</td>
<td>Carriage by Aircraft</td>
</tr>
<tr>
<td>49 CFR 176</td>
<td>Carriage by Vessel</td>
</tr>
<tr>
<td>49 CFR 177</td>
<td>Carriage by Public Highway</td>
</tr>
<tr>
<td>49 CFR 178</td>
<td>Shipping Container Specifications</td>
</tr>
<tr>
<td>49 CFR 179</td>
<td>Specification for Tank Cars</td>
</tr>
</tbody>
</table>

**Title 10**

U.S. Nuclear Regulatory Commission

10 CFR 71 Packaging of Radioactive Materials for Transport and Transportation of Radioactive Materials Under Certain Conditions

**Title 39**

U.S. Postal Service


Much of the material in the rest of this discussion has been adapted from Reference 78. Table 16.4 lists pertinent sources for international regulations. The most recent DOT regulations, as reviewed in Reference 78, are very similar to the IAEA regulations referred to in Table 16.4.
TABLE 16.4

AVAILABILITY OF INTERNATIONAL REGULATIONS


Many of the NRC Agreement states, as well as other states, have required shippers to conform to DOT regulations with respect to intrastate shipments.

For purposes of the federal regulations, radioactive materials are defined as those materials which spontaneously emit ionizing radiation and have a specific activity in excess of $7.4 \times 10^4$ Bq/kg (2 nCi/g) of material. Materials with radioactive concentrations below this are not regulated by either DOT or IAEA with respect to transport of radioactive materials.

1. Packaging Requirements

Three factors which influence the packaging requirements are the radionuclide(s) involved, the quantity of the radionuclide, and the form of the radionuclide material. The term special form is used to describe radioactive materials which if released, may present an external radiation hazard, but are sufficiently contained so that no loose radio-
activity is expected to be released. This implies some characteristic such that loose radioactivity will not be released. For example, a radioactive source in the form of a metal bar, or an encapsulated source such that radioactivity will only be released by destruction of the capsule. Normal form refers to any radioactive materials which do not meet the qualification of special form. Generally, the regulations allow substantially larger quantities of special form materials to be transported. Depending upon the relative hazard of the radionuclide, the precautions to be taken will vary. In 49 CFR 173.435, information on more than 250 radionuclides can be found. In addition, procedures for dealing with unlisted or unknown, or mixtures of radionuclides can be found in Section 173.433. The quantity of the radionuclide allowed to be transported under certain conditions is also related to the relative hazard that the material represents and is related to the potential internal hazard which could result from a release.

a. Type A Packaging

In the present scheme of packaging requirements, every radionuclide is assigned a limit for the total amount of radioactivity of that radionuclide which can be transported in a given type of package. So, there is a quantity listed for the material when it is in normal form, as well as, when it is in special form. These quantities (shown in Table 16.5 for selected radionuclides) are the limits for what is referred to as Type A packaging. In the table, the $A_i$ value refers to the radionuclide in special form and the $A_i$ value is that for normal form. If a given quantity of a radionuclide in a specific form exceeds the limit listed for that form, then Type B packaging is required.

For a mixture of radionuclides, one may usually use the ratio rule:

$$\frac{(\text{Activity})}{A_i} + \frac{(\text{Activity})}{A_i} + \ldots \leq 1, \quad 16.3$$

in which $A_i$ represents the appropriate limit for the particular form (special or normal) for radionuclide $i$, and the Activity$_i$ is the activity of that component in the mixture.
TABLE 16.5
TYPE A PACKAGE QUANTITY LIMITS FOR SELECTED RADIONUCLIDES
(ADDITIONAL RADIONUCLIDES ARE LISTED IN 49 CFR 173.435)

<table>
<thead>
<tr>
<th>Symbol of Radionuclide</th>
<th>Element and Atomic Number</th>
<th>$A_1$(Bq)* (Special Form)</th>
<th>$A_2$(Bq)* (Normal Form)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}$C</td>
<td>Carbon (6)</td>
<td>$3.7 \times 10^{13}$</td>
<td>$2.22 \times 10^{12}$</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>Cesium (55)</td>
<td>$1.12 \times 10^{12}$</td>
<td>$3.7 \times 10^{11}$</td>
</tr>
<tr>
<td>$^{99}$Mo</td>
<td>Molybdenum (42)</td>
<td>$3.7 \times 10^{12}$</td>
<td>$7 \times 10^{11}$</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>Uranium (92)</td>
<td>$3.7 \times 10^{12}$</td>
<td>$7.4 \times 10^{9}$</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>Radium (88)</td>
<td>$3.7 \times 10^{11}$</td>
<td>$1.85 \times 10^{9}$</td>
</tr>
<tr>
<td>$^{201}$Pb</td>
<td>Lead (82)</td>
<td>$7.4 \times 10^{11}$</td>
<td>$7.4 \times 10^{11}$</td>
</tr>
</tbody>
</table>

*Divide Bq by $3.7 \times 10^{10}$ to obtain Ci,

NOTE 1: Quantities exceeding Type A package limits require Type B packaging.

To qualify as a Type A package, the package must be adequate to prevent loss or dispersal of the radioactive contents, and to maintain its radiation shielding ability, if the package is subjected to normal conditions during transport. Typical Type A packages are shown in Figure 16.15, and these conform to the DOT Specification 7A (49 CFR 178.350). Each shipper must make his own assessment and certification of the particular package design with respect to the performance criteria and be prepared to provide a complete certification and documented safety analysis to show the requirements have been met.

Low specific activity (LSA) materials present a reduced hazard because of limited radioactivity. Some LSA materials are designated by name, such as uranium ores and concentrates or unirradiated natural or depleted uranium. For other radionuclides, concentration limits apply for $^{3}$H$_2$O, the limit is $1.85 \times 10^{14}$ Bq/m$^3$ (5 mCi/ml). The allowable concentration values for other radionuclides are related to their normal form values ($A_2$). If the activity is uniformly dispersed, the LSA concentration limits are:
Figure 16.15  Examples of Type A packaging.

\[ A_2 \leq 1.85 \times 10^9 \text{ Bq (0.05 Ci)} \]
\[ \text{Activity/kg} = 3.7 \times 10^6 \text{ Bq/kg (0.1 } \mu \text{Ci/g)} \]

\[ 1.85 \times 10^9 \leq A_2 \leq 3.7 \times 10^{10} \text{ Bq (1 Ci)} \]
\[ \text{Activity/kg} = 1.85 \times 10^8 \text{ Bq/kg (5 } \mu \text{Ci/g)} \]

\[ A_2 \geq 3.7 \times 10^{10} \text{ Bq (1 Ci)} \]
\[ \text{Activity/kg} = 1.11 \times 10^{10} \text{ Bq/kg (300 } \mu \text{Ci/g)} \]

When mixtures are present, one may use the ratio rule, similar to that in equation 16.3. In this case, one adds up all the material in one category of \( A_2 \) values and divides by the concentration limit for that category, and proceeds in this manner for each \( A_2 \) category. If the summation of the ratios for each of the three categories is less than one, the material can be considered LSA. Most radioactive shipments will end up in the LSA category. These shipments usually are sent out in essentially Type A packaging. These shipments are referred to as "non-exclusive use" transportation, and must conform to the LSA limits given above. Exclusive use means that the consignor has exclusive use of the transport conveyance. No loading or unloading can be carried out unless under the direction of the consignor or the consignee. If the transporter uses an "exclusive use" vehicle, the packaging restrictions
are relaxed and need not meet Type A specifications. However, the material must be in a strong, tight package and the vehicle must be a closed transport vehicle. In addition, exclusive use LSA shipments must have packages marked "Radioactive LSA" (see Figure 16.12) and the vehicle must be placarded "Radioactive Material."

b. Type B Packaging

Type B packaging must meet all the requirements for a Type A package and must withstand certain serious accident damage tests. The package must show no loss of containment and only limited loss of shielding. Typical Type B packages are shown in Figure 16.16. As indicated in the figure, these containers must pass the accident tests in 10 CFR 71.77 These include the following:

Figure 16.16  Typical Type B packagings.
(1) A 9.1 m (30 ft) free drop onto an unyielding surface.

(2) A puncture test which is a free drop, over 1 m (approximately 40 inches) onto a .15 m (6 in.) diameter steel pin.

(3) Thermal exposure at 1475°F for 30 min.

(4) Water immersion for 8 hours (for fissile material packaging only).

Except for a limited number of Type B packages described in the regulations (i.e. DOT-6M), all Type B packaging designs require prior approval of the USDOE or NRC before use.

c. Fissile Material Packaging

Over and above radionuclide content, the shipping of fissile material requires certain packaging and shipment procedures to ensure against a criticality incident. Specific requirements are discussed in 49 CFR 173.451 through 173.459 of the DOT regulations and in 10 CFR 71 of the USNRC regulations. The packaging must ensure against nuclear criticality under both normal and hypothetical accident test conditions, and must also prevent loss of contents during transport. Fissile materials are classed into one of three groups (see Table 16.6), according to the degree of control needed to assure nuclear criticality safety.

**TABLE 16.6**

**SHIPMENT CONTROLS FOR FISSILE RADIOACTIVE MATERIALS**

49 CFR - SECTION 173.455

1. **Fissile Class I** - Packages may be transported in unlimited numbers (Transport Index is based only on external radiation levels).

2. **Fissile Class II** - Number of packages limited by aggregate maximum of transport indexes of 50, (50 unit rule). No single package may exceed a transport index of 10. Transport index shall be based on criticality or external radiation level basis, whichever is most restrictive.

3. **Fissile Class III** - Shipments of packages which do not meet the requirements of Fissile Class I or II. Controlled by specific arrangements between the shipper and carrier. (See Section 173.457(b).)
2. **Radiation Limits**

The regulations prescribe radiation limits for the external dose rate for radioactive material packages during transport. These limits are shown in Table 16.7, adapted from 49 CFR 173. The term transport index, which appears in the table, is defined in terms of the maximum dose rate at 1 meter from any accessible exterior surface of the package. It is expressed in units of 10 μSv (1 mrem/h). So, a maximum reading of 100 μSv/h (10 mrem/h) at a meter away from the exterior surface of the package has a transport index (TI)=10. As indicated in Table 16.7, no single package should have a transport index greater than 10, unless it is being shipped by an "exclusive use" vehicle. The TI per package limit is also reduced to 3 when the package is shipped aboard passenger-carrying aircraft.

<table>
<thead>
<tr>
<th>Table 16.7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RADIOACTIVE MATERIALS PACKAGES MAXIMUM RADIATION LEVEL LIMITATIONS</strong></td>
</tr>
<tr>
<td>(49 CFR 173.441(a) AND (b))</td>
</tr>
</tbody>
</table>

**RADIATION DOSE RATE AT ANY POINT ON EXTERNAL SURFACE OF ANY PACKAGE OF RADIOACTIVE MATERIAL MAY NOT EXCEED:**

A. 2 mSv/h (200 mrem/h).
B. 0.1 mSv/h (10 mrem/h) AT ONE METER (TRANSPORT INDEX MAY NOT EXCEED 10).

**UNLESS THE PACKAGES ARE TRANSPORTED IN AN "EXCLUSIVE USE" CLOSED TRANSPORT VEHICLE (AIRCRAFT PROHIBITED) - THEN THE MAXIMUM RADIATION DOSE RATES MAY BE:**

A. 10 mSv/h (1 rem/h) ON THE ACCESSIBLE EXTERNAL PACKAGE SURFACE.
B. 2 mSv/h (200 mrem/h) AT EXTERNAL SURFACE OF THE VEHICLE.
C. 0.1 mSv/h (10 mrem/h) AT TWO METERS FROM EXTERNAL SURFACE OF THE VEHICLE.
D. 20 μSv/h (2 mrem/h) IN ANY POSITION OF THE VEHICLE WHICH IS OCCUPIED BY A PERSON.

In general, the total value of the TI in a shipment is limited to 50, except for "exclusive use" vehicles and cases in which special
arrangements have been made between the shipper and the carrier, satisfying requirements of 49 CFR 173.403(i) and 173.441(b).

The transport index is also used to limit the amount of fissile material in one location under non-exclusive use conditions. In this case, the shipper determines an appropriate TI in accordance with the criteria in 49 CFR 173.455(b). Note that this value of the transport index is not based on the external radiation level but on considerations of nuclear safety. The package may also have an external radiation reading. The TI of the package is then taken as the higher of the two TI values.

In addition to the external radiation level limit, there are also prescribed limits for the level of removable contamination on the package. These limits are shown in Table 16.8 and refer to wipes or smears taken on the package surface. These limits of contamination also apply to the release of the transport vehicle following either "exclusive use" transport or a bulk shipment of LSA material. Health physics surveys and smear samples are provided in order to determine compliance with these limits.

### TABLE 16.8

**REMOVABLE EXTERNAL RADIOACTIVE CONTAMINATION-WIPE LIMITS**

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Maximum Permissible Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bq/m² (dis/min-cm²)</td>
</tr>
<tr>
<td>Beta/gamma-emitting radionuclides; all radionuclides with halflives less than ten days; natural uranium; natural thorium; uranium-235; uranium-238; thorium-232; thorium-228 and thorium-230 when contained in ores or physical concentrates</td>
<td>3.7x10³</td>
</tr>
<tr>
<td>All other alpha-emitting radionuclides</td>
<td>3.7x10²</td>
</tr>
</tbody>
</table>

3. **Warning Labels**

Each package of radioactive material, unless excepted, must be
labeled on two opposite sides, with a distinct warning label. Figure 16.7 shows the three classes of labels used for radioactive materials. The labels are used to alert personnel that the package contains radioactive materials and special handling may be required. A label with an all white background (White I in Figure 16.17), indicates a low external radiation level and the package requires no special handling. If the upper half of the label is yellow (Yellow II in Figure 16.17), the package may have an external radiation level or fissile properties which must be considered during transport. If the package has a yellow label with three stripes, the transport vehicle must be placarded ("Radioactive").

On all the labels, the vertical bars are red. Each label is diamond-shaped, 0.1 m on each side, and has a black solid line border. The following information must be entered on the applicable blank spaces of the label: the name of the radionuclide (the most restrictive radionuclide if a mixture), the activity of the radionuclide and the transport index.

RADIOACTIVE–WHITE I  RADIOACTIVE–YELLOW II  RADIOACTIVE–YELLOW III

Figure 16.17  Radioactive package labels.
The determination of the proper label to use is based upon criteria which are contained in 49 CFR 172.403. These labeling criteria are listed in Table 16.9 for radioactive materials packages and for fissile material packages. Note that the labeling criteria requires the radioactive label for fissile materials, and the appropriate label differs for the fissile class.

4. **Limited Quantities, Instruments and Articles**

Some packages are excepted from some of the requirements of Type A packaging if they contain only limited quantities of radioactivity. These limits may be applied to materials, instruments and articles. The basis for most of these limited quantity values are the $A_1$ and $A_2$ values for the specific radionuclide. The activity limits are shown in Table 16.10, and $A_1$ or $A_2$ values for a given radionuclide can be found in 49 CFR 173.435.

**TABLE 16.9**

**RADIOACTIVE MATERIALS PACKAGES LABELING CRITERIA**

**49 CFR-SECTION 172.403**

<table>
<thead>
<tr>
<th>Transport Index (T.I.)</th>
<th>Radiation Level at Package Surface (RL)</th>
<th>Fissile Criteria</th>
<th>Label Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>RI $\leq 5\mu$Sv/h (.5 mrem/h)</td>
<td>Fissile Class I</td>
<td>White - I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Only</td>
<td>No Fissile Class II or III</td>
</tr>
<tr>
<td>T.I.$\leq1.0$</td>
<td>5 $\mu$Sv/h $\leq$RI$\leq500\mu$Sv/h</td>
<td>Fissile Class I</td>
<td>Yellow - II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fissile Class II with T.I.$\leq1.0$, No Fissile Class III</td>
<td></td>
</tr>
<tr>
<td>1.0$&lt;T.I.$</td>
<td>500 $\mu$Sv/h $\leq$RI$\leq50$ mrem/h</td>
<td>Fissile Class II</td>
<td>Yellow - III</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yellow - III</td>
<td>Fissile Class III</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with 1.0$&lt;T.I.$, Fissile Class III</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 16.10

ACTIVITY LIMITS FOR LIMITED QUANTITIES, INSTRUMENTS AND ARTICLES

<table>
<thead>
<tr>
<th>Nature of contents¹</th>
<th>Instruments and Articles</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Instrument and article</td>
<td>Package</td>
</tr>
<tr>
<td></td>
<td>Limits¹</td>
<td>Limits</td>
</tr>
<tr>
<td>Solids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Special form</td>
<td>$10^{-2} A_1$</td>
<td>$A_1$</td>
</tr>
<tr>
<td>Other forms</td>
<td>$10^{-2} A_2$</td>
<td>$A_2$</td>
</tr>
<tr>
<td>Liquids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tritiated Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt;3.7 \times 10^{12}$ Bq/m³</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$3.7 \times 10^{12}$ to $3.7 \times 10^{13}$ Bq/m³</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$&gt;3.7 \times 10^{13}$ Bq/m³</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Other liquids</td>
<td>$10^{-3} A_2$</td>
<td>$10^{-1} A_2$</td>
</tr>
<tr>
<td>Gases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tritium²</td>
<td>$7.4 \times 10^{11}$ Bq</td>
<td>$7.4 \times 10^{12}$ Bq</td>
</tr>
<tr>
<td>Special form</td>
<td>$10^{-3} A_1$</td>
<td>$10^{-2} A_1$</td>
</tr>
<tr>
<td>Other forms</td>
<td>$10^{-3} A_2$</td>
<td>$10^{-2} A_2$</td>
</tr>
</tbody>
</table>

¹For mixture of radionuclides see Section 173.433(b).

²These values also apply to tritium in activated luminous paint and tritium adsorbed on solid carriers.

The packaging exceptions include not having to provide DOT specification packaging, shipping papers, certification, marking or labeling. Conditions which must be met include:

1. Activity limits per package and, if appropriate, per instrument or article;

2. The materials must be packaged in strong, tight packages that will not leak ANY of the radioactive material during conditions normally incident to transportation;
(3) The radiation level at any point on the external surface of the package cannot exceed 5 \( \mu \text{Sv/h} \) (0.5 mrem/h);

(4) The external surface of the package must be free of significant removable contamination;

(5) For instruments and articles, the radiation level at 0.1 m (4 inches) from any point on the surface of the unpackaged instrument or article may not exceed 100 \( \mu \text{Sv/h} \) (10 mrem/h); and

(6) A prescribed description of the contents on a document which is in, or on, the package, or forwarded with it.

REFERENCES


19. Fraser, D.C. Health Physics Problems Associated with the Production of Experimental Reactor Fuels containing PuO2, Health Physics 12, 1133 (1967).


BIBLIOGRAPHY


NCRP Report No. 37, Precautions in the Management of Patients Who Have Received Therapeutic Amounts of Radionuclides, NCRP Publications, Bethesda, MD (1970).


Faust, L.G., Measured and Calculated Surface Dose Rates of Plutonium and Plutonium Oxide, BNSA-22, Battelle Pacific Northwest Laboratory, Richland, WA (1965).


Steidley, K.D., A 60Co Hot Cell Accident, Health Physics 31, 382 (1976).


16.1 Explain "containment and concentration."

16.2 When should an inert gas be used in a glovebox?

16.3 What factor(s) determine that ordinary gloveboxes may not be adequate for radionuclide work?

16.4 What device may be used instead of a hot cell when the principal hazard is alpha emission?

16.5 What kind of airflow pattern should be designed for glovebox work?

16.6 What are the primary goals of a safety design system?

16.7 What are the four main features to be considered for plutonium-like radionuclides, in devising enclosure safety systems?

16.8 Why is the layout of a facility an important factor in contamination control?

16.9 In addition to design and administrative aspects of control, what actually determines the necessity of additional containment? Why?

16.10 What purpose do fixed monitors perform?

16.11 Name some of the fixed monitors and their specific purposes.

16.12 What is the advantage of continuous monitoring?

16.13 What is the common method used to appraise internal exposure?

16.14 What radionuclide ratio must be known to assess the lung burden of plutonium-239 when using whole body counters?

16.15 What substance is found effective in increasing the urinary elimination of metals? At what time is it most effective?

16.16 Under what circumstances does plutonium exhibit high external radiation fields? What practices may be used to limit external exposure?

16.17 What are the goals that must receive attention in an emergency situation?

16.18 What functions must be carried out in the event of a major radiation incident?

16.19 What factors determine the needed thickness of a particular shielding material?
16.20 What purpose do liners serve in hot cells?

16.21 Why, in determining the thickness of a hot cell wall, should the most intense source that will be used be considered a point source?

16.22 What are some of the individual factors that determine the buildup factor, $b$?

16.23 How should the walls of a hot cell be checked for leakage?

16.24 What principal purposes are served by ventilating systems?

16.25 Why are filters on air inlets to hot cells advisable?

16.26 List some problems that occur in providing and using windows for viewing the inside of hot cells.

16.27 Compare the advantages of the ball-joint manipulator with the advantages of a master-slave manipulator.

16.28 In addition to routine external monitoring of hot cells, for what other events is hot cell monitoring of great importance?

16.29 What hazards may exist in changing air filters for hot cells?

16.30 When is the term contamination generally used?

16.31 List some of the surface decontamination agents frequently used.

16.32 What procedure is generally used for decontaminating skin and hands?

16.33 What compound may be used to remove fission products?

16.34 For what contaminant is a mixture of $\text{KMnO}_4$ and $\text{H}_2\text{SO}_4$ used to remove contamination?

16.35 What precautions are to be taken to remove large pieces of contaminated equipment from gloveboxes?

16.36 What precautions are deemed important when making an entry into a hot cell?

16.37 What are three basic forms of radioactive waste and how are they produced?

16.38 What are the four main activities that are basic sources of radioactive waste production?

16.39 Explain:
   a) concentrate and contain
   b) dilute and disperse.
16.40 What responsibility lies with the waste producer as far as documentation is concerned?

16.41 What is transuranic waste?

16.42 What is the reason to use preservatives for certain solid wastes?

16.43 What problems must be carefully considered when incinerating radioactive waste?

16.44 Why is the acidic liquid waste not mixed with alkaline wastes?

16.45 What purpose do retention tanks serve?

16.46 What special systems need to be supplied to remove radioactive gases?

16.47 What is the limiting specific activity to designate a substance as radioactive for transportation purposes?

16.48 What is "ratio rule"? How is it applied?

16.49 How does Type B packaging differ from Type A packaging?

16.50 Define transport index.