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A Simplified Method for Quantitative Assessment of the Relative Health and Safety Risk of Environmental Management Activities

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**A Simplified Method for Quantitative Assessment
of the Relative Health and Safety Risk
of Environmental Management Activities**

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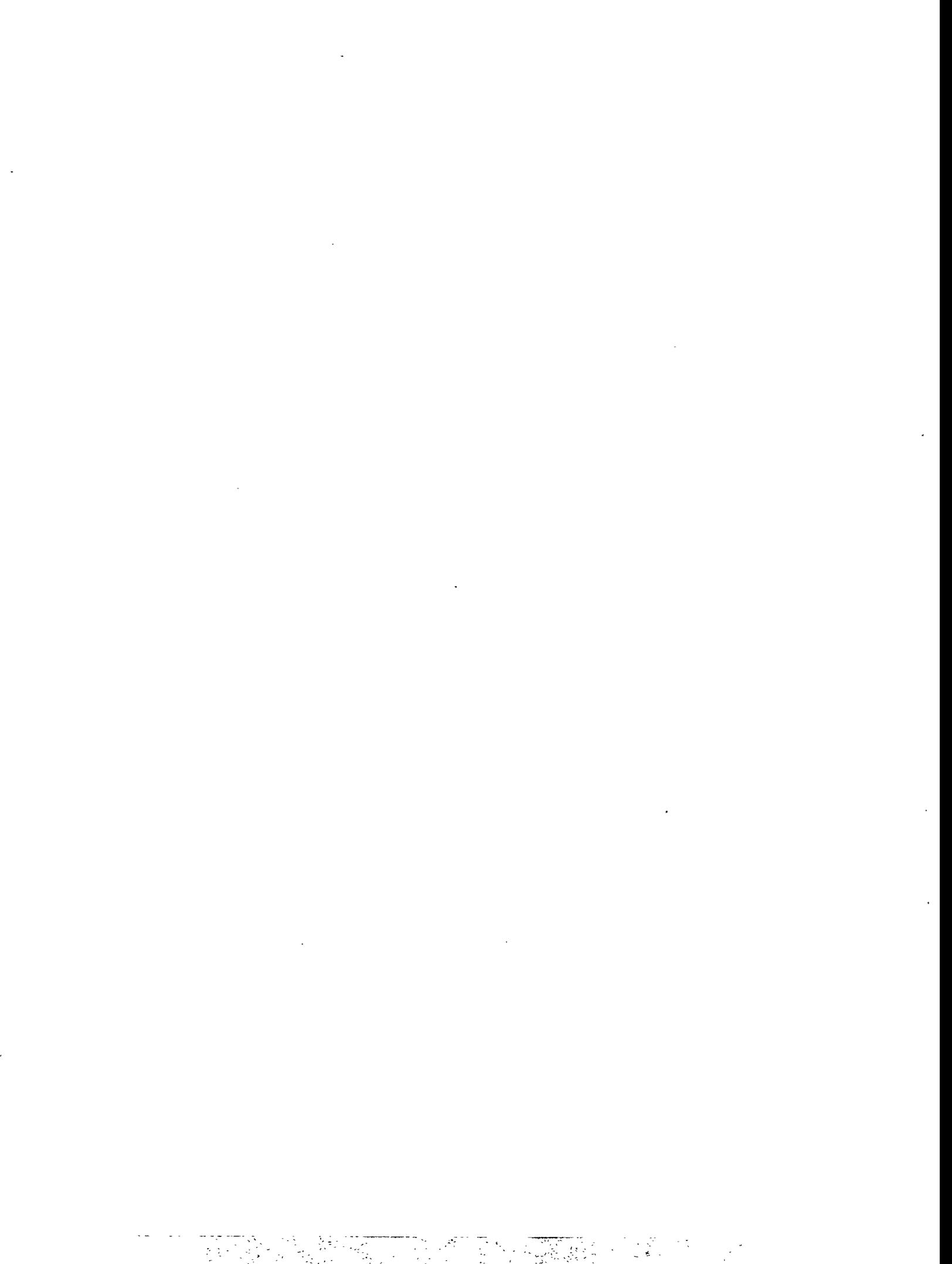
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ABSTRACT

This report presents a simplified method to assess the health and safety risk of Environmental Management activities of the U.S. Department of Energy (DOE). The method applies to all types of Environmental Management activities including waste management, environmental restoration, and decontamination and decommissioning. The method is particularly useful for planning or tradeoff studies involving multiple conceptual options because it combines rapid evaluation with a quantitative approach. The method is also potentially applicable to risk assessments of activities other than DOE Environmental Management activities if rapid quantitative results are desired.



EXECUTIVE SUMMARY

This report presents a simplified method to assess the health and safety risk of Environmental Management activities of the U.S. Department of Energy. The method applies to all types of Environmental Management activities including waste management, environmental restoration, and decontamination and decommissioning. The method is particularly useful for planning or tradeoff studies involving multiple conceptual options.

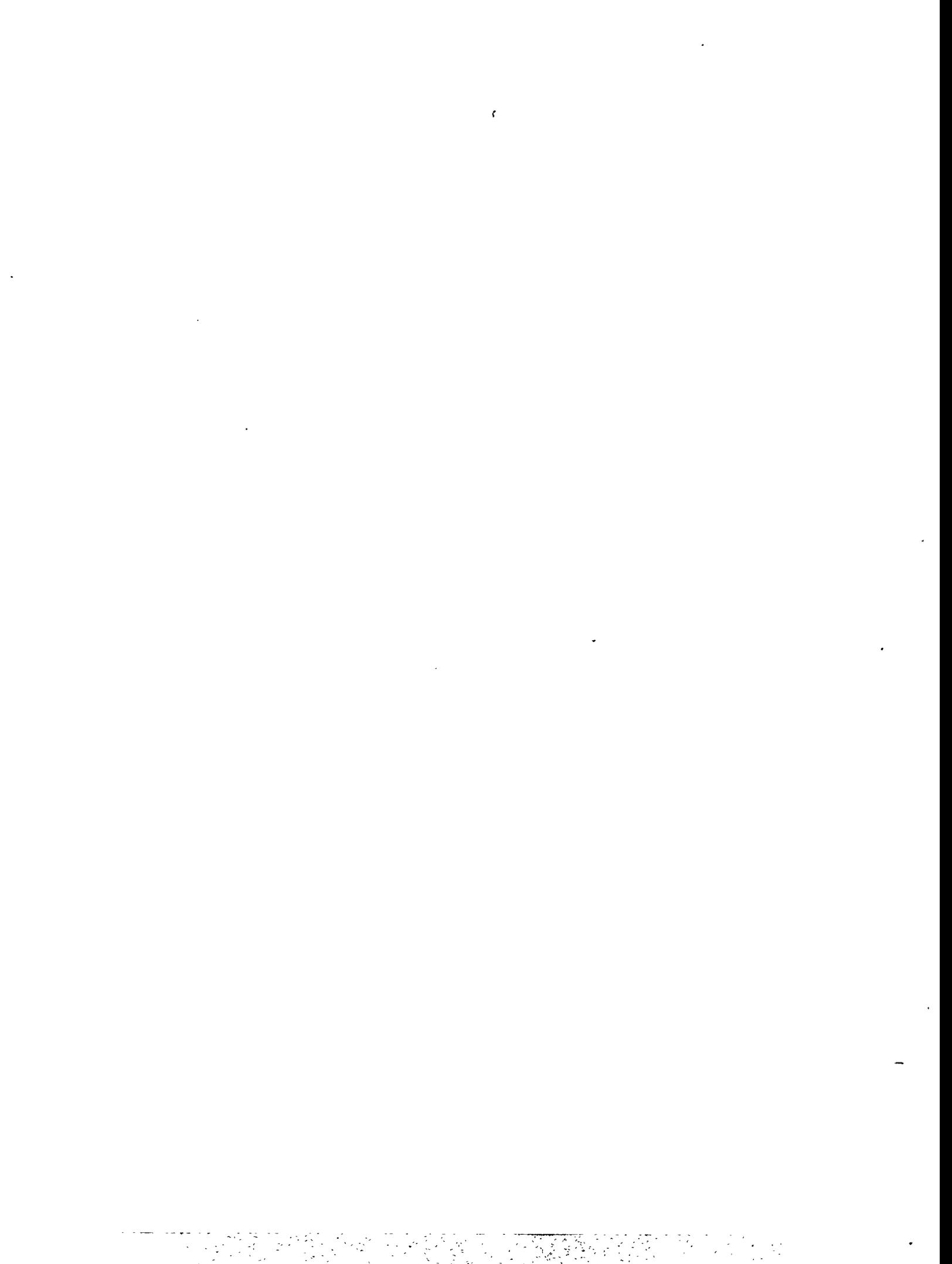
The method fills the substantial void between the two principal categories of risk assessment methods in current use.

- Qualitative methods provide comparatively quick answers but are so simplified that the results are highly subjective, difficult to defend, and may not be reliable
- Results of the detailed quantitative methods, such as formal safety analysis reports, are generally objective, defensible, and reliable, but the evaluations require a great deal of funding and time.

The simplified method provides quantitative values of the **relative risk** to workers and the public from radiological and chemical hazards. (The method also provides quantitative values of the absolute risk associated with industrial hazards.) Although the method is simplified and results can be obtained comparatively quickly, it reduces subjectivity and is more defensible and reliable than the qualitative methods.

The simplified method uses the fundamental equation of risk assessment (i.e., the risk of an activity equals the consequence multiplied by the probability for each adverse scenario, summed over the scenarios). The method uses the principle of aggregation to represent multiple scenarios by a simple set of representative conditions.

The method further develops the fundamental risk equation into 10 risk elements that are multiplied and summed together to estimate the risk. The user of the method selects a value for each risk element from a separate lookup table. The values in the lookup tables were developed by identifying the principal physical parameters that affect each risk element and obtaining ranges of values for the parameters by reviewing available health- and safety-related documents.



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ACRONYMS

ALARA	as low as reasonably achievable
α -LLW	alpha-contaminated low-level waste
ACGIH	American Conference of Governmental Industrial Hygienists
ANL	Argonne National Laboratory
BLEVE	boiling-liquid, expanding-vapor explosion
BNL	Brookhaven National Laboratory
BRA	baseline risk assessment
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CH	contact-handled
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EIS	environmental impact statement
EM	Environmental Management
EPA	U.S. Environmental Protection Agency
ER	environmental restoration
FEMA	Federal Emergency Management Agency
H&S	health and safety
HEPA	high-efficiency particulate air (filter)
HLW	high-level waste
HSRA	health and safety risk assessment

INEL	Idaho National Engineering Laboratory
K_d	sorption coefficient
LANL	Los Alamos National Laboratory
LITCO	Lockheed Idaho Technologies Company
LLNL	Lawrence Livermore National Laboratory
LLW	low-level waste
LWC	lost workday cases
NEPA	National Environmental Policy Act
NPH	natural phenomena hazard
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
PC	performance category
PCB	polychlorinated biphenyl
PEF	particulate emission factor
PPE	personal protective equipment
PRA	probabilistic risk assessment
RCRA	Resource Conservation and Recovery Act
RfD	reference dose
RH	remote-handled
RWMIS	Radioactive Waste Management Information System
SAR	safety analysis report
SF	slope factor
SNF	spent nuclear fuel

SNL	Sandia National Laboratory
SPMS	Safety Performance Measurement System
SRS	Savannah River Site
STEL	short-term exposure limit
TLV	threshold limit value
TRC	total reportable cases
TRU	transuranic
TWA	time-weighted average
WAP	work area protection (feature)
WERF	Waste Experimental Reduction Facility
WIPP	Waste Isolation Pilot Plant
WM	waste management

DEFINITIONS OF SPECIALIZED TERMS

The following specialized terms and definitions are used in this report. Where possible, the definitions were taken from U.S. Department of Energy (DOE) Order 5480.23 (DOE 1992a) or, with adaptation, from the U.S. Environmental Protection Agency (EPA) risk assessment guidance for Superfund (EPA 1989).

absolute risk—quantitative expression(s) of risk in terms of specific expected effects, such as the rate of cancer incidence.

absolute toxicity—quantitative expression(s) of toxicity in terms of specific expected effects from intake of a contaminant.

aggregation—the process of collecting the units or parts into a mass or whole. In engineering and scientific studies, aggregation (or rollup) is an approximation method used widely to help solve problems that are too complex or time consuming to deal with or model in full detail. In aggregation, overall (or average) behavior is ascribed to a range of behaviors of the parts of a system.

barrier—a physical or administrative control mechanism intended to protect a receptor against the potential adverse consequences from a hazard.

contaminant—a substance that can have adverse effects upon a receptor; the two types of contaminants addressed in this report are radiological contaminants (radionuclides) and nonradiological contaminants (hazardous chemicals).

detailed health and safety risk assessment—a health and safety risk assessment in which the potential adverse consequences (and their likelihood) of an activity are evaluated and documented in detail.

detailed risk method—the technical method by which the risk is evaluated in a detailed health and safety risk assessment; detailed risk methods are designated as level 3 and level 4 in this report.

Environmental Management (EM) activity—a field operation involving a waste type for which the DOE Environmental Management organization is responsible.

EM alternative—a set of methods for managing the complete set of waste types under discussion. The set may be so large as to include all of the waste types at an entire DOE site or so small as to address only one waste type or even one stream within a waste type.

expected dose—dose multiplied by the probability of its occurrence.

exposure—contact of an organism with a radiological, chemical, or physical agent.

exposure route—the way in which an organism comes into contact with a radiological, chemical, or physical agent (i.e., by ingestion, inhalation, dermal contact, or external radiation).

fundamental risk equation—risk equals probability multiplied by consequences.

(health and safety) hazard—a source of danger (i.e., material, energy source, or operation) with the potential to cause illness, injury, or death to personnel or damage to a facility or to the environment, without regard for the likelihood or credibility of accident scenarios or consequence mitigation.

health and safety risk—the risk (consequences and probability) associated with a health and safety hazard.

health and safety risk assessment—a documented evaluation of the health and safety risk of an activity.

level 1, 2, 3, and 4 risk assessment—terminology used to suggest the typical level of detail of a risk assessment; level 1 is the least detailed and level 4 is the most detailed.

mobility—the tendency of a waste type to move in response to driving forces and in the absence of external confinement.

project risk—the risk that a project will not be successful.

receptor—the person who could experience the consequences of the intake of or exposure to a hazardous substance.

reference dose—an absolute measure of toxicity used by EPA for the noncarcinogenic effects of a substance.

relative risk—the risk associated with one state or alternative compared with that of another state or alternative or with a baseline value of risk.

relative toxicity—the toxicity of one substance relative to that of another substance or a baseline value.

rest state—an inactive management state for a waste type; storage and disposal are the two types of rest states.

risk—the quantitative or qualitative expression of possible loss that considers both the probability that a hazard will cause harm and the consequences of that event.

risk element—one of the terms in the fundamental risk equation used in this report.

risk measure—a way of expressing risk quantitatively.

simplified health and safety risk assessment—a health and safety risk assessment in which the potential adverse consequences (and their likelihood) of an activity are evaluated only briefly or in a simplified manner.

simplified risk method—the technical method by which the risk is evaluated in a simplified health and safety risk assessment; simplified risk methods are designated as level 1 and level 2 in this report.

slope factor—an absolute measure of toxicity used by EPA for the carcinogenic effects of a substance.

specific toxicity—the toxicity of a substance per unit mass or radioactivity.

state—a step experienced by a waste type in changing from its current situation to its ultimate disposition; rest states and transition states are the two types of states.

toxicity—an indication of a substance's dose-response relationship that is used in risk assessments; the most commonly used toxicity values by the EPA in Comprehensive Environmental Response, Compensation, and Liability Act risk assessments are reference doses and slope factors.

transport pathway—the course a radiological, chemical, or physical agent takes from a source to an exposed organism.

transition state—an active management state for a waste type in which some operation is performed on the waste type; examples of transition states are retrieval, treatment, handling, and shipping.

waste type—a portion of the waste or other materials managed by EM that is under evaluation; the term material type, rather than waste type, is sometimes used because spent nuclear fuel is a material type managed by EM, but it is not necessarily a waste. For simplicity, the term waste type is used in this report.



A Simplified Method for Quantitative Assessment of the Relative Health and Safety Risk of Environmental Management Activities

1. INTRODUCTION

The objective of the simplified risk assessment method developed in this report^a is to fill the gap between qualitative methods, which provide quick response but are often so simplified that they are of limited reliability and defensibility, and detailed quantitative methods, which provide reliable results but are too slow and expensive to be useful for strategic or planning purposes.

The objectives of this report are to

- Present a simplified risk assessment method for quantitatively assessing the **relative health and safety (H&S) risk** of Environmental Management (EM) activities
- Explain the technical basis for the method
- Provide guidance for using the method.

Technical terms related to risk assessment that have special meanings are defined in a list in the front of this report.

1.1 Applicability of Method

The simplified method described in this report applies to waste management (WM), environmental restoration (ER), and decontamination and decommissioning activities. The method is also potentially applicable to risk assessments of activities other than U.S. Department of Energy (DOE) EM activities if rapid quantitative results are desired.

The simplified method can be used to evaluate the relative risk of all types of waste, from spent nuclear fuel (SNF)^b to low-level waste (LLW). Because the simplified method addresses both radiological and nonradiological (e.g., hazardous chemical) contaminants, it can be applied to waste types containing

- Only radiological contaminants

a. As explained in Sections 1 through 4, the method presented in this report provides results that are measures of the **relative risk** from radiological and chemical hazards. The method also provides results that are measures of the **absolute risk** from common industrial hazards.

b. Although spent nuclear fuel is a material type managed by EM and it is not necessarily a waste, for simplicity, the term waste type is used in this report.

- Only nonradiological contaminants (i.e., hazardous waste)
- Both radiological and nonradiological contaminants (i.e., mixed waste).

The method also allows for evaluating the absolute risk to workers from industrial hazards associated with EM activities.

1.2 What is Meant by Health and Safety Risk?

Risk is defined in DOE Order 5480.23 (DOE 1992a) as "the quantitative or qualitative expression of possible loss that considers both the probability that a hazard will cause harm and the consequences of that event."

Because there are several types of possible loss, there are several types of risk. Some types of risk come under the general category of project risk (i.e., the risk that a project will not be successful) (Lockheed Missiles and Space 1994). Project risk includes the risk that the technology will not perform as desired. Another type of project risk is programmatic risk, which relates to the business environment of the project (e.g., possible loss of funding). Other types of project risk include supportability risk, cost risk, schedule risk, and quality risk.

The simplified method presented in this report addresses the H&S risk of an activity. Health and safety risk is a part of project risk (DOE 1995a). Health and safety risk is the risk of adverse health effects to potential receptors, which include members of the public and the workers. The U.S. Environmental Protection Agency (EPA) requires evaluating this risk for members of the public and EM workers in a human health evaluation, or human health risk assessment (EPA 1989). The simplified method does not explicitly address the risk to the environment, which is commonly called the ecological risk (EPA 1992).

Table 1-1 lists the receptors, types of hazards, and types of impacts considered when evaluating H&S risk and the operational phase in which they could exist. Each "X" entry in the table represents the potential for a H&S hazard of the indicated type during typical EM activities.

Table 1-1. Types of health and safety hazards.

Receptors, hazards, impacts	Phase			
	Construction	Operations	Offsite shipping	Storage or disposal
Receptors				
Workers	X	X	X	X
Public		X	X	X
Hazards				
Radiological		X	X	X
Chemical		X	X	X
Industrial	X	X	X	X
Impacts				
Acute	X	X	X	X
Chronic		X	X	X

In the remainder of this report, the term risk refers to human H&S risk only.

1.3 Organization of Document

Section 2 of this report discusses where the simplified risk assessment method of this report fits in the spectrum of methods used to assess H&S risk. Section 3 discusses the basic principles of risk assessment on which the simplified method is based. Section 4 presents the equations used to calculate risk in the simplified method. Sections 5 and 6 contain the lookup tables, which provide values for each element in the risk equations, and the bases for the lookup tables. Section 7 explains how the simplified method deals with routine (normal) exposures and accidental (abnormal) exposures. Section 8 discusses the calculational routines used in applying the method. Section 9 provides a simple analysis of the uncertainties in the method. Finally, Section 10 presents a separate part of the method that estimates the risks to workers from industrial hazards; these risks differ from the radiological and chemical hazards that are addressed in the other sections of the report.

2. TYPES OF HEALTH AND SAFETY RISK ASSESSMENT METHODS

This section discusses the four broad categories of health and safety risk assessment (HSRA) methods and gives examples of the risk assessment methods within each category. It shows where the simplified method fits in the spectrum of methods. Finally, it discusses appropriate applications for each category of HSRA methods.

All risk assessment methods, even the most complex, produce results that are approximate. Because they are not based totally on the historically measured H&S performance of the activity, they are risk prediction methods, not risk measurement methods.

All quantitative risk methods use basically the same fundamental risk equation. The differences lie principally in the level of detail to which the risk elements (terms in the equation) are evaluated.

2.1 Health and Safety Requirements and Criteria

Before listing the four broad categories of HSRAs, it is important to discuss the H&S requirements and criteria that govern EM activities.

The top-level H&S requirement is to protect the public and workers from adverse health effects resulting from EM activities. A large number of lower-level requirements, or H&S criteria, provide standards or measures to ensure the top-level requirement is satisfied.

For a given EM activity, the set of applicable H&S criteria is generally large and depends on the nature of the activity.

The sources of these criteria are DOE Orders, EPA regulations and guidelines, other non-DOE Federal regulations and guidelines, and state and local regulations. The DOE Orders also invoke large numbers of additional requirements, such as consensus national standards promulgated by technical and regulatory organizations.

There are three types of H&S criteria: (1) design criteria, (2) operational criteria, and (3) performance criteria (e.g., maximum allowable doses and limiting concentrations of contaminants in the environment). New DOE facilities are designed to comply with all of these mandatory criteria. Proposed EM alternatives that violate these criteria would not be approved for construction. Therefore, the H&S criteria are a screening device for alternatives involving new facilities. Some existing EM activities may not comply with all H&S criteria [e.g., disposal units that are the subject of remediation under the Comprehensive Environmental Response, Compensation, and Liability Act. (CERCLA)], so the risk of those activities is of interest.

2.2 Four Broad Categories of Health and Safety Risk Assessments

A broad spectrum of methods is available for performing HSRAs. The methods differ primarily in the level of detail to which they evaluate the risk.

No one HSRA method is optimum for all applications. Selecting a HSRA method is driven primarily by two considerations. The first consideration is whether a specific HSRA method is required by the regulations that govern the application. In some cases, no substantial latitude is allowed by the regulations, and the specific method to be used is delineated in detail. The second consideration involves a tradeoff of (a) the level of detail desired in the HSRA and the level of design and environmental data available versus (b) the time and funding available to perform the HSRA.

The many methods for performing HSRAs can be grouped into four broad categories. Figure 2-1 lists the categories and gives examples of each. The four categories are referred to here as level 1, level 2, level 3, and level 4, representing an increasing level of detail from left to right. The categories are based on (a) the level of detail of the analysis, (b) whether the results are quantitative or qualitative, and (c) whether the calculated risks are on an absolute scale or a relative scale.

Relative risks of activities are expressed only on a scale relative to the risk of other activities. Unlike absolute risks, relative risks are not expressed in terms of specific expected effects, such as cancer incidence. Instead, relative risks are unitless because they are the ratio of two risks.

Table 2-1 compares the qualitative or quantitative nature, absolute or relative risk, amount of detail, time required, and application characteristics of the four broad categories of risk assessment methods depicted in Figure 2-1. The entries in Table 2-1 are explained further in the following discussions of the four categories.

Table 2-2 lists several detailed HSRAs that are required for specific types of EM activities, most of which involve HSRAs at level 4 detail. Also shown is the primary purpose of each assessment document and the audience or agency for which the document is prepared.

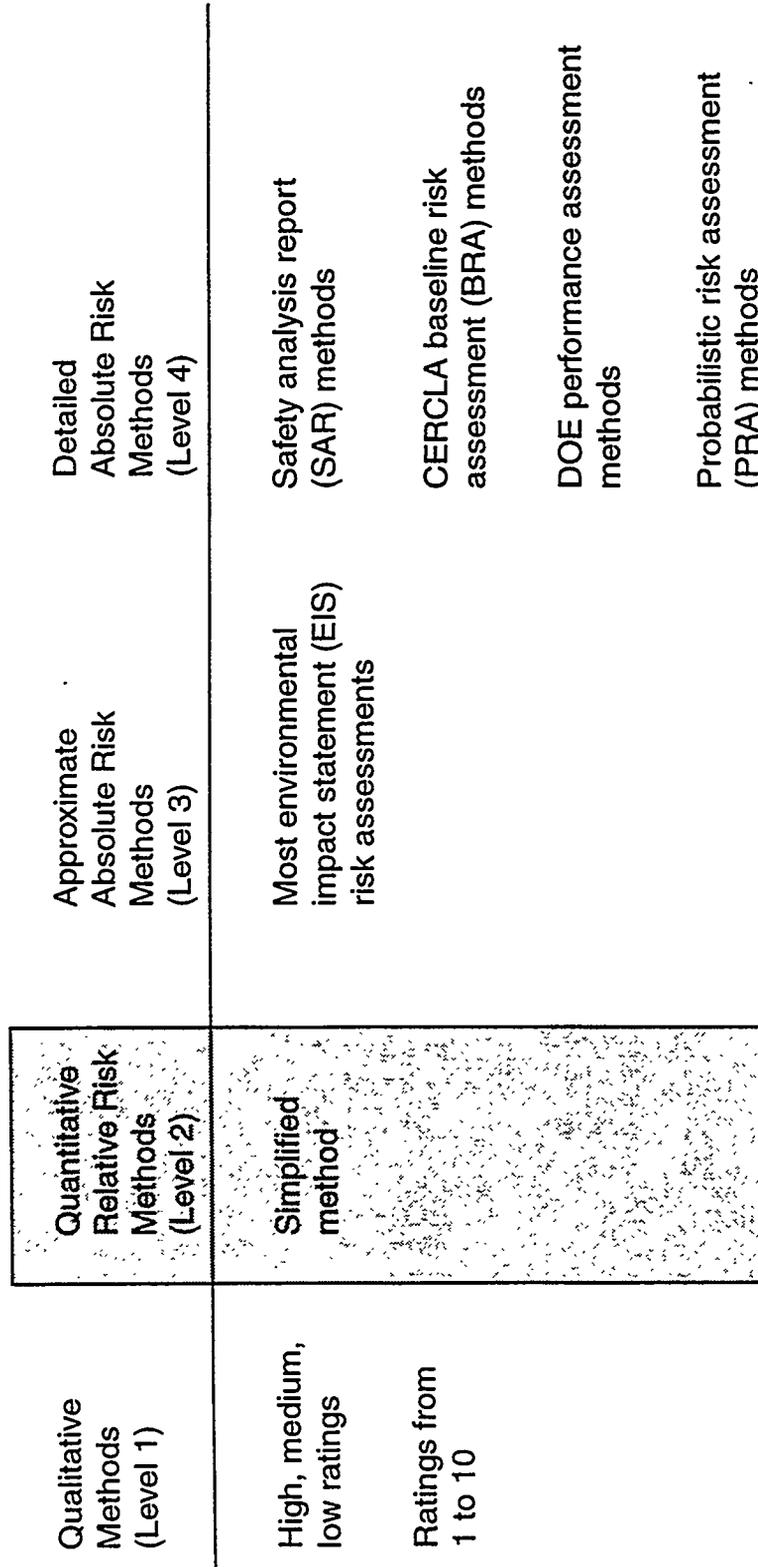
2.2.1 Detailed Absolute Risk Methods (Level 4)

Several H&S regulations require preparing specific, detailed evaluations of the H&S impacts of a proposed activity and prescribe the method for the evaluations. The far right column in Figure 2-1 represents the detailed absolute risk methods that are used to prepare the most detailed HSRAs. These level 4 analyses are in-depth and quantitative, and the results are in the form of absolute risks.

The general approach for the detailed absolute risk methods is to identify the applicable requirements, determine the extent to which the activity satisfies the requirements, and evaluate the residual risk.

Different detailed HSRAs address different parts of the list of H&S hazards in Table 1-1. The detailed HSRAs also calculate different absolute risk parameters (e.g., accident probabilities, radiation doses, probabilities of cancer, and noncancer risks). The detailed HSRAs are prepared for various regulatory bodies and for different phases in the life cycle of a facility or operation. Often, several different HSRAs are required for a major activity.

Least Detailed ← → Most Detailed



E
X
A
M
P
L
E
S

Figure 2-1. Four broad categories of risk assessment methods.

Table 2-1. Characteristics of the four categories of risk assessment methods.

Characteristic	Methods			
	Level 1	Level 2	Level 3	Level 4
Qualitative or quantitative	Qualitative	Quantitative	Quantitative	Quantitative
Absolute risk or relative risk	Relative risk	Relative risk	Absolute risk	Absolute risk
Typical amount of detail in evaluation	Overview information only	Fairly detailed inventory; most other information is more detailed than overview but less than conceptual design	Detail corresponding to that of conceptual design	Great amount of facility or operational detail based on final design or actual facility
Typical time required for a single risk assessment (depends on complexity of activity evaluated)	Minutes to hours	Hours	Months	Months to years
Typical application	Scoping studies to help establish funding priorities	Top-level evaluations of EM alternatives; scoping studies to help establish funding priorities	Compliance with HSRA requirements before design is complete	Compliance with HSRA requirements after design is complete

Table 2-2. Detailed health and safety risk assessments required for specific types of EM activities.

Type of detailed H&S risk assessment	Purpose of the assessment	Audience or agency requiring the H&S risk assessment
Environmental assessment; EIS	Project impacts on public and environment	Public, EPA, other Federal agencies, and state agencies
SAR	Obtain approval to operate facility by demonstrating that hazards are controlled adequately	DOE and U.S. Nuclear Regulatory Commission (NRC)
SAR for packaging	Ensure safety of waste packaging	U.S. Department of Transportation (DOT)
Resource Conservation and Recovery Act (RCRA) Part B permit application	Obtain permit to operate hazardous waste treatment, storage, or disposal facility	EPA or state
H&S plan	Ensure health and safety of workers	Occupational Safety and Health Administration (OSHA)
Performance assessment for waste disposal facilities	Ensure long-term protection of public from disposed radioactive waste	DOE and NRC
CERCLA BRA	Determine need to remediate a site based on risk to human health and environment	EPA, state, and public
Risk-based preliminary remediation goals	Establish remediation performance objectives for technology selected	EPA, state, and public

The detailed HSRAs are complex evaluations. They produce the most rigorous results of the four categories of HSRAs. Unfortunately, they involve major commitments of time (often measured in years rather than in months) and resources. They are, therefore, not well suited for providing quick responses to strategy- or planning-related questions and scenarios. However, they are suitable for rigorous answers to in-depth questions involving operational hazards.

Another limitation of level 4 methods is that they require large amounts of data related to the detailed design of the facility or operation. Typically, such detailed information is not available early in the life cycle of a facility, when strategic or planning studies are needed.

2.2.2 Approximate Absolute Risk Methods (Level 3)

Some H&S regulations, such as those of the National Environmental Policy Act (NEPA), require preparing specific, detailed evaluations of the H&S impacts of a proposed activity before substantial design detail is available. The level 3 methods, called approximate absolute risk methods on Figure 2-2, are appropriate for meeting these regulatory needs.

The level 3 methods are similar in approach to the level 4 methods. However, the level 3 methods yield approximate absolute risk because only conceptual design information is available at the time in the project life cycle when they are prepared. An example of this category of method is the

detailed HSRA prepared in support of an EIS. The analyses are in considerable detail and are quantitative; the results are in the form of absolute risks.

Level 3 HSRAs are complex evaluations that produce fairly rigorous results. They involve major commitments of time (generally measured in months) and resources. They are also not well suited for providing quick responses to planning-related questions and scenarios. Level 3 methods are suitable for fairly rigorous answers to questions about the expected impacts of proposed activities.

2.2.3 Quantitative Relative Risk Methods (Level 2)

2.2.3.1 Performance Criteria for the Method. As Figure 2-2 and Table 2-1 illustrate, there is a large gap—in both the level of detail and the level of effort required—between the qualitative methods (level 1) and the approximate absolute risk methods (level 3). Level 2 methods fill this gap (see dashed box in Figure 2-2).

For EM applications, the performance criteria or constraints that a level 2 method must satisfy include

- The method must facilitate consistent risk results for the full range of waste types, from SNF to LLW, including radioactive waste, hazardous waste, and mixed waste.
- The method must facilitate consistent risk results for the full range of EM activities, including WM, ER, and decontamination and decommissioning; treatment, storage, and disposal; and retrieval, shipping, and any other type of EM operational activity.
- The method must facilitate rapid risk assessments, with a capability to assess hundreds of EM activities in a few days.
- The method must not require large quantities of data or require detailed descriptions of alternatives still in the preconceptual stage.
- The method must be technically rigorous to the extent that the same *general* conclusions would be derived for comparing the risk of two alternatives as would be obtained using a level 3 or 4 risk assessment method.

This requirement implies that the level 2 method must be quantitative, although it estimates only relative risk, not absolute risk. This requirement ensures that the results obtained are reasonable and credible. Although the ratio of risks from a level 2 risk assessment of two EM activities would likely not match that from a level 3 or 4 analysis exactly (even two different level 4 methods can produce results for the same activity that differ substantially), the level 2 and level 3 or 4 results should provide similar general conclusions.

2.2.3.2 The Simplified Method. No existing level 2 methods were identified that satisfied the above performance criteria, so a simplified method was developed. It offers the following benefits:

- Practical application of an early version of the method showed that it accommodates a wide range of waste types and EM activities.
- It is quick; approximately 1,000 simplified risk assessments were performed by four employees in 2 weeks during the practical application. (An early version of the method presented here was used in that application.)
- It does not require large quantities of data.
- It removes much of the subjectivity from which the level 1 methods suffer.
- It is quantitative. It produces estimated values of relative risk.^c The general conclusions drawn from the results are expected to correlate well with the overall results from level 3 and 4 risk assessments.

2.2.3.3 Potential Applications of the Simplified Method. The simplified method should be used in applications that require combining timeliness and the level of detail desired from a level 2 evaluation. Its use is appropriate when quantitative results are needed in a matter of hours or days, and the results need not reflect an in-depth evaluation of activity.

An early version of the simplified method was applied to quick evaluations of Site-wide EM integration alternatives at the Idaho National Engineering Laboratory (INEL). All waste types and all types of EM activities (i.e., WM, ER, and decontamination and decommissioning) were included.

Another promising application of the simplified method is to help prioritize funding needs when risk is one criterion affecting the funding decision. The level 2 method would provide more definitive results than the level 1 methods with a small increase in effort.

Still another potential application is to assist in selecting H&S enhancements using a graded approach. In this approach, funds for H&S enhancements are directed to activities having the greatest risk rather than to all activities equally.

The method is not intended for use in regulatory compliance.

c. In the remainder of the report, when the term risk is used in connection with the simplified method, it means relative risk. The product of this simplified method is a quantitative result, but it has meaning only when compared with other results calculated by the same method. The results have no meaning by themselves. Therefore, the relative risk numerical results should not be compared directly against absolute risk numerical results calculated, for example, in CERCLA BRAs by the methods in EPA (1989).

2.2.4 Simple Qualitative Methods (Level 1)

For certain applications, simple, qualitative HSRAs^d are sufficiently accurate. The level 1 methods used are depicted in the left column of Figure 2-1. The applications require rough relative risk ranking of options and quick calculations. Level 1 methods could be used to develop a relative risk ranking to establish funding priorities for proposed EM activities.

Use of level 1 HSRA methods is restricted by their limited accuracy, however, which is caused by their simplicity. The results do not necessarily correlate in any quantitative way with the results of the level 3 and 4 methods. In fact, level 1 methods that rate risks using numbers (e.g., on a scale from 1 to 10) can produce highly misleading results because of the following potential misinterpretation. An activity with a risk rated as 6, for example, on a scale from 1 to 10 may be interpreted as being twice as risky as an activity with a risk rating of 3 ($6/3 = 2$). Because actual risk values are expected to be distributed approximately lognormally (see Section 9), a risk value of 6 on the 1-to-10 scale may actually be 1,000 times as large as a value of 3 ($10^6/10^3 = 1,000$). Finally, because level 1 methods are quite subjective, the results may be distorted by the viewpoint of the risk analyst.

2.3 Selecting a Risk Assessment Method

Selecting a risk assessment method depends on the application. For some applications, the method is prescribed in the regulations that govern the EM activity. If a method is not prescribed, selecting a category of method to use (level 1, 2, 3, or 4) is based on a balance between the time available for the evaluation and the degree of detail that is necessary and available. If quick results are needed, the choice is generally methods at level 2 or 1. If sufficient time and funds are available for the risk assessment and a detailed evaluation is necessary and justified by the available data, the choice is generally methods at level 3 or 4.

The following considerations provide guidance in selecting an appropriate level method and identify the types of applications for which the simplified level 2 method is suitable:

- The earlier in the project cycle, use less detailed methods.
- The fewer or less reliable the available data on the waste type, the facility design, the operation, and the environmental characteristics, use less detailed methods. A detailed risk assessment cannot produce high-quality results based on unreliable data.
- The greater the required precision of the answer, use more detailed methods.
- For preliminary, screening, or broad decisions, use less detailed methods. For final or specific decisions, use more detailed methods. For example, prepare less-detailed

d. Risk assessment methods that produce numerical results using simple rating scales for risk elements (e.g., ratings from 1 to 10) are considered here to be qualitative because the rating scales are generally not related quantitatively to physical parameters (e.g., leach rates).

preliminary SARs when conceptual design information is available and more-detailed final SARs when final design information is available.

3. TECHNICAL BASIS OF SIMPLIFIED METHOD—OVERVIEW

The top-level technical basis for the simplified method of relative risk assessment rests upon three fundamental concepts related to risk:

1. The fundamental equation of risk assessment
2. The principle of aggregation
3. The concept of hazards, barriers, stresses, and receptors.

This section discusses these concepts. The fundamental equation of risk assessment is discussed in more detail in Section 4.

3.1 Fundamental Equation of Risk Assessment

Risk is assessed for systems. This section defines terms that describe the systems and then summarizes the fundamental risk equation.

3.1.1 EM Alternatives, Waste Types, and Waste-Type States

An EM alternative consists of a set of methods for managing a set of waste types. The set of waste types may include all of the waste types in the DOE complex, at an entire DOE site, only one waste type, or one stream within a waste type.

A waste type is a major subdivision of waste at a DOE site. For example, the following are waste types: (a) all of the stored mixed transuranic (TRU) waste at a DOE site, (b) all of the buried mixed TRU waste at a site, (c) all of the LLW in a small disposal facility, (d) an ER operable unit, (e) all of the LLW to be generated by a facility in the next 20 years, and (f) the SNF stored in a specific facility. Note that a waste type is not necessarily the same as a type of waste, as typically understood.

For a waste type in an EM alternative, operational activities would proceed from the current resting place through a series of steps to a final disposition. Each of these steps is called a state.

There are two types of states: (1) a rest state and (2) a transition state. A rest state is an inactive management state. Storage and disposal are the two types of rest states. A transition state is an active management state in which an operation is performed on the waste type. Examples of transition states are retrieval, treatment, handling, and shipping.

There are minor differences in the way risk is estimated in this report for a rest state and a transition state. Therefore, at some points, the two types of states are addressed separately.

Risk calculations can compare the risks of complete alternatives, waste types within an alternative, or individual states for an alternative and waste type.

3.1.2 Fundamental Risk Equation

The total risk R of an EM alternative is the sum of the risks R_i of the various waste types i :

$$R = \sum_i R_i \quad . \quad (3-1)$$

Each state j for waste type i has an associated risk R_{ij} . The total risk R_i for waste type i is the sum of the risks R_{ij} over all of the rest and transition states j :

$$R_i = \sum_j R_{ij} \quad . \quad (3-2)$$

The following example applies Equation (3-2) to a typical sequence of rest states and transition states for a single waste type:

Rest Transition Transition Rest Transition Rest
state A → state 1 → state 2 → state B → state 3 → state C .

In this example, the waste type is originally in rest state A (e.g., storage). The transition states 1 and 2 (operations such as retrieval, treatment, and shipping) transform the waste type from rest state A to rest state B. For example, rest state B may be interim storage. Transition state 3 places the waste type in its final rest state C. In this example, the total risk R_i for the waste type i is

$$R_i = R_{iA} + R_{iB} + R_{iC} + R_{i1} + R_{i2} + R_{i3} \quad .$$

The remainder of this report focuses on how the simplified method produces risk estimates R_{ij} for various waste types for both rest states and transition states.

The method for estimating the risk R_{ij} of a state starts with the fundamental definition of risk (for simplicity, the subscript ij for risk is not included in the following equations, but it should be understood to be present). The risk R of an adverse impact is defined as the consequence C of the impact multiplied by the likelihood (probability, P) of the impact:

$$R = P \times C \quad . \quad (3-3)$$

When summed over all of the possible impacts k from an activity, the result is the risk associated with the activity:

$$R = \sum_k P_k \times C_k \quad . \quad (3-4)$$

A multitude of possible H&S impacts can result from an activity. Table 1-1 lists all of the types of hazards at the top level; each entry in Table 1-1 could be subdivided many times.

The simplified method does not attempt to identify all of the impacts. Instead, the method evaluates the general characteristics of the state, assigns relative values to the characteristics based on

risk-related physical parameters (e.g., leach rate of a waste form), and multiplies the values together in the same general way that Equations (3-3) and (3-4) would be used in preparing the detailed HSRA listed in Table 2-2. The results of the simplified method are simplified estimates of relative, not absolute, risk.

3.2 Principle of Aggregation

Aggregation is the process of collecting units or parts into a mass or whole. In engineering and scientific studies, aggregation (or rollup) is an approximation method used to solve problems that are too complex or time consuming to model in full detail. In aggregation, overall (or average) behavior is ascribed to a range of behaviors of the parts of a system. If the aggregation is applied carefully, the overall results are reasonably close to the results of more detailed modeling.

One example of applying the principle of aggregation is one- or two-dimensional modeling of phenomena, such as groundwater flow, that actually take place in three dimensions. Another example of aggregation is the use of one- or two-group critical equations in nuclear physics, in which all neutrons are modeled as though they had only one or two specific energy levels rather than a distribution of energy levels (Glasstone and Sesonske 1967).

The advantages of aggregation are that the results of the simplified analysis are available much faster and at a much lower cost. The primary limitation of aggregation is that the results of the simplified analysis are less reliable than the results of a detailed analysis. The challenge in applying aggregation is maximizing the advantages while minimizing the limitation.

The principle of aggregation is used in two ways in the simplified risk assessment method: (1) to aggregate risk measures and (2) to aggregate risk-contributing scenarios.

3.2.1 Aggregation of Risk Measures

Many different risk measures are used in the detailed HSRA listed in Table 2-2. Example risk measures are the maximum dose to the nearest worker, to other workers, to the nearest member of the public, to the nearest population center, and to all people within a 50-mile radius. The various risk measures in common use address various factors. For example, some risk measures represent the radiological risk, while others represent the nonradiological risk. Some address carcinogenic effects, while others address noncarcinogenic effects. Some risk measures address somatic effects, while others address genetic effects. Some risk measures are based on calculating the effects on specific organs of the body; others address the whole-body-equivalent effects. Some risk measures address chronic effects, while others address acute effects. Some risk measures reflect the probability that releases of contaminants will occur, while others simply assume that the releases will occur.

These varied risk measures demonstrate that there is no single measure of risk.

If the results of a risk assessment method are to represent the risk of a wide variety of EM activities, alternatives, waste types, and states, then a large number of risk measures have to be calculated. Even using the detailed HSRA methods (levels 3 and 4), no one method calculates all of the possible risk measures. Therefore, using simplified HSRA methods (levels 1 and 2), it is not

feasible to calculate all of the numerous measures of risk. To meet time and resource constraints, a simplified HSRA uses one or two risk measures for comparing EM alternatives.

In developing the radiological and chemical risk in the simplified method, a single measure was sought that adequately compares the risk of two activities (or the same activity at a different time or place). It was concluded that a measure of the relative risk of an activity could be calculated much faster than measures of absolute risk. When using a measure of relative risk, the calculated risk of an activity is meaningful only when compared with the risk of another activity.

Ideally, if activity A is calculated to be n times as risky as activity B using a single measure of relative risk, then the ratio would also be n for all absolute risk measures. Obviously, this ideal can never be achieved because risk measures do not correlate that simply. The ratios of risk measures for different activities vary even between detailed HSRAs. The risk measure is considered sufficiently reliable if the value of the ratio for the simplified method is reasonably close to that obtained using the level 4 method(s) in a detailed HSRA.

The relative risk measure was developed by using the fundamental equation of risk assessment detailed in Section 4. In the simplified method, all risk measures for radiological and chemical hazards are aggregated into one measure of relative risk based on the fundamental equation of risk. Thus, as an approximation to the absolute risk of an activity involving scores of risk measures, only one risk measure is used. (An exception to this approach is the method used in this report to calculate the risk to workers from industrial hazards. As discussed in Section 10, two absolute risk measures are used to calculate these industrial risks.)

The simplified method assumes that, for overview studies, the ratio of values of a single risk measure for two activities provides a sufficiently accurate indicator.

3.2.2 Aggregation of Risk-Contributing Scenarios

Another complication of risk assessment is that the total risk of an activity involves the sum of the individual risks of a multitude of scenarios, various consequences, and various receptors [see Equation (3-4)]. Table 1-1 lists the types of top-level hazards, but each entry in the table could be subdivided many times. For a complex EM facility, the number of risk-contributing scenarios can number in the thousands or even millions. The scenarios involve different operating conditions, initiating events, propagating events, release mechanisms, transport mechanisms, environmental conditions, and receptors. In summary, the risk-contributing scenarios are a tangled web of possible events and conditions stretching from the initiating events through the ultimate consequences. Even in a detailed HSRA, scenarios must be sorted and screened to identify and evaluate only the more important paths through the web of events and develop a list of manageable scenarios for which detailed evaluation is necessary.

The simplified method does not attempt to evaluate the risk-contributing scenarios in detail. Instead, it uses the principle of aggregation to address the universe of scenarios by

- Considering the large number of paths through the web of possible events

- Examining the limited number of paths expected to be among the most important (based on reviews of numerous detailed HSRAs for similar activities).

The result is a simplified measure of the risk behavior of the activity—a realistic measure of broad behavior that does not necessarily reflect the behavior for any one specific scenario or path through the web of events (e.g., a fire, a dropped container, or a flood). Instead, the method

- Evaluates the general risk-related characteristics (e.g., the mobility of the waste form) of the facility or operation and the waste type
- Assigns a simple set of relative values to each general characteristic based on reviewing the absolute values of several specific parameters that represent the behavior of the general characteristic (e.g., the absolute leach rates, breakup fractions, and respirable fractions of various waste forms)
- Multiplies the relative values of the general characteristics together.

3.3 Concept of Hazards, Barriers, Stresses, and Receptors

The concept of hazards, barriers, stresses, and receptors was pioneered as part of a suite of system safety methods by Nertney and coworkers (e.g., Nertney and Pavlov 1980, Trost and Nertney 1994). The concept is useful in describing the risk behavior of a facility or operation. Some of the elements in the fundamental risk equation are interpreted in later sections of this report in terms of this concept.

Figure 3-1 illustrates the concept. A facility or operation presents risk because it contains a hazard. Radiological and chemical hazards exist because the waste type in the facility or operation has radiological or nonradiological contaminants. In an analogous way, industrial hazards, which are not evaluated using this same approach, exist because an energy source, such as electrical energy or rotating machinery, is in the facility.

As long as the hazard is controlled, no adverse consequences occur. The control generally is provided by physical barriers, such as confinement barriers, high-efficiency particulate air (HEPA) filters, and shielding barriers. Administrative barriers, such as procedural controls or training, are less reliable. Many hazards are controlled by multiple barriers.

The control barriers may be subjected to challenges, or stresses, by phenomena occurring outside or inside the barriers. An example is the mechanical stress induced by dropping a container of waste or by an explosion within a waste container. Other stresses can be thermal, chemical, or electrical.

As long as the stress does not exceed the capability (strength) of the barriers, the hazard will be controlled. If the stress exceeds the strength of the barriers, control of the hazard will be lost. If control of the hazard is lost, the receptors, which include both workers and members of the public, could suffer adverse consequences.

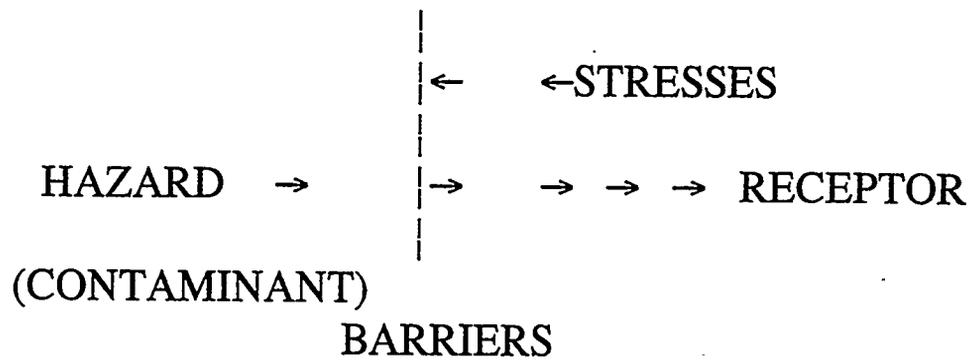


Figure 3-1. The concept of hazards, barriers, stresses, and receptors.

4. TECHNICAL BASIS OF SIMPLIFIED METHOD—DETAILS

Section 4 focuses on the fundamental equation of risk summarized in Section 3.1.2 and borrows from the principle of aggregation and the concept of hazards, barriers, stresses, and receptors presented in Sections 3.2 and 3.3.

4.1 Developing the Risk Equations

Starting with Equation (3-3), the risk from the radiological and chemical hazards of a given state involving a given waste type is expressed as follows:

$$R = P \times C = P \times (I \times ST \times FR \times TE \times HR) \quad (4-1)$$

where

- P = likelihood (probability) of the consequence^e
- C = consequence of the impact
- I = inventory of the contaminants (radionuclides and hazardous chemicals)
- ST = specific toxicity (per unit radioactivity or per unit mass of hazardous chemical) of the contaminant
- FR = fraction of the contaminant that is released from confinement
- TE = effectiveness of the environmental transport pathways in moving the released contaminant from the source to the receptors
- HR = number and proximity of human receptors.

Equation (4-1) is similar in general structure to the equations used for CERCLA BRAs (EPA 1989) and in other level 3 and level 4 methods. The P term has been added here (it is not used in BRAs) to address the probability of an event's occurrence (e.g., a release of contaminants from confinement).

As described below, the simplified method in this study addresses each term in Equation (4-1). Because some of the values used are relative values, the result is a simplified estimate of the relative, not absolute, risk.

e. In this report, close attention is not given to the precise statistical implications of the terms likelihood, probability, and frequency. In the great majority of instances discussed, the events are of very low frequency; the approximations typically used result in the annual frequency equaling the probability of occurrence in a given year.

For convenience in performing the risk calculations, the terms in Equation (4-1) are grouped into numbered risk elements.

Element 1 is the characteristics of the waste type. There are two subelements:

- Element 1a is the quantity of contaminants in the waste type (curies of radioactivity and/or kilograms of hazardous chemicals); this is the I term in Equation (4-1)
- Element 1b is the specific radiotoxicity of the radionuclides (per curie) and/or the specific chemical toxicity (per kilogram) of the hazardous chemicals; this is the ST term in Equation (4-1).

Element 2 is the FR term in Equation (4-1). It expresses the ease with which the contaminants in the waste type could escape confinement (as a result of events or conditions that cause the barriers to fail) and become mobile in environmental transport to the receptors. There are two subelements:

- Element 2a is the mobility of the waste type (e.g., liquid, powder, or sludge); this term reflects the confinement provided to the contaminants by the waste form itself
- Element 2b is the capability of the external confinement barriers to contain the contaminants.

Element 3 expresses the likelihood, or probability, of loss of confinement. This is the P term in Equation (4-1). There are two subelements:^f

- Element 3a is the nature, severity, and probability of environmental stresses (e.g., floods and seismic events) to which the confinement might be subjected
- Element 3b is the nature, severity, and probability of operations-related stresses (e.g., fires and container drops) to which the confinement might be subjected.

Element 4 expresses how effectively the released contaminants could be moved by environmental transport processes (e.g., atmospheric and groundwater transport) to receptors. This is the TE term in Equation (4-1).

Element 5 relates to the presence of human receptors. This is the HR term in Equation (4-1). It has two subelements:

- Element 5a expresses how frequently workers would be located around the waste type, how many workers would be involved, and how closely they would be involved

f. Including Element 2b as part of the P term (Element 3), representing the strength of the confinement, could be useful for conveying understanding, rather than including it as part of the FR term. However, the placement of Element 2b does not affect the result of the risk equation.

- Element 5b expresses how many members of the public are located near the waste type and how close they are to the waste type.

Depending on the units of the terms in Equation (4-1), the result is the risk per unit time of a rest state. [For a transition state, the result is the risk of applying the operation (e.g., vitrification) to all of the material in the waste type.] To obtain the risk over a period of time in a rest state, multiply by the length of time that the waste type is in the rest state. Thus,

- Element 6 is the time that the waste type is in a rest state.

Appendix A demonstrates how the units used for the risk elements propagate through the risk equations.

4.2 Presenting the Risk Equations

Using the risk elements discussed above, the risk of a rest state is given by Equation (4-2) and the risk of a transition state is given by Equation (4-3).

$$R = V_{1a} \times V_{1b} \times V_{2a} \times V_{2b} \times (V_{3a} + V_{3b}) \times V_4 \times (V_{5a} + V_{5b}) \times V_6 \quad (4-2)$$

$$R = V_{1a} \times V_{1b} \times V_{2a} \times V_{2b} \times (V_{3a} + V_{3b}) \times V_4 \times (V_{5a} + V_{5b}) \quad (4-3)$$

Each V entry in the equations is the value selected for a numbered element (e.g., V_{1a} is the value for Element 1a).

The relative risk calculated by means of Equations (4-2) and (4-3) is the risk to the total population of affected workers plus the risk to the total population of affected public. This fact is evident from the $V_{5a} + V_{5b}$ term in the equations. If desired, the worker risk and public risk can be reported separately in the results.

Section 5 gives the lookup tables for the risk elements for rest states. The lookup tables contain numbers from among which the user selects the most appropriate value for each risk element. The values are then used in Equation (4-2).

Section 6 gives guidance for selecting the values of the risk elements for transition states that differ from the corresponding values for rest states. The values are then used in Equation (4-3).

4.3 Refining the Risk Equations

There are some key relationships among the risk elements in Equations (4-2) and (4-3). In Sections 5 and 6, these relationships are addressed in detail. Because of these relationships, the equations actually used to calculate the relative risk are somewhat more complex than Equations (4-2) and (4-3). These refined equations are developed and presented here.

One relationship involves Elements 1a and 1b. In Section 5.1, the contaminants are addressed in groups. For a given state, the number of contaminant groups requiring analysis is generally expected to be six or fewer. Each group of contaminants i is described by a contaminant quantity

V_{1a_i} and a relative toxicity V_{1b_i} . Each group is addressed separately throughout the risk equation, then the risks are added.

A second relationship involves Elements 4, 5a, and 5b. In Element 4, airborne and waterborne releases are addressed separately. This is discussed in Section 5.4. The distances to the various receptor groups affect Elements 4, 5a, and 5b. The products of these terms are, therefore, added over the various distances and receptor groups.

These relationships are shown algebraically in the following more detailed equations that replace Equations (4-2) and (4-3) in actual applications.

For a rest state, the risk R is

$$R = {}_aR + {}_wR \quad (4-4)$$

where

${}_aR$ = risk associated with the airborne pathway

${}_wR$ = risk associated with the waterborne pathway.

The lower left subscripts a and w represent the airborne and waterborne pathways, respectively. As explained later, the waterborne pathway is assumed generally to apply only to disposal states.

The risk ${}_aR$ of the airborne pathway is

$${}_aR = \sum_i {}_aR_i \quad (4-5)$$

where the index i is over the contaminant classes. The maximum value of i is generally expected to be 6 or less.

For a given contaminant class i , the airborne risk ${}_aR_i$ is

$${}_aR_i = V_{1a}, V_{1b}, {}_aV_{2a} V_{2b} (V_{3a} + V_{3b}) \left(\sum_j {}_aV_{4j} {}_aV_{5a_j} + \sum_k {}_aV_{4k} {}_aV_{5b_k} \right) V_6 \quad (4-6)$$

where V_{1a} and V_{1b} are the quantity and relative toxicity of contaminant class i . V_{2b} , V_{3a} , V_{3b} , and V_6 are taken to be independent of i and of pathway (airborne versus waterborne). V_{2a} depends on the pathway. V_{5a_j} represents the j groups of workers, and V_{5b_k} represents the k groups of the public. For each of these groups, the distance from the waste is different, so there are different values of V_4 . The various V_{4j} and V_{5a_j} terms are multiplied then summed. Similarly, the various V_{4k} and V_{5b_k} terms are multiplied then summed.

Similarly, the risk ${}_wR$ of the waterborne pathway is

$${}_wR = \sum_i {}_wR_i \quad (4-7)$$

where the index i again is over the contaminant classes. Equation (4-7) is expected to apply only to disposal states.

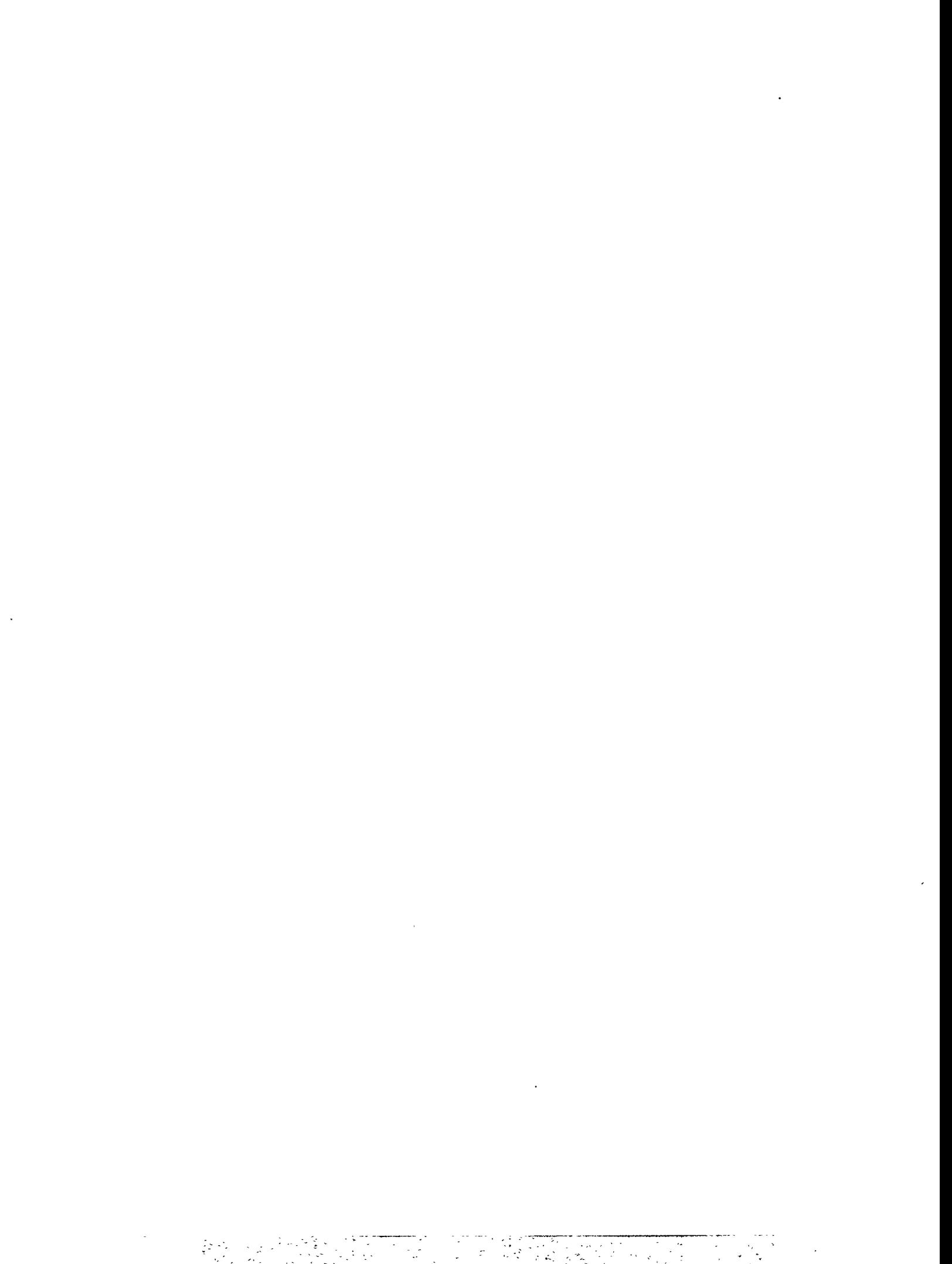
For a given contaminant class i , the waterborne risk ${}_wR_i$ is expressed similarly to the airborne risk:

$${}_wR_i = V_{1a}, V_{1b}, {}_wV_{2a} V_{2b} (V_{3a} + V_{3b}) \left(\sum_j {}_wV_{4j} {}_wV_{5a_j} + \sum_k {}_wV_{4k} {}_wV_{5b_k} \right) V_6 \quad (4-8)$$

where the indexes j and k have the same meaning as before but apply here to the various distances along the waterborne (rather than airborne) pathway. The index i appears in the ${}_wV_{4j}$ and ${}_wV_{4k}$ terms because the waterborne transport depends on the sorption coefficient, which in turn depends on the contaminant class i .

For a transition state, no waterborne pathways are expected. Therefore, the equations are identical to Equations (4-5) and (4-6).

For simplicity, reference hereafter may be made to the risk elements in Equations (4-2) and (4-3). It should be understood, however, that the actual calculations are performed using Equations (4-4) through (4-8).



5. HOW TO ESTIMATE THE RISK OF A REST STATE—LOOKUP TABLES

Figure 5-1 shows the overall method for calculating risk.

This section explains how to select the most appropriate value of each risk element for rest states in Equation (4-2). Sections 5.1 through 5.6 provide a lookup table for each risk element. The lookup tables (or instructional texts, in some cases) are highlighted.

The bases for the values in the lookup tables are discussed in the subsection(s) immediately after the lookup tables.

The approaches used in this report for developing the lookup tables varied among risk elements. In general, the approach was to

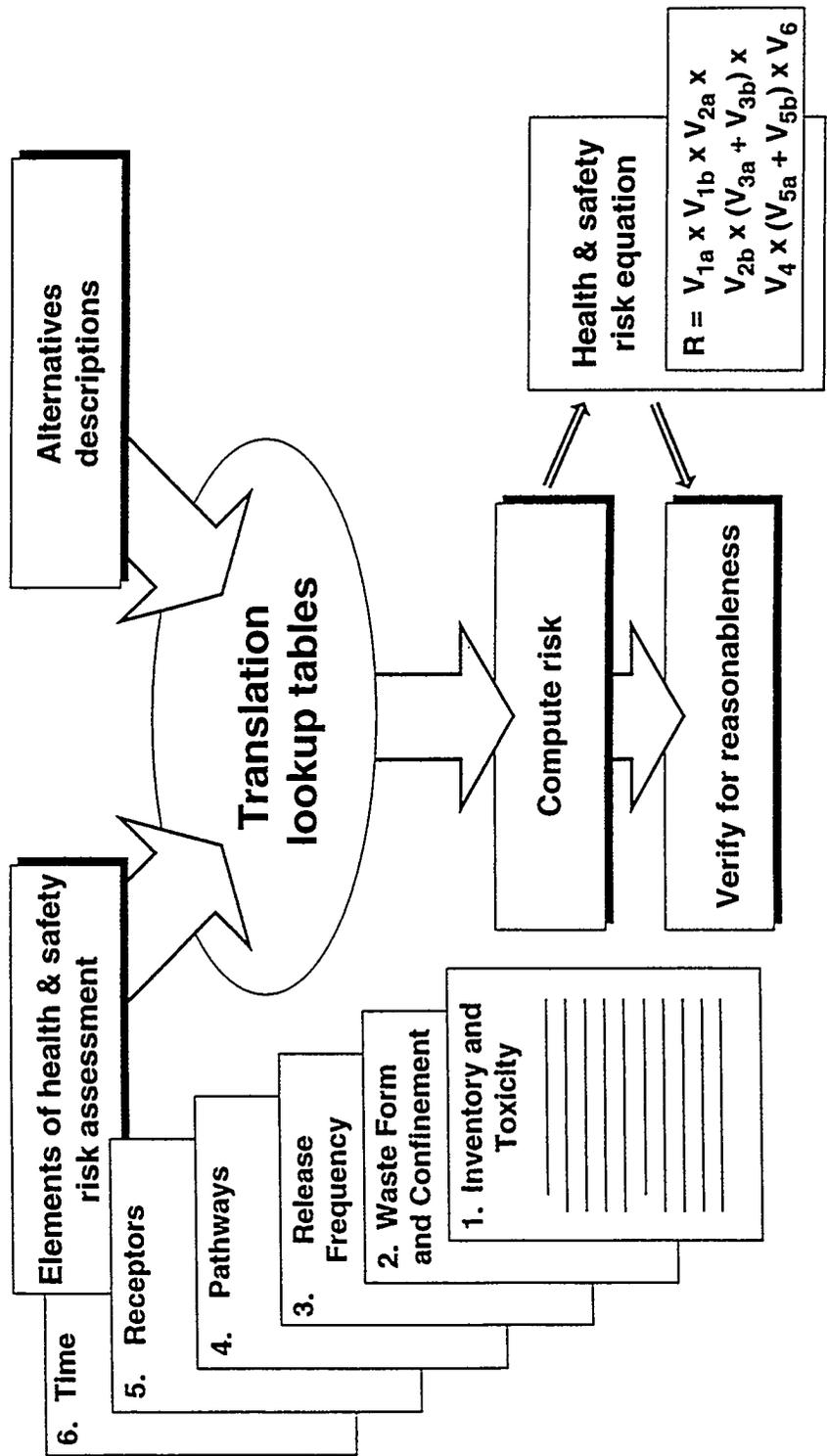
- Identify the key physical parameters that would influence the value of the element if preparing a detailed HSRA, while bearing in mind the possible types of states and the likely dominant transport pathways for each type
- Determine, by consulting several detailed HSRAs or other technical documentation that deals with specific H&S-related parameters, the absolute values for the key parameters for the range of expected situations
- Place the absolute values on a relative scale
- Aggregate the results as necessary for ease of use.

All values are based on the assumption that the EM operations are conducted with a level of control that is typical at DOE facilities.

Interpolation between values in the lookup tables may be necessary in some instances because the guidance cannot cover all possible situations. In addition, risk assessors using this method may want to choose values for some risk elements that reflect unique conditions of particular states.

The values in the lookup tables are composites based on reviewing many types of HSRAs and other documents related to many regulatory requirements. Therefore, the lookup table values will not necessarily reflect the specific regulatory guidance for a specific type of state.

A large number of simplifications were necessary to produce brief lookup tables that provide a rough approximation to the extremely complex actual behavior of facilities, contaminants, etc. These approximations are an unavoidable part of a level 2 risk assessment method.



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Figure 5-1. Computing risk using the simplified method.

5.1 Element 1—Waste Characteristics

5.1.1 Brief Description of Element

Element 1 characterizes the quantity and toxicity of the radiological and nonradiological contaminants in the waste. Element 1a addresses the quantity of contaminants. Element 1b addresses the specific toxicity of the contaminants, that is, the toxicity per unit quantity.^f

The simplified method addresses the risk over future times, based on the initial inventory of contaminants in the state and radioactive decay of the radionuclides. (The method does not distinguish between a case in which no contaminant migration has occurred to date and an otherwise identical case in which the contaminants have already migrated part of the distance toward the receptor.)

Although two subelements make up Element 1, they are addressed jointly in this discussion because of the way they are combined mathematically in Equations (4-4) through (4-8).

The number of contaminants that may be present in waste types is extremely large, and their toxicities vary widely. To preserve the simplicity of the method and reflect the wide range of contaminant toxicities, the contaminants are grouped into classes. The concept of contaminant classes accommodates all waste types—radioactive waste or spent fuel, nonradioactive hazardous waste, and mixed waste—because Equations (4-4) through (4-8) address both radiological and nonradiological contaminants, whether they occur separately or combined.

The classes of radiological and nonradiological contaminants are as follows:

- Radiological contaminants (two classes)

f. Toxicity is an indication of a contaminant's dose-response relationship (EPA 1989). The greater the effect on a receptor for a given dose, the greater the toxicity. This report uses three toxicity terms: absolute, relative, and specific toxicity. Absolute toxicity relates to a range of specific health effects, such as the incidence of cancer, resulting from an intake. Relative toxicity relates to the absolute toxicity of one contaminant divided by the absolute toxicity of a baseline contaminant. Specific toxicity emphasizes that the toxicity terms are on a per curie or per kilogram basis. The toxicity values used in the simplified relative risk equation are specific relative toxicities that are derived from absolute toxicities. Unless indicated by modifiers or by the context, this report uses the term toxicity to represent the specific relative toxicity.

- Long-lived (half-lives > 20 years), alpha-emitting actinides (atomic number of 89 or greater), and any existing (not future) decay products of actinides^g; this class is referred to here as actinides
- All other radionuclides; this class is referred to here as nonactinides.
- Nonradiological contaminants
 - No simple, reliable grouping of hazardous chemicals was identified that allows rapid approximate designation of toxicity, analogous to the use of actinides versus nonactinides for radionuclides. Therefore, the toxicity value must be looked up in supplied tables for each hazardous chemical present in quantities that might affect the risk substantially.^h

In applying Equations (4-4) through (4-8), the quantity of each contaminant class (the V_{1a_i} term) is multiplied by the specific toxicity value of that contaminant class (the V_{1b_i} term). For nonradioactive hazardous waste, the quantities of radionuclides are zero, so the product terms that involve radionuclides have zero value. Likewise, for nonmixed radioactive waste, the quantities of nonradiological contaminants are zero, so the product terms that involve nonradiological contaminants have zero value. For mixed waste, at least one quantity for the radiological and nonradiological contaminants is not zero.

The quantities of contaminants are given in curies of radiological contaminants for each contaminant class and in kilograms for nonradiological contaminants, and they are discussed in Section 5.1.2. The specific toxicities are discussed in Section 5.1.3.

g. Some relatively short-lived, beta-emitting radionuclides have decay products that are long-lived, alpha-emitting radionuclides of substantially higher specific toxicity (see Section 5.1.3.1.3). For example, Pu-241 decays to produce Am-241, Np-237, and other long-lived alpha-emitters of higher toxicity. These decay chains are hybrids in the sense that some chain members are beta-emitters and have the toxicity characteristics typical of beta-emitters, while other chain members are alpha-emitters and have the higher toxicity typically associated with alpha-emitters. There is no precise way to accommodate this situation in a simple method. Fortunately, the relatively high specific activity of Pu-241 implies that only a small activity of the decay products is produced. For example, the peak total activity of the long-lived alpha-emitting radionuclides resulting from the decay of 1 Ci of Pu-241 is only about 0.03 Ci. Therefore, including Pu-241 and similar short-lived transuranic beta-emitters among the nonactinides is a reasonable approximation, given the limited detail of this simplified method.

h. As discussed in Section 5.1.3.2, in practice, only a few hazardous chemicals from among the large number that may exist in a waste type will generally dominate the risk contribution. Therefore, specific toxicities usually need be determined for a limited number of hazardous chemicals (e.g., three or four) in any situation.

5.1.2 Element 1a—Contaminant Quantities

5.1.2.1 Quantities of Radionuclides.

5.1.2.1.1 General Approach for Developing Lookup Table—For a fixed distribution of radionuclides, the risk of an operation is generally proportional to the total radioactivity.ⁱ Therefore, the approach for determining the quantity of radiological contaminants is to (a) use the initial total radioactivity in curies for the value of Element 1a (with separate totals for actinides and nonactinides), (b) adjust that radioactivity for decay to the time period of interest using a separate lookup table, and (c) account for differences in radiotoxicity in Element 1b.

5.1.2.1.2 Lookup Table—Determine the values for Element 1a as follows:

- For Element 1a, with $i = 1$, use the total curies of long-lived, alpha-emitting actinides and any existing (not future) decay products of actinides.
- For the value of Element 1a, with $i = 2$, use the remaining total curies of other radionuclides (nonactinides).
- Adjust the two values to account for radioactive decay. First, determine the beginning and end times of the state. Calculate the midpoint time. Then, for that midpoint time, select the appropriate adjustment factor for radioactive decay from Table 5-1 (actinides) and Table 5-2 (nonactinides) for the waste types indicated across the top of the tables.

No attempt is made to address the contact-handled (CH) and remote-handled (RH) LLW separately in Tables 5-1 and 5-2 because the tables give separate entries for the radioactive decay factor of CH and RH TRU waste and alpha-LLW (α -LLW). It can be seen that, for α -LLW, the results are relatively close in value for CH and RH waste. This is because the list and proportions of actinides present in CH and RH waste are similar; the principal difference is that there are larger concentrations of nonactinides in RH waste, particularly shorter-lived nonactinides. Therefore, the adjustment factors for radioactive decay are similar for the CH and RH waste.

5.1.2.1.3 Basis for Values in Lookup Tables—In general, each waste type for which risk is evaluated contains many radionuclides. In a few risk assessments (e.g., assessments involving sealed radioactive sources), only one or two radionuclides may be present, so dealing with the unique characteristics of each radionuclide may be straightforward. For the multiradionuclide cases, however, the method must accommodate the unique radionuclide distribution of each waste type in a simplified, approximate manner.

The radionuclides are divided into actinides and nonactinides. Within each of these two classes, the radionuclides show a general pattern of toxicities and half-lives. The quantity of radionuclides is measured in curies.

i. It is recognized that the risk of some scenarios is not necessarily linear with the contaminant inventory (e.g., a fire that affects a fixed number of waste containers regardless of the total number present). However, for the majority of scenarios, the risk is expected to be linear with the contaminant inventory. The linear dependence is the most appropriate assumption to use for the contaminant inventory in a simplified method.

Table 5-1. Adjustment factors for radioactive decay (including progeny ingrowth) for various types of waste: actinides.

Time (yr)	SNF ^a	HLW ^b	CH TRU ^c	RH TRU ^c	CH α -LLW ^c	RH α -LLW ^c	LLW ^d
0	1.0E0	1.0E0	1.0E0	1.0E0	1.0E0	1.0E0	1.0E0
10	9.2E-1	9.3E-1	9.5E-1	9.8E-1	9.7E-1	9.7E-1	1.6E0
30	7.9E-1	8.0E-1	9.0E-1	9.2E-1	9.2E-1	9.2E-1	1.4E0
50	6.8E-1	6.9E-1	8.5E-1	8.6E-1	8.7E-1	8.7E-1	1.4E0
100	4.6E-1	4.7E-1	7.5E-1	7.8E-1	7.7E-1	7.7E-1	1.2E0
200	2.1E-1	2.3E-1	6.1E-1	6.6E-1	6.5E-1	6.5E-1	9.7E-1
500	2.8E-2	4.7E-2	4.4E-1	5.1E-1	4.6E-1	4.6E-1	7.8E-1
1,000	8.7E-3	2.7E-2	3.1E-1	4.4E-1	3.3E-1	3.3E-1	6.8E-1

- a. For SNF, time zero corresponds to 1 year after removal from a reactor.
- b. For high-level waste (HLW), time zero corresponds to 1 year after removal from a reactor.
- c. For TRU waste and α -LLW, time zero corresponds to 10 years after the waste was generated.
- d. For LLW, time zero corresponds to the time of waste generation.

Table 5-2. Adjustment factors for radioactive decay (including progeny) for various types of waste: nonactinides.

Time (yr)	SNF ^a	HLW ^b	CH TRU ^c	RH TRU ^c	CH α -LLW ^c	RH α -LLW ^c	LLW ^d
0	1.0E0	1.0E0	1.0E0	1.0E0	1.0E0	1.0E0	1.0E0
10	1.4E0	7.7E-1	6.2E-1	7.3E-1	6.5E-1	7.8E-1	3.8E-1
30	8.8E-1	4.8E-1	2.6E-1	4.4E-1	3.0E-1	4.9E-1	1.9E-1
50	5.4E-1	3.0E-1	1.2E-1	2.8E-1	1.5E-1	3.0E-1	1.5E-1
100	1.7E-1	9.3E-2	3.7E-2	8.6E-2	4.6E-2	9.3E-2	1.0E-1
200	1.6E-2	9.1E-3	2.5E-2	8.4E-3	2.2E-2	1.1E-2	5.0E-2
500	4.0E-4	8.9E-5	1.5E-2	1.3E-4	1.3E-2	1.9E-3	6.7E-3
1,000	2.1E-4	6.4E-5	6.9E-3	5.3E-5	6.1E-3	1.8E-3	6.1E-4

- a. For SNF, time zero corresponds to 1 year after removal from a reactor.
- b. For HLW, time zero corresponds to 1 year after removal from a reactor.
- c. For TRU waste and α -LLW, time zero corresponds to 10 years after the waste was generated.
- d. For LLW, time zero corresponds to the time of waste generation.

Adjusting the total activity of each of the two classes of radionuclides to reflect the change over time caused by radioactive decay, including the ingrowth of progeny, requires some approximations. Tables 5-3a through 5-3g indicate how the approximations were developed. Table 5-3a depicts the analysis for SNF. Tables 5-3b through 5-3g address the other types of waste.

The following assumptions and approximations were used:

- For a given type of waste, the radionuclide distribution applied whether or not the waste was mixed waste.
- For a given type of waste, different radionuclide distributions exist for each subtype (e.g., liquid, sludge, salt cake, and precipitate for HLW) and for each DOE site. Different distributions even exist for the various tanks of HLW in a given tank farm (LITCO 1995a). No attempt was made to compile information on each subtype and for each site. In most cases, the data are representative of INEL waste; for HLW, the most useful data identified are for the Savannah River Site (SRS).
- The activities in the tables were normalized to an initial total activity of 1 Ci for each class of radionuclides (actinides and nonactinides).
- Radioactive decay and ingrowth was computed using the RadDecay computer code, version 4.00, from Grove Engineering, Inc., unless stated otherwise. For radionuclides that are members of decay chains, the activity of the entire chain at future times was included rather than just the activity of the parent radionuclide. For this reason, the future activities for some radionuclides are larger than the initial activities.
- Treating secular equilibrium (such as the equilibrium involving radionuclide pairs Cs-137/Ba-137m, Sr-90/Y-90, Ru-106/Rh-106, and Ce-144/Pr-144) was complex because some inventories reported in the source documents included the decay product explicitly at its equilibrium activity, but other inventories did not include this adjustment. Without detailed knowledge of how the inventory was derived, rigorous assumptions cannot be made, which is a limitation of the simplified method. This report used the reporting scheme of the original source (i.e., either with or without the decay product), then the RadDecay calculations were scaled to reflect whether the decay product was included in the original radioactivity inventories.
- For simplicity, only the radionuclides contributing the majority of the activity over the time period of interest (the first 1,000 years) were included. This assumption does not always reflect adequately the groundwater risk contributions of very long-lived nonactinides (e.g., C-14, I-129, Tc-99, and Nb-94) that may be present in very small activities and are very mobile in subsurface transport. For two of the seven types of waste addressed here (CH TRU and RH TRU waste), the information sources used for the distribution of radionuclides did not include such long-lived nonactinides. For all cases in which those radionuclides were included in the information source, the radionuclides were carried through the present analysis. Their presence is reflected by their long-term contributions (e.g., at 500 and 1,000 years) in the radioactive decay tables for the other five types of waste.

Table 5-3a. (continued).

Radionuclide	Normalized activity									
	At t = 0 year (1 year out of reactor)	At 10 years	At 30 years	At 50 years	At 100 years	At 200 years	At 500 years	At 1,000 years		
	Nonactinides ^c (continued)									
Eu-155	2.2E-2	5.1E-3	2.6E-4	1.4E-5	—	—	—	—		
H-3	1.9E-3	1.1E-3	3.5E-4	1.1E-4	6.7E-6	2.4E-8	—	—		
I-129	1.0E-7	1.0E-7	1.0E-7	1.0E-7	1.0E-7	1.0E-7	1.0E-7	1.0E-7		
Nb-94	—	—	—	—	—	—	—	—		
Pu-241	2.1E-2	1.3E-2	5.5E-3	2.5E-3	7.8E-4	5.3E-4	3.3E-4	1.5E-4		
Sb-125	2.6E-2	2.6E-3	1.8E-5	1.2E-7	—	—	—	—		
Sr-90	4.4E-1	6.9E-1	4.2E-1	2.6E-1	7.8E-2	6.9E-3	4.8E-6	—		
Tc-99	5.6E-5	5.6E-5	5.6E-5	5.6E-5	5.6E-5	5.6E-5	5.6E-5	5.6E-5		
Total	1.0E0	1.4E0	8.8E-1	5.4E-1	1.7E-1	1.6E-2	4.0E-4	2.1E-4		

a. Source of information: Schnitzler (1994). The data are for highly enriched uranium (93% U-235 by mass) fuel from the Advanced Test Reactor at the INEL. The fuel was removed from the reactor 1 year earlier. The calculations were made using the ORIGEN2 computer code and a special-purpose cross-section library developed for the Advanced Test Reactor. Activation products in the cladding are not included but would be considerably smaller in activity than the fission products.

b. The precise definition used here is long-lived (half-lives > 20 years), alpha-emitting actinides, and the currently existing decay products of actinides.

c. The precise definition used here is any radionuclide not falling within the definition of actinides given in footnote b.

Table 5-3b. (continued).

Radionuclide	Normalized activity									
	At t = 0 year (1 year out of reactor)	At 10 years	At 30 years	At 50 years	At 100 years	At 200 years	At 500 years	At 1,000 years		
	Nonactinides ^c (continued)									
Tc-99	5E-5	5.0E-5	5.0E-5	5.0E-5	5.0E-5	5.0E-5	5.0E-5	5.0E-5	5.0E-5	5.0E-5
Total	1.0E0	7.7E-1	4.8E-1	3.0E-1	9.3E-2	9.1E-3	8.9E-5	6.4E-5	6.4E-5	6.4E-5

a. Source of information: DOE (1994a), Table 2.11, which addresses the radionuclide inventory in the HLW (liquid, sludge, salt cake, and precipitate combined) at the DOE SRS. DOE (1994a) provides the most complete inventory obtained for HLW in this study. A less detailed inventory for INEL HLW calcine provided similar results for the principal contributing radionuclides: 52% of the activity is in Cs-137 plus Ba-137m (compared to 58% in the SRS inventory), 45% in Sr-90 and Y-90 (compared to 40%), and 0.6% in actinides (compared to 0.35%). For INEL liquid HLW (LITCO 1995a), the respective percentages are 48%, 47%, and 0.12%.

b. The precise definition used here is long-lived (half-lives > 20 years), alpha-emitting actinides, and the currently existing decay products of actinides.

c. The precise definition used here is any radionuclide not falling within the definition of actinides given in footnote b.

Table 5-3c. (continued).

Radionuclide	Normalized activity									
	At t = 0 year (10 years after generation)	At 10 years	At 30 years	At 50 years	At 100 years	At 200 years	At 500 years	At 1,000 years		
	Nonactinides ^c (continued)									
Pu-241	9.9E-1	6.2E-1	2.6E-1	1.2E-1	3.7E-2	2.5E-2	1.5E-2	6.9E-3		
Sr-90	1.9E-4	3.0E-4	1.8E-4	1.1E-4	3.4E-5	3.0E-6	—	—		
Zr-95	2.4E-4	—	—	—	—	—	—	—		
Total	1.0E0	6.2E-1	2.6E-1	1.2E-1	3.7E-2	2.5E-2	1.5E-2	6.9E-3		

a. Source of information: The INEL Radioactive Waste Management Information System (RWMIS), which contains data for the combined TRU waste plus α -LLW stored at the INEL Radioactive Waste Management Complex. Smith et al. (1995), Appendix B, which addresses the radionuclide inventory in the α -LLW, was used to subtract the activities in the α -LLW, leaving the values for the TRU waste only. Mixed fission product entries and unidentified beta-gamma entries in RWMIS were assumed to be 50% Sr-90 and 50% Cs-137. Mixed activation product entries were assumed to be 100% Co-60.

b. The precise definition used here is long-lived (half-lives > 20 years), alpha-emitting actinides, and the currently existing decay products of actinides.

c. The precise definition used here is any radionuclide not falling within the definition of actinides given in footnote b.

Table 5-3d. (continued).

Radionuclide	Normalized activity								
	At t = 0 year (10 years after generation)	At 10 years	At 30 years	At 50 years	At 100 years	At 200 years	At 500 years	At 1,000 years	
			Nonactinides ^c (continued)						
Sr-90	2.2E-1	3.5E-1	2.1E-1	1.3E-1	3.9E-2	3.5E-3	2.4E-6	—	
Total	1.0E0	7.3E-1	4.4E-1	2.8E-1	8.6E-2	8.4E-3	1.3E-4	5.3E-5	

a. Source of information: The INEL RWMIS, which contains data for the combined TRU waste plus α -LLW stored at the INEL Radioactive Waste Management Complex. Smith et al. (1995), Appendix B, which addresses the radionuclide inventory in the α -LLW, was used to subtract the activities in the α -LLW, leaving the values for the TRU waste only. Mixed fission product entries and unidentified beta-gamma entries in RWMIS were assumed to be 50% Sr-90 and 50% Cs-137. Mixed activation product entries were assumed to be 100% Co-60.

b. The precise definition used here is long-lived (half-lives > 20 years), alpha-emitting actinides, and the currently existing decay products of actinides.

c. The precise definition used here is any radionuclide not falling within the definition of actinides given in footnote b.

Table 5-3e. Development of adjustments for radioactive decay—contact-handled alpha-low-level waste.^a

Radionuclide	Normalized activity									
	At t = 0 year (10 years after generation)	At 10 years	At 30 years	At 50 years	At 100 years	At 200 years	At 500 years	At 1,000 years		
			Actinides ^{b,c}							
Am-241	4.5E-1	4.4E-1	4.3E-1	4.2E-1	3.8E-1	3.3E-1	2.0E-1	9.0E-2		
Pu-238	3.0E-1	2.8E-1	2.4E-1	2.0E-1	1.4E-1	6.2E-2	5.9E-3	2.2E-4		
Pu-239	2.0E-1	2.0E-1	2.0E-1	2.0E-1	2.0E-1	2.0E-1	2.0E-1	1.9E-1		
Pu-240	5E-2	5.0E-2	5.0E-2	5.0E-2	5.0E-2	4.9E-2	4.7E-2	4.5E-2		
U-233	4E-3	4.0E-3	4.1E-3	4.2E-3	4.3E-3	4.6E-3	5.5E-3	6.8E-3		
Total	1.0E0	9.7E-1	9.2E-1	8.7E-1	7.7E-1	6.5E-1	4.6E-1	3.3E-1		
			Nonactinides ^d							
C-14	7E-4	7.0E-4	7.0E-4	7.0E-4	6.9E-4	6.7E-4	6.6E-4	6.2E-4		
Cm-244	3E-3	2.0E-3	9.6E-4	4.5E-4	7.3E-5	9.5E-6	7.9E-6	7.5E-6		
Co-60	5E-3	1.3E-3	9.7E-5	7.0E-6	—	—	—	—		
Cs-137 + Ba-137m	9E-2	7.2E-2	4.5E-2	2.9E-2	9.1E-3	9.1E-4	9.3E-7	—		
H-3	4E-2	2.3E-2	7.4E-3	2.4E-3	1.4E-4	5.0E-7	—	—		
Pu-241	8E-1	5.0E-1	2.1E-1	9.5E-2	3.0E-2	2.0E-2	1.2E-2	5.5E-3		

Table 5-3e. (continued).

Radionuclide	Normalized activity							
	At t = 0 year (10 years after generation)	At 10 years	At 30 years	At 50 years	At 100 years	At 200 years	At 500 years	At 1,000 years
Sr-90+ Y-90	7E-2	5.5E-2	3.4E-2	2.1E-2	6.0E-3	5.5E-4	3.8E-7	—
Total	1.0E0	6.5E-1	3.0E-1	1.5E-1	4.6E-2	2.2E-2	1.3E-2	6.1E-3

a. Source of information: Smith et al. (1995), Appendix B, which addresses the radionuclide inventory in the α -LLW stored at the INEL Radioactive Waste Management Complex.

b. The precise definition used here is long-lived (half-lives >20 years), alpha-emitting actinides, and the currently existing decay products of actinides.

c. By definition, the α -LLW ranges from trace to 100 nCi/g of long-lived, alpha-emitting TRU radionuclides. The exact concentration of this radioactivity is not known. Smith et al. (1995) gives bounding values of radionuclide activities for concentrations of 10 and 100 nCi TRU/g of waste. It was assumed here that the average concentration is 50 nCi TRU/g of waste.

d. The precise definition used here is any radionuclide not falling within the definition of actinides given in footnote b.

Table 5-3f. Development of adjustments for radioactive decay—remote-handled alpha-low-level waste.^a

Radionuclide	Normalized activity									
	At t = 0 year (10 years after generation)	At 10 years	At 30 years	At 50 years	At 100 years	At 200 years	At 500 years	At 1,000 years		
			Actinides ^{b,c}							
Am-241	4.5E-1	4.4E-1	4.3E-1	4.2E-1	3.8E-1	3.3E-1	2.0E-1	9.0E-2		
Pu-238	3.0E-1	2.8E-1	2.4E-1	2.0E-1	1.4E-1	6.2E-2	5.9E-3	2.2E-4		
Pu-239	2.0E-1	2.0E-1	2.0E-1	2.0E-1	2.0E-1	2.0E-1	2.0E-1	1.9E-1		
Pu-240	5E-2	5.0E-2	5.0E-2	5.0E-2	5.0E-2	4.9E-2	4.7E-2	4.5E-2		
U-233	4E-3	4.0E-3	4.1E-3	4.2E-3	4.3E-3	4.6E-3	5.5E-3	6.8E-3		
Total	1.0E0	9.7E-1	9.2E-1	8.7E-1	7.7E-1	6.5E-1	4.6E-1	3.3E-1		
			Nonactinides ^d							
C-14	2E-3	2.0E-3	2.0E-3	2.0E-3	2.0E-3	2.0E-3	1.9E-3	1.8E-3		
Co-60	1E-2	2.7E-3	1.9E-4	1.4E-5	2.0E-8	—	—	—		
Cs-134	1E-2	3.5E-4	4.2E-7	—	—	—	—	—		
Cs-137 + Ba-137m	5.68E-1	4.5E-1	2.9E-1	1.8E-1	5.7E-2	5.7E-3	5.9E-6	—		
Pu-241	2E-3	1.3E-3	5.2E-4	2.4E-4	7.4E-5	5.0E-5	3.1E-5	1.4E-5		

Table 5-3f. (continued).

Radionuclide	Normalized activity							
	At t = 0 year (10 years after generation)	At 10 years	At 30 years	At 50 years	At 100 years	At 200 years	At 500 years	At 1,000 years
			Nonactinides ^d (continued)					
Sr-90 + Y-90	4.05E-1	3.2E-1	2.0E-1	1.2E-1	3.4E-2	3.2E-3	2.2E-6	--
Total	1.0E0	7.8E-1	4.9E-1	3.0E-1	9.3E-2	1.1E-2	1.9E-3	1.8E-3

a. Source of information: Smith et al. (1995), Appendix B, which addresses the radionuclide inventory in the α -LLW stored at the INEL Radioactive Waste Management Complex.

b. The precise definition used here is long-lived (half-lives > 20 years), alpha-emitting actinides, and the currently existing decay products of actinides.

c. By definition, the α -LLW ranges from trace to 100 nCi/g of long-lived, alpha-emitting TRU radionuclides. The exact concentration of this radioactivity is not known. Smith et al. (1995) gives bounding values of radionuclide activities for concentrations of 10 and 100 nCi TRU/g of waste. It was assumed here that the average concentration is 50 nCi TRU/g of waste.

d. The precise definition used here is any radionuclide not falling within the definition of actinides given in footnote b.

- Radionuclides constituting less than $1E-8$ of the original total activity of actinides or nonactinides were not included in the totals. These radionuclides are indicated by a dash in Tables 5-3a through 5-3g.
- For LLW, the times in Table 5-3g represent the time since the waste was generated. For SNF and HLW, the beginning time is 1 year after terminating the irradiation of the fuel in the reactor. For TRU waste and α -LLW, the beginning time is 10 years after the waste was generated.
- Entries for radioactivity are generally given to only one or two significant digits because of the number of approximations that were made. Therefore, the entries in Tables 5-3a through 5-3g may not total exactly unity for time zero. These entries were adjusted slightly when entering the results for later years into Tables 5-1 and 5-2.

A footnote in each table gives the source of the information. The lists of radionuclides were more complete for some waste types because of the intended use for the information in the source document.

The difficulty in dealing with the Pu-241 decay chain was mentioned in footnote g in Section 5.1.1. The chain includes the relatively short-lived beta-emitter Pu-241 (with a lower toxicity) and lower-activity, long-lived alpha-emitting decay products (with a higher toxicity). The simplified method places the Pu-241 with the nonactinides. Unfortunately, at longer times, the long-lived decay products of Pu-241 can be larger contributors than the contributions of other nonactinides, so the nonactinides (which are considered to have the lower toxicity of beta-emitters) should really be considered to have the higher toxicity for the Pu-241 decay products. This is the case with the nonactinides for the following five waste types in Tables 5-3a, 5-3c, 5-3d, 5-3e, and 5-3f:

1. SNF at 500 and 1,000 years
2. CH TRU waste for all times
3. RH TRU waste at 500 and 1,000 years
4. CH α -LLW at all times
5. RH α -LLW at 500 and 1,000 years.

An alternative approach is to include the Pu-241 with the long-lived alpha-emitters, even though the parent is a relatively short-lived beta-emitter. This is a limitation of the simplified method—not all radionuclides fall neatly into the two classes when their decay characteristics and radiotoxicity are examined in detail.

5.1.2.2 Quantities of Hazardous Chemicals.

5.1.2.2.1 General Approach for Developing Lookup Table—For a fixed-composition mixture of hazardous chemicals, the risk of an operation is generally proportional to the total mass of the

chemicals.^j Therefore, the approach for handling the quantity of nonradiological contaminants is to (a) use the quantity in kilograms for the value of Element 1a for each hazardous chemical of concern^k and (b) account for differences in toxicity of various contaminants in Element 1b.

5.1.2.2.2 Lookup Table—Select the value of Element 1a for each hazardous chemical by determining the mass in kilograms.

5.1.2.2.3 Basis for Values in Lookup Table—The basis for using the mass of each hazardous chemical is self-evident. The mass is measured in kilograms.

5.1.3 Element 1b— Specific Toxicity

Sections 5.1.3.1 and 5.1.3.2 develop the relative values to be used for the specific toxicity of radionuclides and nonradiological contaminants (hazardous chemicals). The relative values are derived from aggregations of absolute toxicity values given in the regulatory guidance of EPA, OSHA, and DOE.

For brevity hereafter, the term toxicity is generally used to represent the term specific toxicity, when discussing toxicity per unit quantity of the contaminant.

5.1.3.1 Specific Toxicity of Radionuclides.

5.1.3.1.1 General Approach for Developing Lookup Table—The approach for developing the values of Element 1b for the toxicities of radionuclides was to

- Consider two potential exposure routes: ingestion and inhalation.
- Identify a number of the radionuclides most frequently found in the various waste types, as documented in detailed HSRAs such as CERCLA risk assessments and DOE safety analyses.
- Examine the absolute toxicities of these radionuclides. The published values of absolute toxicity vary depending not only on the exposure route but also on the particular regulations and guidance documents that govern the detailed HSRA.
- Estimate effective dose conversion factor (DCFs), for various waste types.

j. It is recognized that the risk of some scenarios is not necessarily linear with the contaminant inventory (e.g., a fire that affects a fixed number of waste containers regardless of the total number present). However, for the majority of scenarios, the risk is expected to be linear with the contaminant inventory. The linear dependence is the most appropriate assumption to use for the contaminant inventory in a simplified method.

k. In practice, only a few hazardous chemicals from among the large number that may exist in a waste type will generally dominate the risk contribution. Therefore, specific toxicities usually need be determined for a limited number of hazardous chemicals (e.g., three to five) in any situation.

The 22 representative radionuclides listed in Table 5-4 were used for developing the lookup table for all of the approximately 2,500 radionuclides. The shorter list includes most of the predominant actinides and nonactinides identified in a study of INEL LLW. Three less common radionuclides were also considered in the study because of their very long half-lives and their relatively high rate of groundwater transport once released from confinement: H-3, C-14, and I-129. Hydrogen-3 and C-14 were dropped later from use in developing the lookup table because their toxicities were on the order of 10^3 to 10^7 times lower than those for the other radionuclides. Iodine-129 was included in developing the lookup table.

5.1.3.1.2 Lookup Table—Element 1b—Specific Toxicity for Radionuclides—Select the value in Table 5-5 that corresponds to the pathway listed across the top of the table and the radionuclide class of interest down the left side.

If the radionuclide distribution in the waste type being evaluated is radically different from the typical distributions given in Section 5.1.2.1, better accuracy may be achieved by referring to the basic toxicity data given in Section 5.1.3.1.3 and deriving more specific and appropriate values for Element 1b.

5.1.3.1.3 Basis for Values in Lookup Table—Tables 5-6 and 5-7 compare the toxicities of each radionuclide in Table 5-4 for the inhalation and ingestion exposure routes. The following discussion explains the data compiled for each of the two exposure routes.

Inhalation Exposure Route—For the simplified pathways analysis used here, the inhalation exposure route was taken to be synonymous with airborne releases of contaminants. The second column of Table 5-6 lists the slope factors (SFs), taken from EPA (1995b), for the given radionuclides in ascending order of value.

Table 5-4. Radionuclides used to determine values of specific toxicity.

Radionuclides			
Am-241	Eu-155	Pu-241	U-232
Cm-244	I-129	Sr-90	U-233
Co-60	Np-237	Th-228	U-234
Cs-137	Pu-238	Th-230	U-235
Eu-152	Pu-239	Th-232	U-238
Eu-154	Pu-240		

Table 5-5. Element 1b lookup table—specific toxicity for radionuclides.

Radionuclide class	Airborne pathway	Waterborne pathway
Actinides		
TRU		
(CH)	150	2
(RH)	100	1
SNF		
SRS production reactor, graphite reactor	150	2
Other reactors	30	0.5
HLW	350	3
LLW		
INEL, SRS	200	2.5
Disposal sites	600	1.5
Nonactinides	0.15	0.1

The SFs for the actinides are generally on the order of 10^2 to 10^3 times larger than those for the nonactinides, especially for the predominant radionuclides listed earlier.

A similar comparison was made using the DCFs for each of the listed radionuclides. The DCFs, taken from DOE (1988a), are listed in ascending order of value in column 5 of Table 5-6. The DCFs for the actinides are generally on the order of 10^2 to 10^4 times larger than the DCFs for the nonactinides. The toxicity for Pu-241 is much lower than that for the other actinides because it is a relatively short-lived beta-emitter.

Ingestion Exposure Route—The ingestion exposure route is assumed, in this simplified pathways analysis, to be synonymous with waterborne releases of contaminants. The second column of Table 5-7 lists the SFs for the given radionuclides in ascending order of value.

The SFs for the actinides are generally on the order of 10^0 to 10^1 times larger than those for the nonactinides, again especially for the predominant radionuclides listed earlier.

A similar comparison was made using the DCFs for each of the listed radionuclides. The DCFs, taken from DOE (1988a), are listed in ascending order of value in column 5 of Table 5-7. The DCFs for the actinides are generally on the order of 10^1 to 10^2 times larger than the DCFs for the nonactinides.

Table 5-6. Comparison of inhalation slope factors and dose conversion factors for radionuclides.

Inhalation dose slope factor		Inhalation dose conversion factor	
Radionuclide	SF (cancer incidence/pCi)	Radionuclide	DCF (rem/ μ Ci)
Eu-155	9.60E-12	Cs-137 ^a	3.20E-02
Cs-137 ^a	1.91E-11	Eu-155	3.90E-02
Co-60	6.88E-11	Co-60	1.60E-01
Sr-90 ^a	6.93E-11	I-129	1.80E-01
Eu-152	7.91E-11	Eu-152	2.20E-01
Eu-154	9.15E-11	Sr-90 ^a	2.30E-01
I-129	1.22E-10	Eu-154	2.60E-01
Pu-241	2.81E-10	Pu-241	5.70E+00
U-238 ^a	1.24E-08	U-235 ^a	1.29E+02
U-235 ^a	1.30E-08	U-238 ^a	1.29E+02
U-234	1.40E-08	U-233	1.30E+02
U-233	1.41E-08	U-234	1.30E+02
Th-230	1.72E-08	Cm-244	2.70E+02
Th-232	1.93E-08	Th-230	2.70E+02
Cm-244	2.43E-08	Pu-238	3.00E+02
Pu-238	2.74E-08	Pu-239	3.30E+02
Pu-239	2.78E-08	Pu-240	3.30E+02
Pu-240	2.78E-08	Np-237	4.90E+02
Np-237 ^a	3.45E-08	Am-241	5.20E+02
Am-241	3.85E-08	Th-228 ^a	5.73E+02
U-232	5.29E-08	U-232	6.70E+02
Th-228 ^a	9.68E-08	Th-232	1.10E+03

a. Includes the contributions from decay product(s).

Table 5-7. Comparison of ingestion slope factors and dose conversion factors for radionuclides.

Ingestion dose slope factor		Ingestion dose conversion factor	
Radionuclide	SF (cancer incidence/pCi)	Radionuclide	DCF (rem/ μ Ci)
Eu-155	1.65E-12	Eu-155	1.30E-03
Pu-241	5.20E-12	Eu-152	6.00E-03
Eu-152	5.73E-12	Eu-154	9.10E-03
Eu-154	9.37E-12	Co-60	2.60E-02
Co-60	1.89E-11	Cs-137 ^a	5.00E-02
Cs-137 ^a	3.16E-11	Pu-241	8.60E-02
Th-232	3.28E-11	Sr-90 ^a	1.30E-01
Th-230	3.75E-11	U-234	2.60E-01
U-234	4.44E-11	U-238 ^a	2.68E-01
U-233	4.48E-11	U-233	2.70E-01
U-235 ^a	4.70E-11	U-235 ^a	2.76E-01
Sr-90 ^a	5.59E-11	I-129	2.80E-01
U-238 ^a	6.20E-11	Th-230	5.30E-01
U-232	8.12E-11	Th-228 ^a	7.52E-01
I-129	1.84E-10	U-232	1.30E+00
Cm-244	2.11E-10	Cm-244	2.30E+00
Th-228 ^a	2.31E-10	Th-232	2.80E+00
Pu-238	2.95E-10	Pu-238	3.80E+00
Np-237 ^a	3.00E-10	Np-237	3.90E+00
Pu-240	3.15E-10	Pu-239	4.30E+00
Pu-239	3.16E-10	Pu-240	4.30E+00
Am-241	3.28E-10	Am-241	4.50E+00

a. Includes the effects from decay product(s).

In order to provide estimates for element 1b that are waste stream specific, effective DCFs were calculated for actual TRU, SNF, HLW, and LLW radionuclide profiles. The results are summarized in Table 5-8. Results from this table were used to generate the recommended values presented in Table 5-5.

5.1.3.2 Specific Toxicity of Hazardous Chemicals.

5.1.3.2.1 General Approach for Developing Lookup Table—The approach for developing the values of Element 1b for the toxicities of hazardous chemicals was to

- Consider two potential exposure routes: ingestion and short- and long-term inhalation.
- Identify a large number of the hazardous chemicals most frequently found in the various waste types, as documented in detailed HSRAs (e.g., CERCLA risk assessments and DOE safety analyses).
- Examine the absolute toxicities of these hazardous chemicals. The published values of absolute toxicity vary depending not only on the exposure route but also on the particular regulations and guidance documents that govern the detailed HSRA.
- Because the absolute toxicity values for each exposure route are listed in several sets of guidelines, use the following measures of absolute toxicity as given in the stated regulatory sources: (a) the SFs for carcinogenic effects and the reference doses (RfDs) for noncarcinogenic effects, both as given in the EPA's Integrated Risk Information System (EPA 1996) and EPA *Health Effects Assessment Summary Tables* (EPA 1995a) and (b) the threshold limit values (TLVs), in terms of time-weighted averages (TWAs) and short-term exposure limits (STELs). The values of the TWAs and STELS are promulgated in OSHA regulations, but the TWA and STEL values used here are taken from the American Conference of Governmental Industrial Hygienists (ACGIH) publications (e.g., ACGIH 1993) from which OSHA periodically draws information to update its own regulations.
- For each exposure route and each regulatory source, assign each hazardous chemical to one of three groups of toxicity values: high, moderate, or low toxicity.
- For each exposure route, aggregate the toxicity ratings over the various regulatory sources.
- Assign a quantitative value to Element 1b for each of the three ratings that reflects the typical absolute values of toxicity in the regulations. The value is based on correlating the BRA risk equations and the relative risk equations, together with examining the values of the absolute toxicities.

Table 5-8. Effective DCFs for various waste streams.

Waste stream	Radionuclide class	Effective DCF (rem/ μ Ci)	
		Airborne pathway	Waterborne pathway
TRU ¹			
Hanford			
(CH)	Actinide (23%)	130	1.6
	Nonactinide (77%)	0.14	0.1
(RH)	Actinide (4%)	120	1.5
	Nonactinide (96%)	0.12	0.09
INEL			
(CH)	Actinide (99%)	170	1.8
	Nonactinide (1%)	0.12	0.08
(RH)	Actinide (9%)	6.5	0.10
	Nonactinide (91%)	0.19	0.11
LANL			
(CH)	Actinide (99.9%)	140	1.5
	Nonactinide (0.1%)	0.13	0.09
(RH)	Actinide (14%)	36	0.5
	Nonactinide (86%)	0.15	0.10
ORNL			
(CH)	Actinide (100%)	75	0.9
(RH)	Actinide (1%)	270	2.5
	Nonactinide (99%)	0.14	0.08
SRS			
(CH)	Actinide (100%)	250	3.1
Spent Nuclear Fuel ²			
SRS production reactor	Actinide (1%)	140	1.7
	Nonactinide (99%)	0.13	0.09
Hanford N-reactor	Actinide (13%)	30	0.4
	Nonactinide (87%)	0.12	0.09
Graphite reactor	Actinide (1%)	190	2.1
	Nonactinide (99%)	0.13	0.09
Special case commercial reactor	Actinide (25%)	30	0.4
	Nonactinide (75%)	0.11	0.08
University research/test reactor	Actinide (0.1%)	60	0.8
	Nonactinide (99.9%)	0.13	0.09
DOE research/test reactor	Actinide (4%)	25	0.3
	Nonactinide (96%)	0.11	0.08
Foreign research/test reactor	Actinide (0.2%)	15	0.2
	Nonactinide (99.8%)	0.13	0.09

Table 5-8. (continued).

Waste stream	Radionuclide class	Effective DCF (rem/ μ Ci)	
		Airborne pathway	Waterborne pathway
High Level Waste³			
Hanford			
Tank waste (liquid/sludge)	Actinide (0.1%)	280	2.6
	Nonactinide (99.9%)	0.15	0.1
Other waste (capsules)	Nonactinide (100%)	0.09	0.07
Glass canister (following vitrification)	Actinide (0.2%)	410	3.9
	Nonactinide (99.8%)	0.15	0.1
INEL			
Liquid/calcline/glass/grout	Nonactinide (100%)	0.12	0.09
SRS			
Liquid/sludge/glass	Actinide (0.5%)	210	2.7
	Nonactinide (99.5%)	0.13	0.09
WVDP			
Liquid/sludge	Actinide (0.4%)	500	4.4
	Nonactinide (99.6%)	0.13	0.09
Low-Level Waste			
INEL (alpha LLW) ⁴			
Sludge/nonsludge	Actinide (96%)	230	2.4
	Nonactinide (4%)	0.07	0.07
Remote-handled	Actinide (0.2%)	230	2.4
	Nonactinide (99.8%)	0.13	0.09
SRS			
Saltstone ³	Actinide (1%)	210	2.7
	Nonactinide (99%)	0.13	0.09
General class A, B, or C ³ (disposal sites)	Actinide (0.2%)	580	1.4
	Nonactinide (99.8%)	0.15	0.03

1. Monette et al. (1994)

2. DOE (1995b)

3. DOE (1995g)

4. Smith et al. (1995)

5.1.3.2.2 Lookup Table Element 1b—Specific Toxicity for Hazardous Chemicals—In Table 5-9 for the specific toxicity for hazardous chemicals,

- Locate each hazardous chemical known to be in the waste type in substantial quantities.
- Based on the type of pathway (airborne or waterborne) being evaluated, use the value of specific toxicity given for that pathway for the given chemical.
- Some hazardous chemicals not on the list may be present in the waste type in substantial quantities. In that case, refer to the method used in Section 5.1.3.2.3 to derive the values for Element 1b. Using that same method, supply the absolute toxicity values from the various regulatory sources and derive the value of the toxicity element corresponding to those in the lookup table. Unless such additional chemicals are expected to be key risk drivers, however, developing additional relative toxicity values may not be warranted.
- For entries listed as NA (data not available from the regulatory sources consulted), consult other sources of data and select a proportionate value for the specific toxicity.

5.1.3.2.3 Basis for Values in Lookup Table—The same basic approach was used to develop the Element 1b values for hazardous chemicals as for radionuclides in Section 5.1.3.1. However, the situation for hazardous chemicals is complicated by several considerations:

- Because there are many thousands of hazardous chemicals, a shorter list of hazardous chemicals does not necessarily represent most risk assessment applications.
- Both carcinogenic and noncarcinogenic effects must be considered.
- For the inhalation exposure route, both acute and chronic exposures need to be considered.
- The dermal exposure route can be important for a relatively small number of hazardous chemicals in certain pathways. This exposure route was not specifically addressed in the current analysis because a brief review of several detailed HSRAs indicated that the dermal route is seldom a dominant exposure route. However, some of the TLVs and STELs listed in Table 5-10 indicate some hazardous chemicals may contribute significantly to this exposure pathway.

These differences in the toxicity characteristics of radionuclides and hazardous chemicals were taken into account in developing the lookup table for hazardous chemicals.

Table 5-10 shows the information on which the lookup table is based.

The first step in developing Table 5-10 was to identify a large but manageable number of the hazardous chemicals expected to be found most frequently in various waste types. Obviously, not every inventory of hazardous chemicals in every waste type at every DOE site could be reviewed. Instead, a broad cross section of inventories was sampled in the data review. Eight source documents containing inventories of hazardous chemicals in various waste types at various DOE sites were reviewed. The chemicals in the first column of Table 5-10 (approximately 55 organics and 55 inorganics) are the resulting list.

Table 5-9. Element 1b lookup table—specific toxicity for hazardous chemicals.

Chemical	Toxicity group ¹ for ingestion (waterborne pathway)	Value of Element 1b for waterborne pathway	Toxicity group ² for inhalation (airborne pathway)	Value of Element 1b for airborne pathway
Organics				
1,1,1-trichloroethane	NA ³	NA	Low	10 ⁻⁵
1,1,2,2-tetrachloroethane	High	10 ³	Mod	10 ⁻³
1,1,2-trichloro-1,2,2-trifluoroethane	Low	3 × 10 ⁻⁵	Low	10 ⁻⁵
3-methylcholanthrene	NA	NA	NA	NA
Acetic acid	NA	NA	Mod	10 ⁻³
Acetone	Low	3 × 10 ⁻⁵	Low	10 ⁻⁵
Acrylonitrile	High	10 ³	High	0.1
Ammonia	NA	NA	Mod	10 ⁻³
Anthracene	Low	3 × 10 ⁻⁵	NA	NA
Benzene	Mod	3 × 10 ⁻³	Mod	10 ⁻³
n-butyl alcohol	Low	3 × 10 ⁻⁶	NA	NA
sec-butyl alcohol	NA	NA	Low	10 ⁻⁵
Carbon disulfide	Low	3 × 10 ⁻⁶	Low	10 ⁻⁵
Carbon tetrachloride	High	10 ³	Mod	10 ⁻³
Cellulose	NA	NA	Mod	10 ⁻³
Chloroform	Mod	3 × 10 ⁻⁵	Mod	10 ⁻³
Ethyl alcohol	NA	NA	Low	10 ⁻⁵
Ethyl ether	Low	3 × 10 ⁻⁶	Low	10 ⁻⁵
Ethyl benzene	Low	3 × 10 ⁻⁶	Mod	10 ⁻³
Ethylene dichloride	Mod	3 × 10 ⁻³	Mod	10 ⁻³
Formaldehyde	Low	3 × 10 ⁻⁶	High	0.1
Formic acid	Low	3 × 10 ⁻⁶	High	0.1
Glycerin	NA	NA	Mod	10 ⁻³
Hexane	Mod	3 × 10 ⁻⁵	Low	10 ⁻⁵
Hydrazine	High	10 ³	High	0.1
Isopropyl alcohol	NA	NA	Low	10 ⁻⁵
Mercury (organic)	High	10 ³	NA	NA
Methanol	Low	3 × 10 ⁻⁶	Mod	10 ⁻³

Table 5-9. (continued).

Chemical	Toxicity group ^a for ingestion (waterborne pathway)	Value of Element 1b for waterborne pathway	Toxicity group ^a for inhalation (airborne pathway)	Value of Element 1b for airborne pathway
Organics (continued)				
Methyl isobutyl ketone	Mod	3×10^{-3}	Mod	10^{-3}
Methyl ethyl ketone (2-butanone)	Low	3×10^{-4}	Mod	10^{-3}
Methylene chloride	Mod	3×10^{-3}	Low	10^{-2}
Naphthalene	Mod	3×10^{-3}	Mod	10^{-3}
Nitrobenzene	High	10^{-3}	Mod	10^{-3}
Nitrocellulose	NA	NA	NA	NA
Nonane	NA	NA	Low	10^{-5}
Oxalic acid	NA	NA	High	0.1
PCBs	High	10^{-3}	High	0.1
PCBs-aroclor 1016	High	10^{-3}	High	0.1
PCBs-aroclor 1254	High	10^{-3}	High	0.1
Pentane	NA	NA	Low	10^{-5}
Phenanthrene	NA	NA	NA	NA
Pyrene	Mod	3×10^{-5}	NA	NA
Terphenyls	NA	NA	Mod	10^{-3}
Tetrachloroethylene	Mod	3×10^{-3}	Mod	10^{-3}
Toluene	Low	3×10^{-4}	Low	10^{-5}
Tributyl phosphate	NA	NA	Mod	10^{-5}
Trichloroethylene	Mod	3×10^{-3}	Mod	10^{-3}
Trimethyl benzene	NA	NA	Low	10^{-5}
Versene disodium salt	NA	NA	NA	NA
Xylene, mixed	Low	3×10^{-4}	Mod	10^{-3}
Inorganics				
Aluminum	NA	NA	Mod	10^{-3}
Antimony	High	10^{-3}	High	0.1
Arsenic	High	10^{-3}	High	0.1
Barium	Mod	3×10^{-4}	High	0.1
Barium sulfate	NA	NA	Mod	10^{-3}
Beryllium	High	10^{-3}	High	0.1

Table 5-9. (continued).

Chemical	Toxicity group ^a for ingestion (waterborne pathway)	Value of Element 1b for waterborne pathway	Toxicity group ^a for inhalation (airborne pathway)	Value of Element 1b for airborne pathway
Inorganics (continued)				
Bromine	NA	NA	High	0.1
Cadmium	Mod	3×10^{-3}	High	0.1
Calcium hydroxide	NA	NA	Mod	10^{-3}
Calcium oxide	NA	NA	Mod	10^{-3}
Cerium chloride	NA	NA	NA	NA
Chromium-3	Low	3×10^{-6}	High	0.1
Chromium-6	Mod	3×10^{-5}	High	0.1
Cobalt	NA	NA	High	0.1
Copper	Mod	3×10^{-3}	High	0.1
Cyanide, free	Mod	3×10^{-3}	Mod	10^{-4}
Hydrochloric acid	NA	NA	Mod	10^{-3}
Hydrogen fluoride	NA	NA	Mod	10^{-3}
Hydrogen peroxide	NA	NA	Mod	10^{-3}
Lead	NA	NA	High	0.1
Lithium hydride	NA	NA	High	0.1
Lithium oxide	NA	NA	NA	NA
Magnesium fluoride	NA	NA	NA	NA
Magnesium oxide	NA	NA	Mod	10^{-3}
Manganese	Low	3×10^{-6}	High	0.1
Mercury	NA	NA	High	0.1
Mercury nitrate	NA	NA	NA	NA
Nickel	Mod	3×10^{-5}	High	0.1
Nitrate	Low	3×10^{-6}	NA	NA
Nitric acid	NA	NA	High	0.1
Phosphoric acid	NA	NA	High	0.1
Platinum	NA	NA	High	0.1
Selenium	Mod	3×10^{-3}	High	0.1
Silver	Mod	3×10^{-3}	High	0.1
Sodium cyanide	Mod	3×10^{-3}	NA	NA
Sodium hydroxide	NA	NA	NA	NA

Table 5-9. (continued).

Chemical	Toxicity group ^a for ingestion (waterborne pathway)	Value of Element 1b for waterborne pathway	Toxicity group ^a for inhalation (airborne pathway)	Value of Element 1b for airborne pathway
Inorganics (continued)				
Sulfuric acid	NA	NA	High	0.1
Tantalum	NA	NA	Mod	10 ⁻³
Thallium	High	10 ⁻³	High	0.1
Tungsten	NA	NA	High	0.1
Uranium (chemical toxicity)	Mod	3 × 10 ⁻⁵	High	0.1
Zinc	Low	3 × 10 ⁻⁶	Mod	10 ⁻³
Zirconium	Low	3 × 10 ⁻⁶	High	0.1
Explosives	DNA ^b	DNA ^b	DNA ^c	0.1 ^c

a. If the toxicity groups differed among the various toxicity measures, the higher (more conservative) group was used.

b. NA = toxicity data not available in regulatory sources consulted. The toxicity of the given chemical in the given exposure route may not be negligible, however. Lack of toxicity data should be included in the qualitative uncertainty discussion of the risk assessment.

c. For explosives, the toxicity value was taken to be that corresponding to the high toxicity value in the inhalation exposure route (airborne pathway) because of the hazard represented by the explosiveness characteristic. For waterborne pathways, the value was taken to be DNA (does not apply).

Reference citations for the eight source documents are listed at the bottom of Table 5-10. Detailed references are given at the reference section of the report.

Ingestion Exposure Route—The ingestion exposure route assumed in this simplified pathways analysis was taken to be synonymous with waterborne release and transport of contaminants. Two EPA absolute toxicity measures were evaluated to arrive at a value of the toxicity element for this exposure route: the SFs and RfDs.

Column 2 of Table 5-10 lists the oral SFs taken from EPA (1996, 1995a) for the given contaminants, reflecting the carcinogenic effects via this exposure route. Entries with dashes indicate that no SF was found for the chemical. The SFs range from on the order of 10⁻³ to 10⁰. The values were placed into three relative groups:¹ low toxicity (on the order of 10⁻³), moderate toxicity (on the order of 10⁻²), and high toxicity (on the order of 10⁻¹ or 10⁰).

1. For simplicity, throughout this analysis only the exponent of the toxicity value was examined in determining the order of magnitude. Thus, 7E-01 was considered to be on the order of E-01, not on the order of E+00.

Table 5-10. Toxicity of chemicals commonly found in waste types.^a

Chemical/ CAS number	SF oral (mg/kg-d) ¹	Toxicity group	RfD oral (mg/kg-d)	Toxicity group	SF inhalation (mg/kg-d) ¹	Toxicity group	RfD inhalation (mg/kg-d)	Toxicity group	TWA (mg/m ³)	Toxicity group	Short-term exposure limit (mg/m ³)	Toxicity group
Organics												
1,1,1-trichloroethane/ 71-55-6	—	—	—	—	—	—	5.71E-01 ^b	Low	1910	Low	2460	Low
1,1,2,2-tetrachloroethane/ 79-34-5	2.00E-01	High	—	—	2.03E-01	Mod ^c	—	—	6.9 ^d	Mod	—	—
1,1,2-trichloro- 1,2,2-trifluoroethane/ 76-13-1	—	—	3.00E+01	Low	—	—	—	—	7670	Low	9590	Low
3-methylcholanthrene/ 56-49-5	—	—	—	—	—	—	—	—	—	—	—	—
Acetic acid/ 64-19-7	—	—	—	—	—	—	—	—	25	Mod	37	Mod
Acetone/ 67-64-1	—	—	1.00E-01	Low	—	—	—	—	1780	Low	2380	Low
Acrylonitrile/ 107-13-1	5.40E-01	High	1.00E-03	Mod	2.38E-01	Mod	5.71E-04	High	4.3 ^e	Mod	—	—
Ammonia/ 7664-41-7	—	—	—	—	—	—	2.86E-02	Low	17	Mod	24	Mod
Anthracene/ 120-12-7	—	—	3.00E-01	Low	—	—	—	—	—	—	—	—
Benzene/ 71-43-2	2.90E-02	Mod	—	—	2.91E-02	Low	—	—	32	Mod	—	—
n-butyl alcohol/ 71-36-3	—	—	1.00E-01	Low	—	—	—	—	—	—	—	—
sec-butyl alcohol/ 78-92-2	—	—	—	—	—	—	—	—	303	Low	—	—
Carbon disulfide/ 75-15-0	—	—	1.00E-01	Low	—	—	2.00E-01	Low	31 ^d	Mod	—	—
Carbon tetrachloride/ 56-23-5	1.30E-01	High	7.00E-04	High	5.30E-02	Low	—	—	31 ^d	Mod	63	Mod
Cellulose/ 9004-34-6	—	—	—	—	—	—	—	—	10	Mod	—	—
Chloroform/ 67-66-3	6.10E-03	Low	1.00E-02	Mod	8.10E-02	Low	—	—	49	Mod	—	—

Table 5-10. (continued).

Chemical/ CAS number	SF oral (mg/kg-d) ¹	Toxicity group	RfD oral (mg/kg-d)	Toxicity group	SF inhalation (mg/kg-d) ¹	Toxicity group	RfD inhalation (mg/kg-d)	Toxicity group	TWA (mg/m ³)	Toxicity group	Short-term exposure limit (mg/m ³)	Toxicity group
Organics (continued)												
Chlorosulfonic acid/ 7790-94-5	-	-	-	-	-	-	-	-	-	-	-	-
Diisopropyl fluorophosphate/ 55-91-4	-	-	-	-	-	-	-	-	-	-	-	-
Ethanol/ 64-17-5	-	-	-	-	-	-	-	-	1880	Low	-	-
Ethyl ether/ 60-29-7	-	-	2.00E-01	Low	-	-	-	-	1210	Low	1520	Low
Ethyl benzene/ 100-41-4	-	-	1.00E-01	Low	-	-	2.86E-01	Low	434	Low	543	Mod
Ethylene dichloride/ 107-06-2	9.10E-02	Mod	-	-	9.10E-02	Low	-	-	40	Mod	-	-
Formaldehyde/ 50-00-0	-	-	2.00E-01	Low	4.50E-02	Low	-	-	-	-	-	-
Formic acid/ 64-18-6	-	-	2.00E+00	Low	-	-	-	-	9.4	Mod	19	High
Glycerin/ 56-81-5	-	-	-	-	-	-	-	-	10	Mod	-	-
Hexane/ 110-54-3	-	-	6.0E-02	Mod	-	-	5.71E-02	Low	176	Low	-	-
Hydrazine/ 302-01-2	3.00E+00	High	-	-	1.70E+01	High	-	-	0.13 ⁴	High	-	-
Isopropyl alcohol/ 67-63-0	-	-	-	-	-	-	-	-	983	Low	1230	Low
Mercury (organic)/ 7-439-97-6	-	-	1.00E-04	High	-	-	-	-	-	-	-	-
Methanol/ 67-56-1	-	-	5.00E-01	Low	-	-	-	-	262 ⁴	Low	328 ^d	Mod
Methyl ethyl ketone (2-butanone)/ 78-93-3	-	-	6.00E-01	Low	-	-	2.86E-01	Low	590	Low	885	Mod

Table 5-10. (continued).

Chemical/ CAS number	SF oral (mg/kg-d) ¹	Toxicity group	RfD oral (mg/kg-d)	Toxicity group	SF inhalation (mg/kg-d) ¹	Toxicity group	RfD inhalation (mg/kg-d)	Toxicity group	TWA (mg/m ³)	Toxicity group	Short-term exposure limit (mg/m ³)	Toxicity group
Organics (continued)												
Methyl isobutyl ketone/ 108-10-1	—	—	8.00E-02	Mod	—	—	—	—	205	Low	307	Mod
Methylene chloride (dichloromethane)/ 75-09-2	7.50E-03	Low	6.00E-02	Mod	1.65E-03	Low	8.57E-01	Low	174	Low	—	—
Naphthalene/ 91-20-3	—	—	4.00E-02 ^e	Mod	—	—	—	—	52	Mod	79	Mod
Nitrobenzene/ 98-95-3	—	—	5.00E-04	High	—	—	5.70E-04	High	5 ^d	Mod	—	—
Nitrocellulose/ 9006-70-0	—	—	—	—	—	—	—	—	—	—	—	—
Nonane/ 11-84-2	—	—	—	—	—	—	—	—	1050	Low	—	—
Oxalic acid/ 144-62-7	—	—	—	—	—	—	—	—	1	High	2	High
PCBs/ 1336-36-3	7.70E+00	High	—	—	—	—	—	—	0.5	High	—	—
PCBs-areclor 1016/ 12674-11-2	—	—	7.00E-05	High	—	—	—	—	0.5	High	—	—
PCBs-areclor 1254/ 11097-69-1	—	—	2.00E-05	High	—	—	—	—	0.5	High	—	—
Pentane/ 109-66-0	—	—	—	—	—	—	—	—	1770	Low	2210	Low
Phenanthrene/ 85-01-8	—	—	—	—	—	—	—	—	—	—	—	—
Pyrene/ 129-00-0	—	—	3.00E-02	Mod	—	—	—	—	—	—	—	—
Terphenyls/26140-60-3	—	—	—	—	—	—	—	—	5	Mod	—	—
Tetrachloroethylene (tetrachloroethene)/ 127-18-4	5.20E-02 ^f	Mod	1.00E-02	Mod	2.00E-03 ^f	Low	—	—	170	Low	685	Mod

Table 5-10. (continued).

Chemical/ CAS number	SF oral (mg/kg-d) ^a	Toxicity group	RfD oral (mg/kg-d)	Toxicity group	SF inhalation (mg/kg-d) ^a	Toxicity group	RfD inhalation (mg/kg-d)	Toxicity group	TWA (mg/m ³)	Toxicity group	Short-term exposure limit (mg/m ³)	Toxicity group
Organics (continued)												
Toluene/ 108-88-3	—	—	2.00E-01	Low	—	—	1.14E-01	Low	188 ^d	Low	—	—
Tributyl phosphate/ 126-73-8	—	—	—	—	—	—	—	—	2.2	Mod	—	—
Trichloroethylene (trichloroethene)/ 79-01-6	1.10E-02 ^f	Mod	—	—	6.00E-03 ^f	Low	—	—	269	Low	537	Mod
Trimethyl benzene	—	—	—	—	—	—	—	—	123	Low	—	—
Trimethylolpropane triester/ 77-99-6	—	—	—	—	—	—	—	—	—	—	—	—
Versene disodium salt/ 139-33-3	—	—	—	—	—	—	—	—	—	—	—	—
Xylene, mixed/ 1330-20-7	—	—	2.00E+00	Low	—	—	—	—	434	Low	651	Mod
Inorganics												
Aluminum/ 7429-90-5	—	—	—	—	—	—	—	—	10	Mod	—	—
Antimony/ 7440-36-0	—	—	4.00E-04	High	—	—	—	—	0.5	High	—	—
Arsenic/ 7440-38-2	1.50E+00	High	3.00E-04	High	5.02E+01	High	—	—	0.01	High	—	—
Barium/ 7440-39-3	—	—	7.00E-02	Mod	—	—	1.43E-04	High	0.5	High	—	—
Barium sulfate/ 7727-43-7	—	—	—	—	—	—	—	—	10	Mod	—	—
Beryllium/ 7440-41-7	4.30E+00	High	5.00E-03	Mod	8.40E+00	Mod	—	—	0.002	High	—	—
Bromine/ 7726-95-6	—	—	—	—	—	—	—	—	0.66	High	2.0	High
Cadmium/ 7440-43-9	—	—	1.00E-03	Mod	6.30E+00	Mod	—	—	0.01	High	—	—

Table 5-10. (continued).

Chemical/ CAS number	SF ^a oral (mg/kg-d) ¹	Toxicity group	RfD oral (mg/kg-d)	Toxicity group	SF inhalation (mg/kg-d) ¹	Toxicity group	RfD inhalation (mg/kg-d)	Toxicity group	TWA (mg/m ³)	Toxicity group	Short-term exposure limit (mg/m ³)	Toxicity group
Inorganics (continued)												
Calcium hydroxide/ 1305-62-0	-	-	-	-	-	-	-	-	5	Mod	-	-
Calcium oxide/ 1305-78-8	-	-	-	-	-	-	-	-	2	Mod	-	-
Cerium chloride/ 7790-86-5	-	-	-	-	-	-	-	-	-	-	-	-
Chromium-3/ 7440-47-3	-	-	1.00E+00	Low	-	-	-	-	0.5	High	-	-
Chromium-6/ 7440-47-3	-	-	5.00E-03	Mod	4.20E+01	High	-	-	0.05	High	-	-
Cobalt/ 7440-48-4	-	-	-	-	-	-	-	-	0.05	High	-	-
Copper/ 7440-50-8	-	-	3.00E-02 ^f	Mod	-	-	-	-	1	High	-	-
Cyanide, free/ 57-12-5	-	-	2.00E-02	Mod	-	-	-	-	5 ^g	Mod	-	-
Hydrochloric acid/ 7647-01-0	-	-	-	-	-	-	5.71E-03	Mod	-	-	-	-
Hydrogen fluoride/ 7664-39-3	-	-	-	-	-	-	-	-	2.6	Mod	-	-
Hydrogen peroxide/ 7722-84-1	-	-	-	-	-	-	-	-	1.4	Mod	-	-
Lead/ 7439-92-1	-	-	-	-	-	-	4.29E-04	High	0.15	High	-	-
Lithium hydride/ 7580-67-8	-	-	-	-	-	-	-	-	0.025	High	-	-
Lithium oxide/ 12057-24-8	-	-	-	-	-	-	-	-	-	-	-	-
Magnesium/ 7439-95-4	-	-	-	-	-	-	-	-	-	-	-	-
Magnesium fluoride/ 7783-40-6	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-10. (continued).

Chemical/ CAS number	SF oral (mg/kg-d) ¹	Toxicity group	RfD oral (mg/kg-d)	Toxicity group	SF inhalation (mg/kg-d) ¹	Toxicity group	RfD inhalation (mg/kg-d)	Toxicity group	TWA (mg/m ³)	Toxicity group	Short-term exposure limit (mg/m ³)	Toxicity group
Inorganics (continued)												
Magnesium oxide/ 1309-48-4	-	-	-	-	-	-	-	-	10	Mod	-	-
Manganese/ 7439-96-5	-	-	4.20E-01	Low	-	-	1.43E-05	High	5	Mod	-	-
Mercury/ 7439-97-6	-	-	-	-	-	-	8.57E-05	High	0.1	High	-	-
Mercury nitrate/ 10045-94-0	-	-	-	-	-	-	-	-	-	-	-	-
Nickel/ 7440-02-0	-	-	2.00E-02	Mod	-	-	-	-	1	High	-	-
Nitrate/ 14797-55-8	-	-	1.60E+00	Low	-	-	-	-	-	-	-	-
Nitric acid/ 7697-37-2	-	-	-	-	-	-	-	-	5.2	Mod	10	High
Phosphoric acid/ 7664-38-2	-	-	-	-	-	-	2.86E-03	Mod	1	High	3	High
Platinum/ 7440-06-4	-	-	-	-	-	-	-	-	1	High	-	-
Potassium chloride/ 7447-40-7	-	-	-	-	-	-	-	-	-	-	-	-
Potassium dichromate/ 7778-50-9	-	-	-	-	-	-	-	-	-	-	-	-
Potassium nitrate/7757-79-1	-	-	-	-	-	-	-	-	-	-	-	-
Potassium phosphate/ 7778-53-2	-	-	-	-	-	-	-	-	-	-	-	-
Potassium sulfate/ 7646-93-7	-	-	-	-	-	-	-	-	-	-	-	-
Selenium/ 7782-49-2	-	-	5.00E-03	Mod	-	-	-	-	0.2	High	-	-
Silver/ 7440-22-4	-	-	5.00E-03	Mod	-	-	-	-	0.1	High	-	-

Table 5-10. (continued).

Chemical/ CAS number	SF oral (mg/kg-d) ¹	Toxicity group	RfD oral (mg/kg-d)	Toxicity group	SF inhalation (mg/kg-d) ¹	Toxicity group	RfD inhalation (mg/kg-d)	Toxicity group	TWA (mg/m ³)	Toxicity group	Short-term exposure limit (mg/m ³)	Toxicity group
Inorganics (continued)												
Sodium/ 7440-23-5	-	-	-	-	-	-	-	-	-	-	-	-
Sodium chloride/ 7647-44-5	-	-	-	-	-	-	-	-	-	-	-	-
Sodium cyanide/ 143-33-9	-	-	4.00E-02	Mod	-	-	-	-	-	-	-	-
Sodium dichromate/ 10588-01-9	-	-	-	-	-	-	-	-	-	-	-	-
Sodium hydroxide/ 1310-73-2	-	-	-	-	-	-	-	-	-	-	-	-
Sodium nitrate/ 7631-99-4	-	-	-	-	-	-	-	-	-	-	-	-
Sodium phosphate/ 7632-05-5	-	-	-	-	-	-	-	-	-	-	-	-
Sodium potassium/ 11135-81-2	-	-	-	-	-	-	-	-	-	-	-	-
Sodium sulfate/ 7757-02-6	-	-	-	-	-	-	-	-	-	-	-	-
Sulfuric acid/ 7664-93-9	-	-	-	-	-	-	2.00E-01	Low	1	High	3	High
Tantalum/ 7440-25-7	-	-	-	-	-	-	-	-	5	Mod	-	-
Thallium/ 7440-28-0	-	-	8.00E-05	High	-	-	-	-	0.1 ⁴	High	-	-
Tungsten/ 7440-33-7	-	-	-	-	-	-	-	-	5	Mod	10	High
Uranium/ 7440-61-1	-	-	3.00E-03	Mod	-	-	-	-	0.2	High	0.6	High
Zinc/ 7440-66-6	-	-	3.00E-01	Low	-	-	-	-	10	Mod	-	-
Zirconium/ 7440-67-7	-	-	3.00E+00	Low	-	-	-	-	5	Mod	10	High

Table 5-10. (continued).

Chemical/ CAS number	SF		RfD		SF		RfD		TWA		Short-term	
	oral (mg/kg-d) ⁻¹	Toxicity group	oral (mg/kg-d)	Toxicity group	inhalation (mg/kg-d) ⁻¹	Toxicity group	inhalation (mg/kg-d)	Toxicity group	(mg/m ³)	Toxicity group	(mg/m ³)	exposure limit (mg/m ³)
Low	10 ⁻³		10 ¹		10 ³		10 ⁰		≥100		≥1,000	
			10 ⁰		10 ⁻²		10 ¹					
			10 ¹				10 ²					
Moderate	10 ⁻²		10 ²		10 ⁻¹		10 ¹		>1-100		>30-1,000	
			10 ³		10 ⁰							
High	10 ⁻¹		10 ⁴		10 ¹		10 ⁴		≤1		≤30	
			10 ⁵				10 ⁵					

a. Information sources for the presence of hazardous chemicals in various waste types are Dames & Moore (1994), DOE (1994b), DOE (1995b,c), Fillmore (1993), Jessmote et al. (1995), and LITCO (1995b,c). Information sources for values of absolute toxicities are EPA (1995a, b, 1996) for SFs and RfDs and ACGIH (1993) for TWAs and STELs.

b. Source: EPA 1993, "Chronic Inhalation RfD for 1,1,1-trichloroethane," Environmental Criteria and Assessment Office, correspondence from Joan S. Doallertide, EPA ECAO to Carol Sweeney, EPA Region 10.

c. Mod = moderate.

d. Potential significant contribution to the overall exposure by the dermal route by contact with vapors or direct contact with skin.

e. Source: EPA 1995, "Systemic Toxicity Information for Naphthalene," Environmental Criteria and Assessment Office, correspondence from Joan S. Doallertide, EPA ECAO, to Wayne Pierre, EPA Region 10.

f. Source: EPA 1995, "Script for Superfund Technical Support Center Question on Tetrachloroethylene, Trichloroethylene, and Styrene," Environmental Criteria and Assessment Office.

g. Source: EPA 1991, "Interim Oral RfD for Copper," Environmental Criteria and Assessment Office, correspondence from Pei-Fung Hurst, EPA ECAO to Leigh Woodruff, EPA Region 10.

h. Thallium oral RfDs are presented as a carbonate, chloride, and sulfate. The oral RfD for thallium nitrate is 9E-05 mg/kg-d.

The classification ratings for the toxicity values, in terms of order of magnitude, are listed at the bottom of the table. The classification ratings were selected to place approximately one-third of the contaminants for which toxicity data were listed in each rating group. The toxicity distributions also were considered in setting the classification ratings because clusters of values were placed into the same group. The toxicity group for each chemical based on this measure is listed in column 3.

The noncarcinogenic effects of each chemical via the ingestion exposure route are represented by the oral RfDs in column 4, again taken from EPA (1996, 1995a). The values range from on the order of 10^{-5} to 10^1 . At the bottom of column 4, the classification ratings for the toxicity values are given for dividing the chemicals into three groups on the basis of the value of the oral RfD. The toxicity group for each chemical based on this measure is listed in column 5.

To aggregate the two EPA absolute toxicity measures for carcinogenic and noncarcinogenic effects for the ingestion exposure route, two rules were followed:

1. The relative toxicity of a chemical was determined by the highest group listed in columns 3 and 5.
2. A chemical rated as a High in either column was assigned a *relative* toxicity value of 10^{-3} . If the highest rating was Moderate, a value of 3×10^{-5} was assigned. If a Low in either column is the highest rating, a value of 3×10^{-6} was assigned. (The basis for these numerical values is provided in Section 5.1.4 and Appendix B.)

The results appear in Table 5-10.

Inhalation Exposure Route—For the simplified pathways analysis used here, the inhalation exposure route was taken to be synonymous with airborne release and transport of contaminants. Four measures of absolute toxicity were evaluated. Two EPA toxicity measures, indicative of long-term, chronic effects, were evaluated to arrive at a value of the toxicity element for this exposure route: the SFs and RfDs. Two OSHA toxicity measures, indicative of shorter-term effects, were also included in the evaluation.

Column 6 of Table 5-10 lists the inhalation SFs taken from EPA (1995a and 1996) for the given contaminants, reflecting the carcinogenic effects via this exposure route. Entries with dashes indicate that no SF was found for the chemical. The SFs range from on the order of 10^{-3} to 10^1 . Again, the values were placed into three groups based on the classification ratings listed at the bottom of the table. The toxicity group for each chemical based on this measure is listed in column 7.

The noncarcinogenic effects of each chemical via the inhalation exposure route are represented by the oral RfDs in column 8, again from EPA (1995a and 1996). The values range from on the order of (almost) 10^0 to 10^{-5} . At the bottom of column 8, the classification ratings are given for dividing the chemicals into three groups on the basis of the value of the inhalation RfD. The toxicity group for each chemical based on this measure is listed in column 9.

The EPA inhalation toxicity values are based on long-term exposures. To supplement these values with values representing shorter-term exposures based on occupational conditions, two OSHA toxicity measures from ACGIH (1993) were used. The values of the TLV-TWA represent the average concentration for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be exposed day after day without adverse effect. Values are given in column 10. The TLV-STEL is a 15-minute exposure that should not be exceeded during a workday. Values are given in column 12.

The values of the TWA range from on the order 10^{-3} to 10^3 . The values of the STEL range from 10^{-1} to 10^4 . At the bottom of columns 10 and 12, the classification ratings are given for dividing the chemicals into the three groups. The toxicity groups for each chemical based on these measures are given in columns 11 and 13.

To aggregate the EPA and OSHA toxicity measures for carcinogenic and noncarcinogenic effects for the inhalation exposure route, two rules were followed:

1. The relative toxicity of a chemical was determined by the highest group listed in columns 7, 9, 11, and 13.
2. A chemical rated as a High in any of these four columns was assigned a relative toxicity value of 0.1. If the highest rating was a Moderate, a value of 10^{-3} was assigned. If a Low was the highest rating, a value of 10^{-5} was assigned. (The basis for these values is provided in Section 5.1.4 and Appendix B.)

The results appear in Table 5-9.

5.1.4 Correlation of the Values Selected for the Relative Toxicities of Radionuclides and Hazardous Chemicals

No exact correlation of the relative toxicities between radionuclides and hazardous chemicals is possible. The listed value for the toxicity of a hazardous chemical depends on the exposure route and on the particular body of regulations. In addition, the regulatory values of the absolute toxicity for radionuclides reflect only carcinogenic effects, whereas those for hazardous chemicals reflect both carcinogenic and noncarcinogenic effects. In spite of these challenges, an approximate correlation was developed so that the relative toxicities of hazardous chemicals and radionuclides in the lookup tables would be on the same scale, to the extent feasible in this simplified method. By doing this, the contributions of radionuclides and hazardous chemicals can legitimately be summed in the fundamental risk equations of the simplified method. (The ability to sum these terms is important to retain the simplicity of the method.) This correlation is demonstrated in detail in Appendix B.

Sections B-3.1.1 and B-3.2.1 also demonstrate that the toxicity values of radionuclides for the inhalation and ingestion exposure routes are on the same numerical basis.

5.2 Element 2—Susceptibility of Contaminants to Release and Movement

Element 2 characterizes the susceptibility of the contaminants in the waste to release and movement from their confined condition into the air or water for subsequent transport to a receptor. There are two subelements. Element 2a addresses the mobility of the waste form if the confinement fails, and Element 2b addresses the resistance of the confinement (external to the waste form) to failure.^m

5.2.1 Element 2a—Mobility of Waste Form

5.2.1.1 Brief Description of Element. Element 2a addresses the confinement provided by the waste form itself (i.e., the tendency of an unconfined waste form to disperse as a result of conditions associated with a release). The physical forms in which waste may exist vary widely in their tendency to disperse following an accident. Liquids and gases may be quite mobile, and some solids are highly immobile.

5.2.1.2 General Approach for Developing Lookup Table. The lookup table for waste form mobility was based on the types of release scenarios that could reasonably be expected to occur and the corresponding transport pathways. The types of scenarios and pathways vary with the type of state.

Storage facilities are usually located aboveground to facilitate later retrieval of the waste, leading ultimately to disposal. For most facilities of this type, the risk is dominated by the airborne transport pathway, leading to the inhalation exposure route. Water basin storage of SNF or of canisters containing solidified HLW is a possible exception; both waterborne and airborne transport can occur.

Disposal facilities, on the other hand, are generally located belowground. For such facilities, the waterborne transport pathway, leading to the ingestion exposure route, is usually dominant (Smith et al. 1995). However, inadvertent human intrusion into disposed waste after loss of institutional control can result in contaminant transport by both airborne and waterborne pathways.

For transition states, only airborne releases are generally expected.

The approach was as follows:

- Identify the physical forms expected to be encountered most often in the risk assessments
- Review the literature for values of physical parameters related to contaminant mobility from each physical form in airborne releases

m. The inclusion of Element 2b as part of the P term in Equation (4-1) [Element 3 in Equations (4-2) and (4-3)] might be more useful for conveying understanding than including it as part of the FR term. However, the placement of Element 2b does not affect the result of the risk equation.

- Review the literature for values of physical parameters related to contaminant mobility from each physical form in waterborne releases
- For each physical form, select mobility values for airborne transport and for waterborne transport.

Nine physical forms, representing a broad spectrum of possible waste forms (from gas to glass), were selected for evaluation.

5.2.1.3 Lookup Table—Element 2a. From Table 5-11, select the mobility value for the physical form that corresponds most closely to the waste form of interest and for the transport pathway.

5.2.1.4 Basis for Values in Lookup Table.

5.2.1.4.1 Airborne Releases—The second column of Table 5-11 lists the mobility values for airborne releases. The values for airborne release correspond to the airborne release fraction commonly used in accident analyses. This term is defined as the fraction of material that becomes suspended in air and is made available for transport under a specific set of induced physical stresses. The values also reflect multiplication by the respirable fraction of the released material. This term is defined as the fraction of airborne material as particles that can be transported through the air and inhaled into the human respiratory system, commonly assumed to include particles of 10 μ aerodynamic equivalent diameter and less.

Table 5-11. Element 2a lookup table—mobility.

Physical form of waste	Mobility for airborne releases	Mobility for waterborne releases
Gas or vapor from a highly volatile liquid	1	1
Low-volatility liquid or bulk quantity of volatile liquid	3×10^{-3}	10^{-4}
Loose contamination on surface of solids	10^{-3}	10^{-3}
Powder (with 10% of mass in particulate within respirable size range)	10^{-3}	8×10^{-4}
Calcine (a granular solid)	6×10^{-4}	6×10^{-4}
Sludge	3×10^{-4}	3×10^{-4}
Cement and concrete	10^{-4}	10^{-5}
Glass and ceramic	10^{-5}	10^{-5}
Metals (nonpyrophoric)	10^{-5}	2×10^{-5}

The sources for the values are as follows:

- DOE (1994c) provides a comprehensive collection of data on airborne release fractions and respirable fractions generated over the past several decades in more than 200 publications. Most of the airborne values selected here are based on a review of the data compiled in that document.
- Some of the airborne values selected for glasses, ceramics, and cements are based on impact data for those waste forms compiled from several sources in Smith et al. (1995).
- The value selected for sludge is midway between those for powder and for cement.
- Calcine is a granular solid. The calcine waste form for the INEL HLW is mostly from 200 μ to 500 μ in diameter. The respirable fraction (i.e., < 10 μ in diameter), is typically on the order of 6% by mass (WINCO 1987). The mobility value for calcine was developed by starting with the 10^{-3} value for a powder with 10% respirable fraction, then multiplying by the ratio of respirable fractions: $10^{-3} \times (6 \times 10^{-2})/10^{-1} = 6 \times 10^{-4}$.

The values of the airborne release fractions (without considering the respirable fraction) were compared against the generic values in DOE (1992b). The values were found generally to be similar.

The number of distinct potential release scenarios is virtually unlimited; the number of distinct physical forms is very large (e.g., the mobility of each powder depends on its unique particle size distribution); and the number of detailed release phenomena is also large. No one number selected for the mobility of a given general physical form of the waste can possibly represent the exact conditions of all possible release scenarios and for all specific physical forms. Therefore, to maintain simplicity, the data were aggregated over ranges of accident conditions and specific physical forms. This aggregation required a substantial amount of professional judgment. The airborne mobility values selected represent an aggregation over the values for the four main types of potential serious releases: (1) spills, (2) fires, and (3) explosions all in facilities and (4) impact forces from drilling and excavation associated with intrusion into a disposal site. The values given for the airborne mobility represent a geometric mean using the most applicable data for these four types of accidents.

5.2.1.4.2 Waterborne Releases—Data for waterborne release fractions are scarce except for some waste forms and waste types. The situation is complicated by the fact that contaminant release to subsurface water is highly site-specific. In addition, waterborne release rates for even the same waste form can vary by factors of 10 to 100, depending on subtle differences in waste composition and treatment parameters. Therefore, only rough estimates can be provided of the relative waterborne release rates of contaminants from different physical forms of the waste.

Contaminants are released from a subsurface waste form by one of three mechanisms: (1) surface washoff from the surface of a solid, (2) diffusion through a porous waste form such as cement, or (3) dissolution of the waste form with resulting release of the contaminant. The dissolution mechanism can involve the corrosion of a metallic waste form containing the contaminant or the dissolution of a nonmetal (such as glass) containing the contaminant.

No compilation of waterborne release data analogous to DOE (1994c) was located. Therefore, the following approach was used. Smith et al. (1995) contains extensive calculations of the dose from waterborne transport of a given radionuclide inventory in cements, glasses, ceramics, and sludge and by simple surface washoff. Approximately 100 parametric evaluations were made of the groundwater dose from a given inventory of α -LLW, covering seven widely different waste forms, five disposal sites, and a wide range of assumptions about the transport processes.

The results for the cements in Smith et al. (1995) were quite sensitive to (a) whether credit was taken for chemical interactions of the radionuclides with the internal surfaces of the cement and (b) the assumed longevity of the cement. The value chosen in this report was intermediate between the most favorable and least favorable results for the cement.

The dependencies studied in Smith et al. (1995) would be expected to differ if a waste type other than α -LLW had been evaluated or if a different burial unit design had been used. Nevertheless, the results of the study are of interest in this report because they include both actinides and nonactinides and because the study was a comprehensive parametric evaluation.

For glass, ceramic, cement/concrete, sludge, and solids with surface contamination, the approach used here was the following:

- Identify waste forms in the Element 2a lookup table that were evaluated in Smith et al. (1995).
- Identify cases in Smith et al. (1995) in which only the waste form was varied, then examine the ratio of the resulting doses for the two different waste forms. [In some instances, the performance at several sites was evaluated in Smith et al. (1995), so the geometric average of the different ratios for the different sites was used here.]
- Form a corresponding ratio for the mobility of the two waste forms in the Element 2a lookup table. Scale the results from the leach rates for glass and ceramic (typically about 10^{-5} g/cm²-day) in Smith et al. (1995).

NOTE: For physical waste forms that release contaminants by a dissolution mechanism, the mobility values for waterborne releases in the Element 2a lookup table are the dissolution rates—the principal measure of waterborne mobility of a waste form—in units of grams per square centimeter per day. For physical forms that release contaminants by diffusion or surface washoff, the mobility values are scaled to roughly equivalent values, in the same units, by examining the resulting doses.

- For metals, the corrosion rates vary greatly from one metal to another and from one set of groundwater chemistry conditions to another. Corrosion rates for three metals were determined as explained below. The geometric mean of these three values was used as the waterborne mobility, after rounding upward to allow for pitting and other localized phenomena. Two of the three values were the maximum and minimum corrosion rates for steels, based on data in Sullivan and Suen (1989). Steels ranging from carbon steel to 316 stainless steel were included; the rates had been measured in numerous soils. The third value was the corrosion rate for beryllium in INEL soils (Nagata 1993). The units are grams per square centimeter per day.

- For calcine and powders, the values were developed by using the results in Smith et al. (1995). The reference presented doses predicted from groundwater release of radionuclides in waste forms that are broken-up ceramics. For a uniform cubical particle size of 1 mm = 1,000 μ , the total surface area over all particles would be 1,000 times that of a single 1-m cube having the same mass. With a particle size of 0.1 mm = 100 μ , the surface area would be 10,000 times that of a 1-m cube. Smith et al. (1995) showed that increasing the surface area by a factor of 1,000 (corresponding to 1,000- μ particles) increased the dose by a factor of about 40, compared with the dose from an approximately 1-m ceramic monolith. Increasing the surface area by a factor of 10,000 (corresponding to 100- μ particles) increased the dose by a factor of about 80 compared with that from an approximately 1-m monolith. Further increases in the surface area of the waste form did not increase the dose because other parts of the groundwater pathway became limiting to the rate of transport. The mobility value selected for calcine, with most particles having a diameter of 200 μ to 500 μ , was 60 times that of a ceramic monolith, or 6×10^{-4} . The value selected for powders was 80 times that of a ceramic monolith, or 8×10^{-4} .
- For liquids and gases (or vapors), no specific data were located that would allow forming the ratio of the mobility of liquids and gases to the known mobility of specific types of solids. For both liquids and gases, the transport rates (and, therefore, the mobilities) would be expected to be much higher than for solids. The liquid value was estimated (without substantial justification) to be 100 times the mobility of the most mobile solid, or 10^{-1} . Rough approximations based on INEL mathematical modeling of the subsurface transport of volatile organics at the Radioactive Waste Management Complex suggested that the ratio of vapor transport rates to liquid transport rates was on the order of 10^1 . The value for gas or vapor, therefore, was chosen to be $10^1 \times 10^{-1} = 10^0 = 1$.

5.2.2 Element 2b—Confinement Capability

5.2.2.1 Brief Description of Element. Element 2b represents the effect on the risk as a result of the barriers between the waste and the transport pathways (the air and/or groundwater). Element 2b can be thought of as the relative strength of the confinement (the conditional probability of confinement failure, given that a confinement challenge occurs).

For aboveground facilities, the barriers between the waste and the atmosphere include the waste containers and any additional engineered barriers. For belowground facilities, the barriers include the subsurface geologic formation separating the waste from the groundwater and the air, as well as any additional engineered barriers.

5.2.2.2 General Approach for Developing Lookup Table. Several factors affect the relative protection provided by a set of confinement barriers. In addition, the nature of the confinement barriers can vary greatly from one situation to another. Therefore, considerable simplification was required to produce easily used values for this risk element.

The approach for developing the lookup table for Element 2b was as follows:

- Identify the various types of rest states to be considered
- Identify the types of barriers (natural and engineered) associated with each type of rest state
- Estimate the relative strength of sets of barriers.

5.2.2.3 Lookup Table—Element 2b. Table 5-12 is the lookup table for Element 2b.

The values assume that the barriers are in a series configuration. The values should be reduced by a factor of 3 to 10 if a barrier is massive (e.g., steel or concrete that is several inches thick, as in SNF shipping casks). If a barrier does not satisfy the applicable standards (e.g., a facility whose ventilation system has numerous noncompliances with standards), the value of Element 2b should be increased by a factor of 3 to 10.

Table 5-12. Lookup table for Element 2b.

Type of facility	Confinement	Value
Aboveground or belowground	No engineered confinement or flimsy engineered barriers (e.g., cardboard boxes) or severely degraded engineered barriers (e.g., badly rusted drums); groundwater pathway (long-term)	1
	Single engineered barrier in good condition ^a	1E-1 ^b
	Two engineered barriers in good condition ^a	1E-2 ^b
	Three engineered barriers in good condition ^a	3E-3 ^b
Belowground only	Near-surface burial ^c	1E-2
	Near-surface burial with multilayer engineered cap ^{d,c}	1E-3 ^d
	Intermediate-depth burial	1E-4
	Deep geological disposal	1E-5

a. Engineered barriers are generally assumed to last a maximum of 50 years. Multilayered caps over disposal or storage units and very substantial barriers (e.g., calcine bins) may be assumed to last a maximum of 500 years.

b. Additional credit (reduction by a factor of 3 to 10) can be taken if the barrier is massive, such as a SNF shipping cask.

c. These values also apply to abovegrade earth-covered disposal structures such as tumuli.

d. Cap is multilayer (e.g., designed and constructed in accordance with NRC regulations in 10 Code of Federal Regulations (CFR) 61 or with the EPA/NRC guidance on mixed waste disposal facilities).

For aboveground facilities, credit can be taken for various numbers of engineered barriers. For belowground facilities, multiplicative credit can be taken for both engineered and geologic barriers. However, the life that can be assumed for engineered barriers is typically limited to 50 years for barriers such as metal drums and 500 years for massive barriers such as concrete and steel calcine bins [e.g., see Philipose (1996)]. For example, the value of Element 2b for waste in a massive concrete container in near surface burial without an engineered cap would be $[(1E-1)/3] \times 1E-2 = 3E-4$ for the first 500 years and $1E-2$ thereafter.

For long-term disposal, it is assumed that there is no confinement (other than the waste form itself) beyond the lifetime of barriers, for the groundwater pathway.

5.2.2.4 Basis for Values in Lookup Table. The values for Element 2b show a relative level of protection considering facility type (i.e., aboveground or belowground) and the condition and number of confinement barriers.

A conditional failure probability of 1 is assigned for aboveground states with no engineered barriers or with flimsy engineered barriers (e.g., a cardboard box) or severely degraded engineered barriers, such as a badly rusted metal drum or a damaged wooden box. A value of 1 implies that the risk method assumes no credit for a barrier.

The value for Element 2b is reduced as the number of barriers in series increases if a barrier is in good condition. Data giving specific values for various numbers of barriers are scarce.

For aboveground rest states, it is assumed that waste storage conditions are monitored as required by regulations and that container leaks that could result in groundwater transport are observed and corrected quickly.

For belowground confinement, near-surface burial is assigned a value of $1E-02$. The bases for assigning a value of $1E-02$ rather than of 1 are that there are fewer successful challenges to belowground confinement barriers and the potential for loss of the soil barrier is small. In addition, the rate of water infiltration to the waste type decreases as the waste is placed belowground, then as an engineered cap is added, then as the disposal depth is increased. For example, the value of Element 2b is reduced by a factor of 10 if there is a multilayer engineered cap (e.g., one that complies with NRC regulations in 10 Code of Federal Regulations (CFR) 61 or with the EPA/NRC guidance on mixed waste disposal facilities). A multilayer cap can reduce the water infiltration rate by a factor of 100 or more, depending on the design details. Another consideration is that the likelihood of successful intrusion decreases as the disposal depth increases.

Factors relating to migration of contaminants through the subsurface geologic formation (vadose zone) to the groundwater after release from engineered confinement are discussed in Element 4 in Section 5.4. Contaminant dispersion and decay are modeled by the parameter T in Table 5-18 in that section.

5.3 Element 3—Severity and Likelihood of Challenges to Contaminant Confinement

5.3.1 Introduction

Element 3 relates to the potential challenges to contaminant confinement. Challenges to confinement are generally from environmental events (Element 3a), such as flooding, seismic events, and high wind, and from operational events (Element 3b) such as fires, explosions, and material handling accidents. The Element 3a and 3b values are summed in Equation (4-2) and, thus, are aggregates of the confinement challenges of natural phenomena and operational events.

Table 5-13 displays a method for combining the frequency and severity (immediate consequences) of an event. It is adapted from the method recommended by DOE for use in SARs for nuclear facilities (DOE 1994d) and by the Federal Emergency Management Agency (FEMA), DOT, and EPA for assessing chemical emergencies (FEMA et al. 1989).

The rows in Table 5-13 rank the severities of events from high to negligible depending on the severity of the challenge to contaminant confinement. A high severity event has the potential to affect most or all of the contaminant. Therefore, a high severity was assigned a value of 1. The moderate, low, and negligible severity values were reduced by successive factors of 10. A negligible severity event has a value of 10^{-3} , indicating that 0.1% or less of the contaminant inventory is affected.

Table 5-13. Ranking matrix for frequency and severity of challenges to contaminant confinement.^a

Potential severity		Annual frequency levels							
		Anticipated			Unlikely		Incredible		
		Likely		Extremely unlikely					
Relative severity level and value	Definition	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
High (1)	Event with the potential for involving most or all of the contaminant	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
Moderate (10^{-1})	Event with the potential for involving approximately 10% of the contaminant	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}
Low (10^{-2})	Event with the potential for involving approximately 1% of the contaminant	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}
Negligible (10^{-3})	Event with the potential for involving approximately 0.1% or less of the contaminant	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}

a. Source: adapted from DOE (1994d).

The frequency columns of Table 5-13 include descriptive terms commonly used in DOE SARs to describe the frequency of an event (see definitions in Table 5-14). These terms range from anticipated events to incredible events and reflect the frequency at which the event is expected to occur during the operation of the facility or activity.

The importance of the event is determined by assigning a severity term and a frequency term for each event and then reading the number at their intersection in Table 5-13. A value of 1 represents the highest possible importance (high frequency and high severity). A value of 10^{-10} represents the lowest possible importance (low frequency and low severity).

Use of this method allows for the aggregation of natural phenomena and operational events on the same scale because the same values are used for severity and frequency, regardless of the type of challenge. This commonality results in values for each type of challenge that can be added together without further scaling or modification.

The following subsections arrive at frequencies and severities for the natural phenomena and operational events and provide a basis for developing the lookup tables for Elements 3a and 3b for rest states.

5.3.2 Element 3a—Confinement Challenges from Environmental Events

5.3.2.1 Brief Description of Element. The value of Element 3a expresses the nature, severity, and frequency of environmental stresses (e.g., floods, seismic events, extreme winds) to which the contaminant confinement might be subjected. The effectiveness (relative strength) of the confinement barriers is expressed in Element 2b and is not evaluated in Element 3.

5.3.2.2 General Approach for Developing Lookup Table. The approach for developing the lookup table for Element 3a was as follows:

- Identify the set of natural phenomena hazards (NPHs) that would present the greatest challenge to the confinement barriers
- Review DOE standards, SARs, EISs, and other technical documents that provide information on NPHs

Table 5-14. Descriptions of frequency levels.

Frequency level	Frequency (per yr)	Description
Anticipated	$> 10^{-1}$	Event is likely to occur several times during the facility or operation lifetime
Likely	$> 10^{-2}$ to 10^{-1}	Event is likely to occur during the facility or operation lifetime
Unlikely	$> 10^{-4}$ to 10^{-2}	Occurrence is unlikely, or event is not expected to occur but may occur during the lifetime of the facility or operation
Extremely unlikely	$> 10^{-6}$ to 10^{-4}	Occurrence is extremely unlikely, or event is not expected to occur during the lifetime of the facility or operation.
Incredible	$< 10^{-6}$	Occurrence is so unlikely that a reasonable scenario is not conceivable.

- Determine frequency and severity levels for NPHs
- Combine the frequency and severity values into a frequency-severity value on Table 5-13.

5.3.2.3 Lookup Table—Element 3a. The Element 3a lookup table is Table 5-15.

Several DOE EISs (DOE 1995b,d) and SARs (LITCO 1995d,e,f) were reviewed to obtain a representative list of NPHs. The review indicated that the following NPHs are generally considered in detailed HSRAs: seismic events, strong winds or tornadoes, floods, fires (external to the facility in question), and volcanic activity (at the INEL, the Hanford Site, and Los Alamos National Laboratory). In most cases, however, seismic events are dominant with respect to NPH risk. For this simplified method, seismic events, strong winds or tornadoes, and floods are considered.

Table 5-15. Element 3a lookup table—environmental challenges to confinement.

NPH event	Frequency (1/yr)	Severity	Frequency-severity value (1/yr): Element 3a ^a	Selection criteria
Seismic (beyond design basis)	1E-4	High	1E-4	Storage facility not meeting NPH design criteria
	1E-4	Moderate	1E-5	PC 2 (Hazard Category 3) storage facility
	1E-4	Low	1E-6	PC 3 (Hazard Category 2) storage facility; aboveground disposal state
	1E-4	Negligible	1E-7	Belowground disposal state
Strong wind/tornado (beyond design basis)	1E-4	High	1E-4	Storage facility not meeting NPH design criteria
	1E-4	Moderate	1E-5	PC 2 (Hazard Category 3) storage facility
	1E-4	Low	1E-6	PC 3 (Hazard Category 2) storage facility; aboveground disposal state
Flood (beyond design basis)	1E-4	Moderate	1E-5	Storage facility not meeting NPH design criteria
	1E-4	Low	1E-6	PC 2 (Hazard Category 3) storage facility
	1E-4	Negligible	1E-7	PC 3 (Hazard Category 2) storage facility; aboveground disposal state

a. The total for Element 3a is the sum of the frequency-severity values from seismic events, strong winds and tornadoes, and floods, as applicable.

5.3.2.4 Basis for Values in Lookup Table. The frequency-severity value of a NPH at a given location can be determined by evaluating the minimum design criteria for structures requiring confinement of hazardous materials. The design criteria for NPH are based on the magnitude of the event at an acceptable return period. The more critical the facility performance, the larger the return period and the more stringent and costly the design basis.ⁿ

The design basis criteria for protection of DOE facilities against NPHs are mandated by DOE Order 5480.28, "Natural Phenomena Hazards Mitigation," (DOE 1993a) and are implemented by a series of DOE standards. The DOE Order and implementing standards are used to establish frequency-severity values for NPHs at each of the selected DOE sites.

DOE (1994e) gives design and evaluation criteria in terms of site-specific events (i.e., seismic events, extreme winds, tornadoes, and flooding) at a return period corresponding to the NPH classification of the facility. For NPH assessments, DOE (1993a) requires that nuclear facilities be classified on a performance category (PC) scale of 0 through 4 where facilities rated 0-1 are nonmission-critical facilities without the need for confinement of hazardous materials, facilities rated 2-3 contain hazardous materials and confinements, and facilities rated 4 are generally nuclear reactors. Performance Category 2 design and evaluation criteria appear to be appropriate for most EM activities and were used as a baseline in developing the data for Element 3a. Performance Category 2 roughly corresponds to Hazard Category 3 (Low hazard) in the terminology of DOE-STD-1027-92 (DOE 1992b).

5.3.2.4.1 Basis for Seismic Values in Lookup Table—For the base case seismic frequency-severity value, it is assumed that the storage facility is a PC 2 design. This implies a design basis seismic frequency of $1E-3/yr$ and a corresponding confinement structure failure probability of 0.5, resulting in a performance goal of $5E-4/yr$. These values are independent of the particular DOE site in question. However, most of the seismic risk for DOE facilities occurs from seismic events beyond the design basis. Therefore, the seismic event covered in this simplified risk model is one that is substantially more severe than the design basis. Based on seismic hazard curves (Sobel 1993), such a seismic event has a frequency of approximately $1E-4/yr$, independent of the DOE site in question.

The severity of seismic events ranges from High (nearly all of the contaminant is affected by the event) to Low or Negligible (DOE 1995d). For the base case PC 2 facility, a severity level of Moderate is assumed. For a PC 3 facility, which corresponds to a Hazard Category 2 (Moderate hazard) facility, the severity level is Low. For a facility that does not meet seismic design criteria, a High severity level should be used because failure of the building could impact more of the waste. Finally, a severity level of Low should be used for aboveground disposal states and Negligible for belowground disposal states.

n. It is recognized that a more exact approach is to consider the entire spectrum of severities of a type of confinement challenge, divide the spectrum into several regions, evaluate the frequency and severity for each region, and add the contributions from each region. However, such an approach is considerably more complex. This report uses this approach only for transportation events.

Frequency-severity values for seismic events are summarized in Table 5-15. The values range from 1E-4/yr for a facility not meeting seismic criteria to 1E-7 for belowground disposal.

5.3.2.4.2 Basis for Strong Wind and Tornado Values in Lookup Table—The design criteria discussed previously for seismic events also apply for strong winds and tornadoes. The strong wind (or tornado) event modeled for the simplified risk model is substantially beyond the design basis. Similar to the seismic event, the frequency is assumed to be 1E-4/yr. Also similar to the seismic event, the severity level is assumed to range from High to Low. (For belowground disposal states, strong winds or tornadoes are assumed to have no effect on the waste.) Resulting frequency-severity values are summarized in Table 5-15.

5.3.2.4.3 Basis for Flooding Values in Lookup Table—The design criteria discussed previously for seismic events also apply for floods. The flood event modeled is substantially beyond the design basis. Similar to the seismic event, the frequency is assumed to be 1E-4/yr. However, the severity levels for floods are assumed to be one level lower than those for seismic events and for strong winds or tornadoes. Resulting frequency-severity values are summarized in Table 5-15.

5.3.3 Element 3b—Confinement Challenges from Operational Events

5.3.3.1 Brief Description of Element. The value of Element 3b expresses the nature, severity, and frequency of operational events to which the contaminant confinement might be subjected. The effectiveness (relative strength) of the confinement barriers is expressed in Element 2b and is not evaluated in Element 3.

5.3.3.2 General Approach for Developing Lookup Table. The approach for developing the lookup table for Element 3b was as follows:

- Identify the set of operational events that would present the greatest challenge to the confinement barriers
- Review SARs, EISs, and other technical documents that provide useful information about these events
- Determine frequency and severity levels for these operational events
- Using Table 5-13, combine the frequency levels and severity levels to arrive at frequency-severity values.

To obtain a representative set of accidents for rest states (storage and disposal), several DOE EISs (DOE 1995b,d) and SARs (LITCO 1995d,e,f) were reviewed for dominant accidents. This review identified the following types of accidents (other than NPH) for storage facilities: fires, explosions, handling accidents, container degradation, criticality, and aircraft impact. The accidents chosen for Element 3b rest states include the following: fire, facility explosion, waste container explosion, and inadvertent intrusion into the waste (for disposal states only).

Handling accidents associated with the movement of waste are covered in Element 3b for transition states. Container degradation is assumed to occur for disposal states, but it is ignored for storage states because of the relatively short times generally assumed for such states. Criticalities are included in Element 3b for transition states but not in storage or disposal states because of the generally passive nature of these states. Finally, aircraft impact accidents are not included in this model because their frequencies are typically termed Incredible (less than 1E-6/yr) and the frequency-severity values will be less than those for other events. At some locations, however, it may be necessary to include aircraft impact accidents.

5.3.3.3 Lookup Table—Element 3b. The Element 3b lookup table is Table 5-16. The user should select the appropriate value of frequency-severity for each relevant operational event. These values are then added to give the value of Element 3b.

Table 5-16. Element 3b lookup table—operational challenges to confinement.

Operational event	Frequency (1/yr)	Severity	Frequency-severity value (1/yr): Element 3b ^a	Selection criteria
Fire (unmitigated)	1E-2	Moderate	1E-3	Storage of poorly characterized waste in unvented containers; storage of large amounts of combustible waste with inadequate fire protection
	1E-3	Moderate	1E-4	Storage of well-characterized waste with adequate fire protection
	1E-4	Moderate	1E-5	Storage of well-characterized waste with adequate fire protection
	1E-5	Moderate	1E-6	Storage of waste form that is difficult to combust with adequate fire protection; disposal state
Facility explosion	1E-3	Moderate	1E-4	Storage facility with natural gas or fuel lines present
	1E-5	Moderate	1E-6	Storage facility with very little explosion potential; disposal state
Container explosion	1E-2	Low	1E-4	Storage of poorly characterized waste in unvented containers
	1E-4	Low	1E-6	Storage of well-characterized waste in vented containers; disposal state
Intrusion into the waste	1E-3	Negligible	1E-6	Disposal facility only (drilling, excavation, animal/insect transport, or plant uptake)
Waste migration into groundwater	1E-3	High	1E-3	Disposal facility

a. The total for Element 3b is the sum of the frequency-severity values from fire, facility explosion, container explosion, and waste intrusion, if applicable.

The bases for selecting operational events and the corresponding frequency-severity values are found in the following subsections.

5.3.3.4 Basis for Values in Lookup Table. Rest states are static. Any handling and treatment of the waste, including damage to containers while they are being emplaced, is addressed by the method for transition states (Section 6.3).

For storage, the primary set of operational challenges to confinement can be broadly described as fires, facility explosions, and waste container explosions. The potential challenges for disposal are limited to fires and container explosions and intrusion into the waste after loss of institutional control. In the following subsections, frequency and severity levels are assigned to each of these events.

5.3.3.4.1 Fires—The initiators and types of potential fires are highly facility-specific. However, most fires can be categorized as electrical, flammable liquid, or combustible material fires. Spontaneous combustion and pyrophoric material fires may be possible for some facilities.

To determine appropriate fire frequencies for DOE facilities and processes, two EISs were reviewed. For unmitigated fires, DOE (1995b) indicates a range of frequencies of 1E-3/yr to 1E-7/yr at the INEL for WM and ER facilities and processes. DOE (1995d) indicates a range of unmitigated frequencies of 1.5E-2/yr to less than 1E-4/yr for existing and hypothetical DOE facilities and processes. Factors affecting the fire frequency included the following: presence and amount of combustible materials, presence of electrical equipment, poor housekeeping, existence of poorly characterized waste, and existence of adequate fire detection and suppression. Based on this information, a base unmitigated fire frequency of 1E-3/yr is used for storage of well-characterized waste with adequate fire detection and suppression. If poorly characterized waste is present or large amounts of combustible material are present with inadequate fire detection and suppression, then a frequency of 1E-2/yr is suggested. If the waste form is difficult to combust and adequate fire detection and suppression is present, then a frequency of 1E-4/yr is suggested. Finally, for disposal, a frequency of 1E-5/yr is suggested because of the type of waste form generally present and the lack of other types of ignition sources. These frequencies are summarized in Table 5-16.

The severity of the fire (i.e., the fraction of waste that may be affected by the fire) depends on the available fuel loading in the facility and the type of barrier being challenged. Several studies of the effects of fire on waste containers have been performed.

Snook (1992) performed fire propagation and loading tests on 55-gal steel drums stacked on wooden pallets. Data from the tests indicated that temperatures of 810°F were obtained from the ignition source. The test demonstrated that the wooden pallets did not self-ignite and basically self-extinguished after the ignition source was consumed. The test also illustrated that drum pressures, structural deformation, and pallet instability were insignificant at these temperatures.

Bucci et al. (1994) summarized fire challenge tests performed by Westinghouse Hanford Company and Lawrence Livermore National Laboratory. The purpose of these tests was to provide data regarding the behavior and severity of fires involving radioactive combustible wastes stored in metal drums at DOE sites. The test results indicate that, during extremely hot fires (> 1,000°F) fueled by a flammable liquid or large amounts of combustible materials, the seals on metal drums containing combustible materials will

fail, venting gases from the drum and blowing the drum lids off a small percentage of the drums because of high internal pressures.

Several radiant heat and fire tests have been performed on improved plywood containers for waste. The results of radiant heat and fire tests reported by Lindsay and Domning (1972) on DOT 7A plywood boxes coated with fiberglass-reinforced polyester indicate that the polyester ignited after 60 seconds of radiant heat from a 1,300°F fire. At 31 minutes of exposure, most of the polyester had been consumed and fire and smoke subsided in the heated area. Slow charring of the plywood was noted during the remaining 20 minutes of the tests. Similar radiant exposure of an uncoated container produced surface ignition of the plywood in 20 seconds. Burnthrough of the 5-ply 3/4-in. plywood occurred in about 31 minutes.

Another fire test involved challenging a fiberglass-reinforced polyester container in a pool of burning (1,300–1,800°F) mineral spirits. The result of the 20-minute test was that there was no perceptible rise in temperature inside the box and that little combustion of the polyester had occurred on the top and sides. There was combustion on the bottom; however, it did not consume all of the polyester and no damage was apparent to the plywood in any area except that directly above one of the supports.

Tests reported in Brown (1979) indicate that the elapsed time for a fire to penetrate a DOT 7A fiberglass-reinforced polyester box is in excess of 40 minutes.

Fires impacting substantial barriers, such as a SNF shipping or storage cask or storage pool, would have little impact on the barrier or the waste (LITCO 1995e).

The discussion above indicates that a severity level of Moderate (Table 5-13) can be assigned to operational challenges from unmitigated fires. The basis for this assignment is that, during very hot fires, numerous waste containers may breach.

5.3.3.4.2 Facility Explosion—Similar to what was done for fire frequencies, two DOE EISs were reviewed for facility explosion frequencies. DOE (1995b) lists a range of facility explosion frequencies from 2E-4/yr to 3E-6/yr. DOE (1995d) lists a range of facility explosion frequencies of 1.5E-2/yr to 1E-6/yr. Both of these ranges include waste treatment and storage facilities. Factors affecting the facility explosion frequency included mainly the existence or absence of explosive sources such as natural gas lines or fuel lines. For storage facilities with natural gas or fuel lines, a facility explosion frequency of 1E-3/yr is used. This base frequency is reduced to 1E-5/yr for storage facilities with little or no explosion potential and for disposal facilities. These frequencies are summarized in Table 5-16.

Similar to facility fires, explosions were assigned a severity level of Moderate.

5.3.3.4.3 Waste Container Explosion—Some waste containers have the potential for generating flammable mixtures of gas or high pressures inside the container. The possible mechanisms for gas generation include radiolysis, thermal degradation, bacteriological decomposition, chemical corrosion, and radioactive decay involving the emission of alpha particles.

The DOE has issued a Safety Notice (DOE 1993b) regarding eight events involving drum fires, overpressurizations, and explosions which occurred from 1970 to 1985. Waste container overpressurizations and explosions usually have the potential for affecting only one or two additional containers.

An estimate for the frequency of such explosions was developed as follows. The Radioactive Waste Management Complex at the INEL stores and disposes of many thousands of sealed radioactive waste containers. For the past 44 years, the Radioactive Waste Management Complex has been receiving containers of radioactive waste from the INEL and other DOE sites (primarily the Rocky Flats Plant) and placing them in underground disposal and aboveground storage. Because of the large number of drums and the potential for gas pressure build-up, the Radioactive Waste Management Complex SAR (LITCO 1995d) specifically addresses this issue. The SAR reports a drum explosion event frequency of $3E-02/yr$ when venting drums through the drum vent facility (a transition state). For storage of vented waste containers, the explosion frequency should be much lower. For this case, a waste container explosion frequency of $1E-4/yr$ is assumed for storage facilities. If unvented waste containers are present, then a frequency of $1E-2/yr$ is used. These frequencies are summarized in Table 5-16. Such an explosion would be expected to affect no more than several waste containers, at the most (as confirmed by informal tests involving mockup drums). Therefore, a severity level of Low is used.

5.3.3.4.4 Intrusion into the Waste—Intrusion into the waste after the loss of institutional control is considered only for disposal states. Intrusion can involve inadvertent excavation, inadvertent drilling, transport of waste to the surface by animals or insects, or plant uptake.

Over an assumed disposal time period of 1,000 years (see Section 5.6), waste intrusion is expected to occur. Assuming that intrusion does occur in 1,000 years, the frequency for such an event can be approximated by $1E-3/yr$.

The severity of intrusion is represented by the estimated fraction of waste in disposal that would be affected by the intrusion. Smith et al. (1995) and Maheras et al. (1994) indicate that typical excavations of disposed waste may affect on the order of 0.1% of the waste. Also, the preliminary performance assessment for the Waste Isolation Pilot Plant (WIPP) (SNL 1992) indicates that 0.02% of the waste would be transported to the surface, given inadvertent drilling. Finally, transport of waste to the surface by animals, insects, or plants is expected to affect even smaller percentages of the buried waste (Maheras et al. 1994). Therefore, a severity level of Negligible is used for waste intrusion events.

5.3.3.4.5 Waste Migration to Groundwater—For disposal states, migration of contaminants is assumed to occur over a 1,000-year period. Therefore, the frequency of the event is $1E-3/yr$. The severity is assumed to be high; therefore, all of the waste may be affected.

5.4 Element 4—Environmental Transport Effectiveness

5.4.1 Brief Description of Element

Element 4 characterizes the effectiveness of the environmental pathways through which the contaminants in the waste type move from the source to the receptor. This section addresses transport via the airborne and waterborne (groundwater) pathways. All subordinate pathways (e.g., the groundwater-irrigation-crop ingestion pathway) are assumed to be reflected in simple versions of these two pathways.

Section 5.1.1 explained how Elements 1a and 1b are closely interrelated. Similarly, Elements 4 and 5 are closely interrelated. The effectiveness of environmental transport of the contaminants depends on the locations of the receptors. Section 5.5 discusses the interactions of V_4 and V_5 . Section 5.5.3 includes recommended values of the combined Elements $4 \times (5a + 5b)$ for various DOE sites and facilities. As a time-saving measure, recommended values can be used instead of the lookup tables for the individual Elements 4, 5a, and 5b for airborne transport.

5.4.2 General Approach for Developing Lookup Tables

The general approach for developing the lookup tables was to use existing transport calculation methods to determine downstream concentrations of contaminants at various distances via airborne and waterborne transport. The downstream concentrations were compared to determine relative transportabilities for airborne and waterborne transport of contaminants.

As will be seen, the relative transportability values for groundwater transport in this method are site-specific. They depend on the local values of vadose zone water transport time, groundwater velocity, and sorption coefficients. The relative transportability values for airborne transport in this method are generic. For simplicity, no attempt was made to tailor them to local meteorological conditions.

5.4.3 Lookup Tables—Element 4

Tables 5-17 and 5-18 are the lookup tables for the Element 4. They contain the relative transportability values for air and groundwater, respectively.

Lookup tables that combine Elements 4, 5a, and 5b for airborne transport are provided as a time-saving measure in Section 5.5.3.

The air transportability values are used for risk calculations for both transition states and aboveground storage states in Table 5-17. The groundwater transportability values in Table 5-18 are used for risk calculations for disposal states and underground storage states.

The relative air transportabilities given in Table 5-17 are independent of windspeed.

Table 5-17. Lookup table for Element 4—relative air transportabilities.^a

Distance (d) to receptor (m)	Value of relative air transportability
d ≤ 100	1
100 < d ≤ 300	3E-1
300 < d ≤ 500	8E-2
500 < d ≤ 1,000	3E-2
1,000 < d ≤ 2,000	1E-2
2,000 < d ≤ 10,000	1E-3
10,000 < d ≤ 20,000	4E-4
20,000 < d	1E-4

^a See Section 5.5.3 for recommended values of the combined Element 4 × (5a + 5b).

For determining the relative groundwater transportabilities in Table 5-18, the value of the sorption coefficient (K_d) of the released contaminant is required. As a time-saving measure for the user, generic values for K_d are included in the table. However, if desired, actual site data can be used for the K_d s.

5.4.4 Basis for Values in Lookup Tables

5.4.4.1 Relative Air Transportability. Tables 5-19 through 5-20 show the process used to arrive at the values for the relative transportability of contaminants through the air. The relative transportabilities reflect the fraction of the released contaminant that can reach a potential receptor downwind.

Dispersion coefficients were calculated based on the simple Gaussian Plume model at various downwind distances for six different meteorological stability classes. (No attempt was made to address organic contaminants that are heavier or lighter than air, deposition of particulate contaminants, etc.) Using the Gaussian model and assuming a groundlevel release,^o the dispersion coefficients can be found using the following equation:

$$\chi/Q = 1/(\pi\sigma_y\sigma_zu) \tag{5-2}$$

^o No attempt was made to address elevated releases because stack heights are not known for these hypothetical facilities.

Table 5-18. Lookup table for Element 4—relative groundwater transportabilities.

Distance (d) to receptor (m)	Value of relative groundwater transportability ^{a,b,c}
$d < 100$	$(1E-4) \times T / (K_d \times R_v)$
$100 < d \leq 300$	$(4E-5) \times T / (K_d \times R_v)$
$300 < d \leq 500$	$(2E-5) \times T / (K_d \times R_v)$
$500 < d \leq 1,000$	$(6E-6) \times T / (K_d \times R_v)$
$1,000 < d \leq 2,000$	$(3E-6) \times T / (K_d \times R_v)$
$2,000 < d \leq 10,000$	$(2E-7) \times T / (K_d \times R_v)$
$10,000 < d < 20,000$	$(4E-8) \times T / (K_d \times R_v)$
$20,000 < d$	$(1E-8) \times T / (K_d \times R_v)$

a. The following generic values are suggested for the K_d based on the contaminants present:

Actinides (except uranium), polychlorinated biphenyls (PCBs)	$K_d = 1,000$
Metals, uranium, polyaromatic hydrocarbons, pesticides	$K_d = 100$
Strontium, yttrium, phthalates	$K_d = 10$
Technetium, nonmetals, other organic chemicals	$K_d = 1$

b. Use the following estimated values for the R_v based on the site's groundwater velocity:

Groundwater velocity $> 1E5$ m/yr	$R_v = 100$
$1E3$ m/yr $<$ groundwater velocity $\leq 1E5$ m/yr	$R_v = 10$
Groundwater velocity $< 1E3$ m/yr	$R_v = 1$

It is expected that, for most sites, the value of $R_v = 1$. For example, the groundwater velocity values are approximately 570, 7, and 22 m/yr for the INEL, SRS, and Hanford Site, respectively (Smith et al. 1995; Martin Marietta 1994; Wood et al. 1994a).

c. To determine values for T (vadose zone transport time decay factor), estimate transport time from Table 5-35 and take the corresponding radioactive decay value from Tables 5-1 and 5-2.

where

χ/Q = dispersion coefficient, s/m^3

σ_y = standard deviation of the plume concentration in the crosswind direction at a downwind distance x , m

σ_z = standard deviation of the plume concentration in the vertical direction at a downwind distance x , m

u = wind velocity, m/s.

Because several methods exist for estimating the standard deviations in Equation (5-2), five correlations of the standard deviations were examined: (1) Hilsmeier-Gifford, (2) Markee, (3) Pasquill-Gifford, (4) McElroy-Pooler, (also known as Briggs Urban), and (5) Briggs Rural. However, for the purposes of this simplified model development, only the general Pasquill-Gifford method was used.

A windspeed of 6 m/s was assumed to determine the dispersion coefficients. The ratios of transportabilities as a function of distance would not change substantially if a different windspeed had been used. This conclusion was verified in a computer run using a windspeed of 1 m/s.

The Pasquill-Gifford standard deviations were taken from (NRC 1982). The calculated dispersion coefficients for the six stability classes are given in Table 5-19. The relative transportabilities, found by dividing the coefficient at 100 m into the remaining coefficients, are listed for each stability class in Table 5-20. The relative transportability is 1.0 at 100 m and diminishes exponentially until it reaches a value on the order of $5E-5$ at 100,000 m.

For simplicity, approximate values for the relative transportability in air were developed for eight separate distance ranges in Table 5-21. Because the relative transportability is a measure of the fraction of the released contaminant that reaches the receptor, the closest distance in the table has a normalized value of 1. The relative air transportability values range from 1 to $1E-4$ over the eight ranges of distance.

5.4.4.2 Relative Groundwater Transportability. Tables 5-22 through 5-35 show the process used to arrive at the values for the relative transportability of contaminants through the groundwater. The relative transportabilities reflect the fraction of the released contaminant that can reach the drinking water well of a potential receptor downstream.

Downstream concentrations were calculated using the GWSCREEN computer program (Rood 1993). GWSCREEN is based on an analytical solution to the advection-dispersion equation for groundwater transport in a homogeneous porous medium of infinite lateral extent and finite thickness with constant, unidirectional flow. In this simplified analysis, four input parameters have a major effect on the downstream concentrations: (1) dispersivity, (2) downstream distance, (3) groundwater velocity, and (4) K_d . The effects of these four parameters on the concentration at the receptor well were examined individually and then in combination.

Table 5-21. Relative air transportabilities as a function of distance.

Distance (d) to receptor (m)	Value (normalized to 1 for d ≤ 100 m)
d ≤ 100	1
100 < d ≤ 300	3E-1
300 < d ≤ 500	8E-2
500 < d ≤ 1,000	3E-2
1,000 < d ≤ 2,000	1E-2
2,000 < d ≤ 10,000	1E-3
10,000 < d ≤ 20,000	4E-4
20,000 < d	1E-4

Table 5-22. Groundwater concentrations (Ci/m³ or kg/m³) as a function of downstream distance and sorption coefficient.^a

Distance (m)	K _d =0	K _d =0.1	K _d =1	K _d =10	K _d =100	K _d =1,000
100	1.8E-7	7.2E-8	1.1E-8	1.2E-9	1.2E-10	1.2E-11
200	7.6E-8	3.0E-8	4.7E-9	5.0E-10	5.0E-11	5.0E-12
300	4.4E-8	1.8E-8	2.8E-9	2.9E-10	2.9E-11	2.9E-12
400	2.9E-8	1.2E-8	1.8E-9	1.9E-10	1.9E-11	1.9E-12
500	2.1E-8	8.5E-9	1.3E-9	1.4E-10	1.4E-11	1.4E-12
600	1.6E-8	6.5E-9	1.0E-9	1.1E-10	1.1E-11	1.1E-12
700	1.3E-8	5.1E-9	7.9E-10	8.4E-11	8.4E-12	8.4E-13
800	1.0E-8	4.1E-9	6.4E-10	6.8E-11	6.8E-12	6.8E-13
900	8.5E-9	3.4E-9	5.3E-10	5.6E-11	5.7E-12	5.7E-13
1,000	7.1E-9	2.8E-9	4.4E-10	4.7E-11	4.7E-12	4.7E-13
2,000	2.1E-9	8.6E-10	1.3E-10	1.4E-11	1.4E-12	1.4E-13
5,000	3.8E-10	1.5E-10	2.4E-11	2.5E-12	2.5E-13	2.5E-14
10,000	9.6E-11	3.8E-11	6.0E-12	6.4E-13	6.4E-14	6.4E-15

a. The source was 1 Ci/m³ of generic radioactivity with no decay or 1 kg/m³ of a generic hazardous chemical.

Table 5-23. Relative groundwater transportabilities as a function of downstream distance and sorption coefficient.

Distance (m)	$K_d=0$	$K_d=0.1$	$K_d=1$	$K_d=10$	$K_d=100$	$K_d=1,000$	Arithmetic average
100	1.0	1.0	1.0	1.0	1.0	1.0	1.0
200	4.2E-1	4.2E-1	4.2E-1	4.2E-1	4.2E-1	4.2E-1	4.2E-1
300	2.5E-1	2.5E-1	2.4E-1	2.5E-1	2.5E-1	2.5E-1	2.5E-1
400	1.6E-1	1.6E-1	1.6E-1	1.6E-1	1.6E-1	1.6E-1	1.6E-1
500	1.2E-1	1.2E-1	1.2E-1	1.2E-1	1.2E-1	1.2E-1	1.2E-1
600	9.0E-2	9.0E-2	8.9E-2	9.0E-2	9.0E-2	9.0E-2	9.0E-2
700	7.1E-2	7.0E-2	7.0E-2	7.0E-2	7.0E-2	7.0E-2	7.0E-2
800	5.7E-2	5.7E-2	5.7E-2	5.7E-2	5.7E-2	5.7E-2	5.7E-2
900	4.7E-2	4.7E-2	4.7E-2	4.7E-2	4.7E-2	4.7E-2	4.7E-2
1,000	3.9E-2	3.9E-2	3.9E-2	3.9E-2	3.9E-2	3.9E-2	3.9E-2
2,000	1.2E-2	1.2E-2	1.2E-2	1.2E-2	1.2E-2	1.2E-2	1.2E-2
5,000	2.1E-3	2.1E-3	2.1E-3	2.1E-3	2.1E-3	2.1E-3	2.1E-3
10,000	5.3E-4	5.3E-4	5.3E-4	5.3E-4	5.3E-4	5.3E-4	5.3E-4

Table 5-24. Aggregation of relative groundwater transportabilities as a function of downstream distance only.

Distance (d) to receptor (m)	Aggregated value of relative transportability
$d \leq 100$	1
$100 < d \leq 300$	4E-1
$300 < d \leq 500$	2E-1
$500 < d \leq 1,000$	6E-2
$1,000 < d \leq 2,000$	3E-2
$2,000 < d \leq 10,000$	2E-3
$10,000 < d \leq 20,000$	4E-4
$20,000 < d$	1E-4 ^a

a. Value estimated from analogous air transportability results (Table 5-20) versus Table 5-23 at 10,000 m.

Table 5-25. Relative groundwater transportabilities as a function of sorption coefficient.

Distance (m)	$K_d=0$	$K_d=0.1$	$K_d=1$	$K_d=10$	$K_d=100$	$K_d=1,000$
100	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0
200	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0
300	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0
400	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0
500	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0
600	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0
700	1.5E+4	6.0E+3	9.E+2	9.9E+1	1.0E+1	1.0
800	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0
900	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0
1,000	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0
2,000	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0
5,000	1.5E+4	6.0E+3	9.4E+2	1.0E+2	1.0E+1	1.0
10,000	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0
Average	1.5E+4	6.0E+3	9.4E+2	9.9E+1	1.0E+1	1.0

Table 5-26. Relative groundwater transportabilities as a function of downstream distance and sorption coefficient.

Distance (d) to receptor (m)	Aggregated value of relative transportability
$d \leq 100$	$(1)/K_d$
$100 < d \leq 300$	$(4E-1)/K_d$
$300 < d \leq 500$	$(2E-1)/K_d$
$500 < d \leq 1,000$	$(6E-2)/K_d$
$1,000 < d \leq 2,000$	$(3E-2)/K_d$
$2,000 < d \leq 10,000$	$(2E-3)/K_d$
$10,000 < d \leq 20,000$	$(4E-4)/K_d$
$20,000 < d$	$(1E-4)/K_d$

Table 5-27. Sorption coefficients for certain elements at various DOE sites.

Element	INEL/Nevada Test Site		Savannah River Site		Hanford Site	Arithmetic average
	Sediment	Basalt	Sand	Soil		
Hydrogen	0E+0	0E+0	0.0E+0	0.0E+0	0E+0	0.0E+0
Krypton	0E+0	0E+0	ND	ND	ND	0.0E+0
Iodine	5E-2	5E-2	6.0E-1	1.0E+0	0E+0	3.4E-1
Technetium	1E-1	2E+0	3.6E-1	1.0E-1	0E+0	5.2E-1
Carbon	0E+0	0E+0	2.0E+0	5.0E+0	0E+0	1.4E+0
Strontium	2E+0	2E+0	1.5E+1	1.0E+1	1E+0	6.0E+0
Yttrium	2E+0	2E+0	1.5E+1	1.0E+1	1E+0	6.0E+0
Barium	6E+1	6E+1	ND ^a	ND	ND	6.0E+1
Cesium	2E+1	2E+1	2.8E+2	1.0E+2	1E+0	8.4E+1
Cerium	1E+2	1E+2	ND	ND	ND	1.0E+2
Cobalt	1E+2	1E+2	ND	ND	ND	1.0E+2
Nickel	1E+2	1E+2	4.0E+2	3.0E+2	ND	2.2E+2
Uranium	1E+3	1E+2	3.5E+1	5.0E+1	0E+0	2.4E+2
Americium	7E+2	7E+1	1.9E+3	1.5E+2	1E+2	5.8E+2
Plutonium	2E+3	2E+2	5.5E+2	1.0E+2	1E+2	5.9E+2
Curium	7E+2	7E+1	4.0E+3	1.5E+2	1E+2	1.0E+3
Thorium	1E+3	1E+2	3.2E+3	3.0E+3	ND	1.8E+3

a. ND = no data given in source document (Smith et al. 1995).

Table 5-28. Aggregation of elemental (inorganic) sorption coefficients.

Type of element	Aggregated value of sorption coefficient
Actinides (except uranium)	1E+3
Metals/uranium	1E+2
Strontium/yttrium	1E+1
Nonmetals	1

Table 5-29. Aggregation of sorption coefficients as a function of organic carbon sorption coefficient (K_{oc}) values.

K_{oc}	Aggregated value of sorption coefficient
$K_{oc} > 50,000$	1E+3
$5,000 > K_{oc} \geq 50,000$	1E+2
$500 > K_{oc} \geq 5,000$	1E+1
$K_{oc} \leq 500$	1

Table 5-30. Aggregation of sorption coefficients for organic compounds.

Chemical	Aggregated value of sorption coefficient
PCBs	1E+3
Polyaromatic hydrocarbons, pesticides	1E+2
Phthalates	1E+1
Other organic chemicals	1

Table 5-31. Groundwater concentrations as a function of downstream distance and groundwater velocity.

Distance (m)	1E2 (m/yr)	1E3 (m/yr)	1E4 (m/yr)	1E5 (m/yr)	1E6 (m/yr)
100	9.6E-7	7.1E-7	1.8E-7	2.3E-8	2.4E-9
200	2.4E-7	2.1E-7	7.6E-8	1.1E-8	1.2E-9
300	1.1E-7	1.0E-7	4.4E-8	7.1E-9	7.9E-10
400	6.0E-8	5.8E-8	2.9E-8	5.2E-9	5.9E-10
500	3.9E-8	3.8E-8	2.1E-8	4.1E-9	4.7E-10
600	2.7E-8	2.6E-8	1.6E-8	3.3E-9	3.9E-10
700	2.0E-8	1.9E-8	1.3E-8	2.8E-9	3.3E-10
800	1.5E-8	1.5E-8	1.0E-8	2.4E-9	2.9E-10
900	1.2E-8	1.2E-8	8.5E-9	2.1E-9	2.5E-10
1,000	9.7E-9	9.6E-9	7.1E-9	1.8E-9	2.3E-10
2,000	2.4E-9	2.4E-9	2.1E-9	7.6E-10	1.1E-10
5,000	3.6E-10	3.9E-10	3.8E-10	2.1E-10	4.5E-11
10,000	6.0E-11	9.7E-11	9.6E-11	7.1E-11	1.8E-11

Table 5-32. Relative groundwater transportabilities as a function of groundwater velocity.

Distance (m)	1E2 (m/yr)	1E3 (m/yr)	1E4 (m/yr)	1E5 (m/yr)	1E6 (m/yr)
100	4.0E+2	3.0E+2	7.5E+1	9.6	1.0
200	2.0E+2	1.8E+2	6.4E+1	9.3	1.0
300	1.3E+2	1.3E+2	5.6E+1	9.0	1.0
400	1.0E+2	9.8E+1	5.0E+1	8.8	1.0
500	8.2E+1	8.0E+1	4.5E+1	8.7	1.0
600	6.9E+1	6.8E+1	4.1E+1	8.5	1.0
700	5.9E+1	5.9E+1	3.8E+1	8.4	1.0
800	5.2E+1	5.1E+1	3.5E+1	8.2	1.0
900	4.7E+1	4.6E+1	3.3E+1	8.2	1.0
1,000	4.3E+1	4.2E+1	3.1E+1	7.9	1.0
2,000	2.2E+1	2.2E+1	1.9E+1	6.9	1.0
5,000	8.1E+0	8.7E+0	8.4E+0	4.7	1.0
10,000	3.3E+0	5.4E+0	5.3E+0	3.9	1.0
Average	9.4E+1	8.3E+1	3.9E+1	7.9	1.0

Table 5-33. Groundwater relative velocity factor.

Groundwater velocity (m/yr)	Groundwater relative velocity factor (R_v)
$v \leq 1E+03$	1
$1E+03 < v \leq 1E+05$	10
$v > 1E+05$	100

Table 5-34. Relative groundwater transportabilities as a function of downstream distance, sorption coefficient, and relative groundwater velocity factor.

Distance (d) to receptor (m)	Aggregated value of relative transportability
$d \leq 100$	$(1)/(K_d \times R_v)$
$100 < d \leq 300$	$(4E-1)/(K_d \times R_v)$
$300 < d \leq 500$	$(2E-1)/(K_d \times R_v)$
$500 < d \leq 1,000$	$(6E-2)/(K_d \times R_v)$
$1,000 < d \leq 2,000$	$(3E-2)/(K_d \times R_v)$
$2,000 < d \leq 10,000$	$(2E-3)/(K_d \times R_v)$
$10,000 < d \leq 20,000$	$(4E-4)/(K_d \times R_v)$
$20,000 < d$	$(1E-4)/(K_d \times R_v)$

Table 5-35. Approximate times of water transport through the vadose zone for major DOE Environmental Management sites.

Site	Representative approximate transport time (yr)	Source
Hanford Site	450	Wood et al. (1994a)
INEL	30-50	Maheras et al. (1994) Loehr et al. (1994)
Los Alamos National Laboratory	1,000-4,000	Hollis et al. (1995)
Oak Ridge National Laboratory	5-20	Martin Marietta (1994)
Rocky Flats Plant	9-14	DOE (1995e)
Savannah River Site	4.5	Martin Marietta et al. (1994)

Other parameters, such as infiltration rate, depth to groundwater, moisture content, and porosity affect the concentration, but only by way of the transport time, which in turn determines the amount of radioactive decay that occurs before reaching the receptor. Concentrations of contaminants with short half-lives will be affected by these parameters; therefore, the parameters are addressed separately in this model.

5.4.4.2.1 Dispersivity—A general rule of thumb for dispersivity in porous media such as sediment and soil is to assume that the longitudinal dispersivity is 10% of the distance to the receptor and the transverse dispersivity is 5% of the distance to the receptor. For fractured media, the actual dispersivity can be higher. However, since the 10% and 5% values are a conservative assumption for fracture flow, these values were used for all the calculations in developing this model.

5.4.4.2.2 Downstream Distances—Groundwater concentrations calculated using GWSCREEN at various downstream distances and for various K_d s are given in Table 5-22.^p The groundwater velocity was held constant for these calculations. (The source was 1 Ci/m³ of generic radioactivity with no decay or 1 kg/m³ of a generic hazardous chemical.)

The concentration in each column at 100 m was then divided into the remaining concentrations to determine the relative groundwater transportability as a function of downstream distance. These relative transportabilities are listed in Table 5-23. The transportabilities range from 1.0 at 100 m to 5E-4 at 10,000 m.

Column 8 of Table 5-23 shows the average relative transportability for each distance. Using these values, the aggregate relative groundwater transportabilities based on several representative downstream distances were determined and are shown in Table 5-24.

5.4.4.2.3 Sorption Coefficient—Using the concentrations in Table 5-22, relative groundwater transportabilities as a function of K_d were calculated by dividing the smallest concentration in each row into the remaining concentrations. These relative transportabilities are listed in Table 5-25.

The relative transportabilities range from approximately 1E+04 for a K_d of 0 to 1 at a K_d of 1,000. The last row of Table 5-25 shows the average relative transportabilities for each value of the sorption coefficient. The relative transportabilities are almost inversely proportional to the value of K_d , particularly for K_d values ≥ 1 .

Combining this information with the relative groundwater transportabilities as a function of downstream distance given in Table 5-24 leads to new transportabilities as a function of both distance and sorption coefficient. These new relative transportabilities are given in Table 5-26. The effect of the sorption coefficient is shown as $1/K_d$ in each entry.

To make the method easier to use, the sorption coefficients for various elements and compounds were examined. A small set of generic lookup values for several types of contaminants was developed as explained in the following paragraphs.

p. The units for all K_d values in this report are milliliters per gram.

Sorption coefficients for various elements (inorganics) at the INEL, Nevada Test Site, SRS, and Hanford Site were obtained from Smith et al. (1995) and are listed in Table 5-27. The coefficients for the INEL and for the Nevada Test Site were taken to be the same in the reference and are listed for both sediment and basalt. The coefficients for the SRS are given for both sand and soil, while those given for the Hanford Site are for all types of media.

Column 7 of Table 5-27 gives the arithmetic average value for the sorption coefficients for each element. The nonmetals tend to have the smaller values, while actinides tend to have the larger values. The few exceptions to this are technetium, strontium, uranium, and yttrium.

Using the average values from Table 5-27, the sorption coefficients for the elements were aggregated into the four categories given in Table 5-28.

For organic chemicals, the K_d value was calculated from the K_{oc} value and an assumed 0.3% organic carbon in the unsaturated zone, based on INEL values. Per Warren et al. (1990), the K_d for organic chemicals can be calculated by Equation (5-3):

$$K_d = K_{oc} \times (\%OC/100) \quad (5-3)$$

where

K_{oc} = organic carbon sorption coefficient for the specific compound

%OC = percent of organic carbon in the soil.

Using Equation (5-3) and assuming a value of 0.3% for the organic carbon content in the soil (the carbon content for the INEL), the various values for K_{oc} yield the resulting aggregated sorption coefficients listed in Table 5-29.

EPA (1990) contains a list of organic chemicals in several categories; for the chemicals in each category, K_{oc} is given. The K_{oc} values of each category were reviewed. The results are listed in Table 5-30.

5.4.4.2.4 Groundwater Velocity—A new set of groundwater concentrations was calculated using GWSCREEN at various downstream distances and at groundwater velocities ranging from 1E+02 to 1E+06 m/yr. The concentrations are listed in Table 5-31. The sorption coefficient was set to a value of 0 for these calculations.

The smallest concentration in each row of Table 5-31 was then divided into the remaining concentrations to determine the relative transportability as a function of the groundwater velocity. These relative transportabilities are listed in Table 5-32; a function of distance, they range from approximately 1E+02 to 1 (see bottom row of Table 5-32).

The last row of Table 5-32 shows the aggregated (average) relative transportabilities for each velocity. These average values were then aggregated into the simplified values of the relative velocity factor (R_v) given in Table 5-33. The R_v factor will eventually appear in the denominator of the relative transportability; the value of the factor increases with velocity because the relative transportability decreases with velocity.

From Table 5-32, it can be seen that, at distances up to 2,000 m, the relative transportability decreases uniformly as the velocity (and the velocity effect) increases. (At longer distances, the relative transportability is relatively independent of velocity, for velocities up to $1E5$ m/yr.) Combining this information with the relative groundwater transportabilities as a function of downstream distance and sorption coefficient given in Table 5-26 leads to new transportabilities as a function of distance, sorption coefficient, and groundwater velocity. These new relative transportabilities are given in Table 5-34.

5.4.4.2.5 Adjustment for Vadose Zone Transport—The groundwater transportability discussions thus far have addressed only groundwater transport. In most cases, contaminants in the waste will have to migrate first through the vadose zone before encountering the groundwater.

The time required for a contaminant to migrate through the vadose zone depends on the moisture infiltration rate; the moisture content of the medium; the distance to the groundwater (i.e., the thickness of the vadose zone); the sorption coefficient of the contaminant; and other factors.

The effect of the K_d s has already been incorporated into the relative groundwater transportability (see Section 5.4.4.2.3).

Radioactive decay takes place during the vadose zone transport. This effect reduces the activity of the radionuclides that undergo groundwater transport. (Obviously, this effect does not apply to hazardous chemicals. The vadose zone transport simply delays the time at which the dose from the chemical is delivered to the receptor.)

The factor T is used here to represent the radioactive decay that occurs during vadose zone transport. T is the fraction of the radioactivity that still exists after the contaminant has migrated from the waste to the groundwater. In the simplified method, the value of T is determined as follows:

- Estimate the travel time from the release of the radionuclides until they reach the groundwater.

As stated earlier, the effect of the K_d has already been taken into account in the groundwater transport evaluation of Section 5.4.4.2.3. Thus, for simplicity, water (rather than contaminant) transport times in the vadose zone are used here.

The precise calculation of vadose transport times is complex. Even detailed HSRA for the same location can arrive at substantially different answers (e.g., differing by a factor of 2 or more) because of using different data or degrees of conservatism.

Table 5-35 provides approximate vadose zone travel times for the major DOE sites and is based on a brief review of detailed HSRA documents for the sites. If desired, the user can substitute more appropriate values for a specific location.

- For that transport time, in years, look up the radioactive decay factor.

Tables 5-1 and 5-2 provide weighted-average decay factors for actinides and nonactinides for seven types of waste. Values are given for times ranging from 0 to 1,000 years.

- The selected decay factor is the value of T.
- Insert the value of T into the expression for the relative groundwater transportability in Table 5-36.

5.4.4.3 Correlation of the Values Selected for Air and Groundwater Relative Transportabilities.

5.4.4.3.1 Purpose and Approach—The values developed thus far for Element 4 are consistent within an individual transport pathway (i.e., air or water). However, the values of the groundwater relative transportabilities had to be normalized to those for airborne transport before placing them in the lookup table for Element 4 waterborne transport. The normalization was needed so the air and waterborne relative transportabilities would be on the same scale, to the extent feasible. The conceptual model for combined air and groundwater pathway modeling is shown in Figure 5-2.

For air and groundwater pathway modeling, the product of the Elements 2a, 2b, and (3a + 3b) determines the fraction of the contaminant inventory that is released to the air or groundwater. (Combined Element 3a + 3b also determines the frequency of environmental and operational challenges.) Once the contaminant is released to the air or groundwater, Element 4 models the contaminant dispersion. The dispersion results for air (Table 5-21) and groundwater (Table 5-36) indicate similar results for dispersion versus distance from the point of contaminant release (assuming $T = K_d = R_v = 1$). Therefore, the correlation of Element 4 simplifies to a comparison of intake rates for humans. For inhalation, the typical intake rate is 20 m³/d. For ingestion (drinking water from a well, which draws from the groundwater), the typical rate is 2 L/d. Converting L to m³ results in 2E-3 m³/d for ingestion. Therefore, the inhalation rate is 10,000 times higher than the ingestion rate. This implies that the Element 4 results for groundwater modeling (Table 5-36) must be divided by 10,000 in order to correlate them with the air pathway modeling. Therefore, the correlated results for Element 4 for groundwater modeling are presented in Table 5-37.

Table 5-36. Relative groundwater transportabilities as a function of downstream distance, sorption coefficient, relative groundwater velocity factor, and vadose zone transport time decay factor.

Distance (d) to receptor (m)	Aggregated value of relative transportability
$d \leq 100$	$(1) \times T/(K_d \times R_v)$
$100 < d \leq 300$	$(4E-1) \times T/(K_d \times R_v)$
$300 < d \leq 500$	$(2E-1) \times T/(K_d \times R_v)$
$500 < d \leq 1,000$	$(6E-2) \times T/(K_d \times R_v)$
$1,000 < d \leq 2,000$	$(3E-2) \times T/(K_d \times R_v)$
$2,000 < d \leq 10,000$	$(2E-3) \times T/(K_d \times R_v)$
$10,000 < d \leq 20,000$	$(4E-4) \times T/(K_d \times R_v)$
$20,000 < d$	$(1E-4) \times T/(K_d \times R_v)$

Table 5-37. Revised relative groundwater transportabilities after correlation with relative air transportabilities.

Distance (d) to receptor (m)	Aggregated value of relative transportability ^a
$d \leq 100$	$(1E-4) \times T/(K_d \times R_v)$
$100 < d \leq 300$	$(4E-5) \times T/(K_d \times R_v)$
$300 < d \leq 500$	$(2E-5) \times T/(K_d \times R_v)$
$500 < d \leq 1,000$	$(6E-6) \times T/(K_d \times R_v)$
$1,000 < d \leq 2,000$	$(3E-6) \times T/(K_d \times R_v)$
$2,000 < d \leq 10,000$	$(2E-7) \times T/(K_d \times R_v)$
$10,000 < d \leq 20,000$	$(4E-8) \times T/(K_d \times R_v)$
$20,000 < d$	$(1E-8) \times T/(K_d \times R_v)$

a. Values have been rounded to one significant figure.

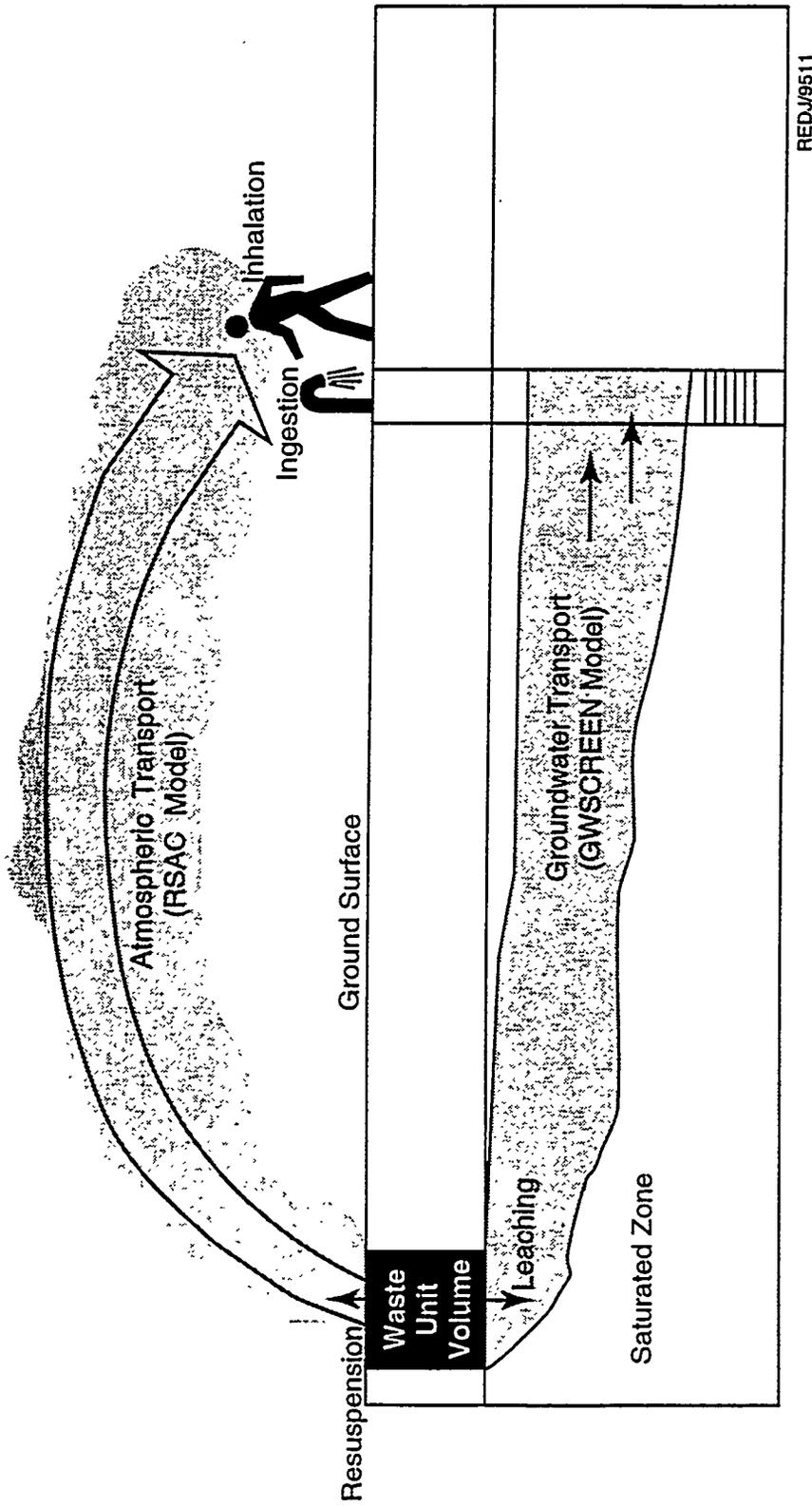


Figure 5-2. Conceptual model for normalizing airborne and waterborne transport.

5.5 Element 5—Presence of Human Receptors

Element 5 relates to the presence of humans who are potential receptors for the contaminants in the waste type. Both workers (in Element 5a) and members of the public (in Element 5b) are considered in the method. The values of the two elements are added in Equations (4-6) and (4-8). If desired, the values can be kept separate so that the risks to workers and to the public can be reported separately.

The human receptors who could be affected by the hazards in the waste type can be thought of as consisting of four groups. Three of these groups consist of workers. The first group is the relatively small number of workers who deal directly with the waste type or are located in the immediate area. Examples are equipment or process operators and health physics technicians. These people are located close enough that they could be affected directly by a wide variety of exposure scenarios. The second group is the other workers who are located in the same building or facility but who are in a different work location and do not deal directly with the waste type. These people generally would not be affected in minor accidents but could be affected in major accidents. The third group is workers located still farther away in other facilities at other areas of the same DOE site. The distance from the waste type to these workers can range from a few hundred feet to tens of miles.

The fourth group of receptors is the public who reside offsite. Some members of the public are located close to the site boundary; others are farther away. Only major accidents would be expected to affect the third and fourth groups.

Section 5.5.1 addresses the relative risk that the first three groups (the workers) are subjected to by virtue of their proximity to the waste type. Section 5.5.2 addresses the relative risk that the fourth group (the public) is subjected to by virtue of their proximity to the site.

Section 5.4.1 mentioned the close interaction between Elements 4 and 5. The refined risk expressions are given in Equations (4-6) and (4-8). As shown there, the products of Element 4 with Elements 5a and 5b are summed over indices j and k representing the various groups of receptors located at various distances from the waste type.

Section 5.5.3 includes recommended values for the combined Elements $4 \times (5a + 5b)$ for airborne and groundwater transport. The recommended values can be used as a time-saving measure.

5.5.1 Element 5a—Workers

5.5.1.1 Brief Description of Element. Element 5a represents the presence of the workers—how many workers are in the vicinity of the waste type, what fraction of their time is spent in that location, and how well they are protected. Protective features can include the presence of engineered work area protection (WAP) features, such as shielding walls, and the use or availability of personal protective equipment (PPE), such as respirators. Emergency procedures, such as evacuation, can also provide protection but are not addressed in the simplified method.

5.5.1.2 General Approach for Developing Lookup Table. The approach for developing the lookup table for Element 5a, representing the proximity of the workers, was as follows:

- Identify the principal factors (e.g., time of exposure and shielding/protection) that affect the consequences to the workers; indicate whether each factor tends to increase or decrease the consequences
- Express the factors in the form of a simplified equation that produces the value for Element 5a, assuming the only exposure routes to workers are inhalation and direct radiation
- Develop a lookup list for each factor in the simplified equation
- Correlate the instructions with those for the lookup tables for Element 4.

5.5.1.3 Lookup Table--Element 5a. The value of Element 5a for each group i is determined by the following expression (a maximum of the three groups discussed earlier is recommended, but greater than three groups can be used):

$$Element\ 5a_i = \frac{N_i \times F_i}{WAP_i \times PPE_i} \quad (5-4)$$

where

- i = 1, 2, 3 is an index representing the three groups of workers (those dealing directly with the waste type, others in the same building, and those in other parts of the site).
- N_i = the number of workers in group i (persons)
- F_i = the time fraction of the 24-hour day that the workers in group i are at the location (unitless); normally, the maximum value of F for workers is 1/3 (i.e., 8 hr/24 hr day)
- WAP_i = the degree of protection or hazard reduction provided by design features in the work area for group i , based on the entries below (unitless)
 - $WAP_i = 1$ if there are no engineered protective features (i.e., the release or radiation field would not be diminished by protective features)
 - $WAP_i = 3$ if minimal protection is provided by means of controlled airflows, shielding, etc.
 - $WAP_i = 10$ if substantial protection is provided
 - $WAP_i = 100$ if highly reliable control of airflows, massive shielding, etc. are provided

PPE_i = the degree of protection or hazard reduction provided to group i by personnel protective equipment, based on the entries below (unitless)

PPE_i = 1 if no protective equipment is provided

PPE_i = 3 if protective equipment is not worn but is readily available

PPE_i = 10 if protective equipment is worn.

Note: WAP values > 1 should be used only if the accidents modeled in Elements 3a and 3b do not affect the design features of interest.

The parameter representing the distance of the workers from the waste type is included in the lookup table (Table 5-17) for airborne transport for Element 4. For distances > 100 m, the corresponding values from the Element 4 lookup table should be used. Thus, the value is 1 for a distance of 100 m. No adjustment to the value of Element 5a for distance is needed in such cases. However, the first two groups of workers are generally located < 100 m from the waste type. For distances D that are < 100 m, use the Element 4 value for 100 m then multiply the value of Element 5a by the factor $[100/D(m)]^2$.

The Element 5a _{i} values are then multiplied by the corresponding Element 4 values for the assumed distance to each work group i and summed [see Equations (4-6) and (4-8)].

5.5.1.4 Basis for Values in Lookup Table. Obviously, no simplified approach can accurately represent the effects of potential exposures of workers who labor in a wide variety of facility configurations and operational modes. Because of the impossibility of predicting the exact conditions at the time of a future exposure (e.g., exact locations of workers and evacuation times), even detailed HSRAs such as SARs generally do not evaluate highly specific scenarios for the precise effects on workers. Instead, the consequences are calculated for generic locations such as 100-m downwind.

The approach chosen for Element 5a in the simplified method is to provide simple lookup tables based on the parameters that would largely determine the effects on the workers if those effects were calculated in detail.

For each of the three groups of workers discussed above, five factors were identified that would be expected to determine, to a large measure, the total effects on the workers in a given group:

1. The number of workers, N (persons), in the group
2. The time fraction, F (unitless), of each 24-hr/day that the workers are located at the given work station

3. The distance, D (in m), separating the workers and the waste type (this factor is included in the Element 4 values but must be adjusted if $D < 100$ m)
4. The degree of protection or hazard reduction, WAP (unitless), provided by design features in the work area, such as ventilation systems and shielding walls
5. The degree of protection or hazard reduction, PPE (unitless), such as respirators.

The effects on the workers would be expected to increase linearly as N and F increase. The effects would be expected to decrease as D, WAP, and PPE increase.

Equation (5-4) in Section 5.5.1.3 represents this behavior. For all of the listed factors except distance, a linear or inverse dependence of Element 5a on the factor was used.

The distance factor is included in Element 4. In Equation (5-5), an inverse square relationship was chosen to adjust the value for Element 5a if distance < 100 m. The inverse square relationship applies when calculating (a) many direct radiation exposures and (b) outdoor airborne transport with an intermediate stability class for the dispersion coefficients (EPA 1988). For some indoor accidents in confined spaces with the inhalation exposure mode, however, an inverse cube dependence of dose on distance can be used (e.g., LITCO 1995d). For accidents involving ventilation systems, little dilution may occur as the contaminants move through the ductwork. The inverse-square dependence of Element 5a on distance (for distances < 100 m) was chosen to represent an aggregate over the various types of conditions that might exist.

To summarize, for distances ≥ 100 m, the distance effect has been incorporated in the relative airborne transportabilities in the lookup table values for Element 4 and need not be addressed in Element 5a. For distances < 100 m, the distance factor must be adjusted by multiplying by $(100/D)^2$, where D is in meters.

The WAP factor represents the fractional reduction of the impacts because of work area protective measures that are design features. For example, if a protective design feature is designed to reduce exposures by a factor of 10 in all scenarios, a value of 10 is assigned to the WAP factor in Equation (5-4). Admittedly, assigning values accurately for this factor over a range of scenarios is difficult.

The PPE factor represents the fractional reduction of the impacts because of personal protective equipment. If a respirator worn by the worker reduces inhalation doses by a factor of 10, a value of 10 is assigned to the PPE factor in Equation (5-4). In general, different values for the various factors may apply for each of the three groups of workers.

5.5.2 Element 5b—Public

5.5.2.1 Brief Description of Element. Element 5b represents the presence of the public—how many members of the public are in the vicinity of the site that manages the waste type and how close the public is located.

5.5.2.2 General Approach for Developing Lookup Table. The approach for developing the lookup table for Element 5b, representing the proximity of the public was as follows:

- Start with Equation (5-4) for Element 5a, representing the proximity of the workers
- Revise the equation as necessary to reflect the proximity of the public
- Develop a lookup table for the results of using different values for each factor in Equation (5-4)
- Correlate the instructions with those for the lookup tables for Element 4.

5.5.2.3 Lookup Table—Element 5b. For each public population group j in the vicinity of the waste type operations, a value should be selected for Element 5b. The value is simply the number of people in group j . The Element 5b _{j} values are then multiplied by the corresponding Element 4 _{j} value for the assumed distance to each population group and summed [see Equations (4-6) and (4-8)].

$$\text{Element } 5b_i = N_j$$

where

- i = an index representing the various cities, towns, or rural areas that would be the largest contributors for the effects on the public. In practice, use of only three to five groups of members of the public up to a distance of about 50 mi should provide sufficient accuracy.

5.5.2.4 Basis for Values in Lookup Table. Again, no simplified approach can accurately represent the effects of potential accidents on members of the public who live in a wide variety of cities, towns, and rural areas and have a variety of lifestyles. It is impossible to predict the exact conditions at the time of a future accident (e.g., exact locations of members of the public), even in detailed HSRAs.

The approach chosen for Element 5b is the same as that used for Element 5a but with modifications to represent the situation for the public. Basing Elements 5a and 5b on the same Equation (5-4) helps ensure the consistency and compatibility of the values used for these two subelements. The two subelements are added together in the Equations (4-6) and (4-8).

A simple lookup table was developed based on the main factors that would determine the effects on the public if the effects were calculated in detail.

For the public, the same five factors were considered as for the workers:

- The number of people, N (persons), in the group; in the case of the public, a population group might consist of all of the people who live in a given nearby city or town or rural area or in a given range of distances.
- The time fraction, F (unitless), represents the fraction of each 24-hr/day that the people are at the given location; the public is conservatively assumed to be located at their normal places of residence 24 hr/day, so the value of this factor is 1.
- The distance, D (in meters), separating the public and the waste type; the lookup tables for Element 4 incorporate the distance effect. The public is normally located at least 100 m away from the waste type, so no adjustments to the Element 4 values are expected to be necessary.
- The degree of protection or hazard reduction, WAP (unitless), provided by design features in the work area; for the public there is no protection from design features, so the value of this factor is unity.
- The degree of protection or hazard reduction, PPE (unitless), provided by personnel protective equipment such as respirators; for the public there is no protection from PPE, so the value of this factor is unity.

With the modifications discussed above, Equation (5-4) for Element 5a becomes Equation (5-5) for Element 5b. Only one of the five factors is relevant.

$$\text{Element } 5b_i = N_i \quad (5-5)$$

where

- i = an index representing the various cities, towns, or rural areas that would be the largest contributors for the effects on the public. In practice, use of only three to five groups of members of the public up to a distance of about 50 mi should provide sufficient accuracy.

5.5.3 Recommended Values for Elements $4 \times (5a + 5b)$ —A Time-Saving Measure

As a time-saving measure, recommended values have been calculated for the product of Elements $4 \times (5a + 5b)$. In lieu of calculating values for these products by the method discussed in Sections 5.5.1 and 5.5.2, the user can elect to use the precalculated values given in Tables 5-38 and 5-39. It should be noted that the recommended values have been calibrated to result in person-rem risk results. This was done so the accident results could be added to the normal exposure predictions outlined in Section 7 of this report.

Table 5-38. Lookup table of recommended values for combined element $4 \times (5a + 5b)$.

DOE site ^a	Elements $4 \times 5b^b$	Elements $(4 \times 5a)^{b,c}$	Elements $(4 \times 5a)^{b,d}$	Combined Elements $4 \times (5a + 5b)^{b,d}$
ANL-East	350	10	See Table 5-39	$360 + (4 \times 5a)_{\text{facility}}$
BNL	250	6	See Table 5-39	$256 + (4 \times 5a)_{\text{facility}}$
ETEC	400	0.4	See Table 5-39	$400 + (4 \times 5a)_{\text{facility}}$
FEMP	130	8	See Table 5-39	$138 + (4 \times 5a)_{\text{facility}}$
Hanford	13	1.3	See Table 5-39	$14.3 + (4 \times 5a)_{\text{facility}}$
INEL	5	3	See Table 5-39	$8 + (4 \times 5a)_{\text{facility}}$
KAPL-K	350	13	See Table 5-39	$363 + (4 \times 5a)_{\text{facility}}$
KCP	280	15	See Table 5-39	$295 + (4 \times 5a)_{\text{facility}}$
K-25	35	10	See Table 5-39	$45 + (4 \times 5a)_{\text{facility}}$
LANL	10	6	See Table 5-39	$16 + (4 \times 5a)_{\text{facility}}$
LBL	1,000	13	See Table 5-39	$1013 + (4 \times 5a)_{\text{facility}}$
LLNL	270	30	See Table 5-39	$300 + (4 \times 5a)_{\text{facility}}$
Mound	250	6	See Table 5-39	$256 + (4 \times 5a)_{\text{facility}}$
MSP	830	0	See Table 5-39	$830 + (4 \times 5a)_{\text{facility}}$
NTS	0.5	2	See Table 5-39	$2.5 + (4 \times 5a)_{\text{facility}}$
ORNL	35	12	See Table 5-39	$47 + (4 \times 5a)_{\text{facility}}$
Pantex	9	6	See Table 5-39	$15 + (4 \times 5a)_{\text{facility}}$
PGDP	23	7	See Table 5-39	$30 + (4 \times 5a)_{\text{facility}}$
Pinellas	350	4	See Table 5-39	$354 + (4 \times 5a)_{\text{facility}}$
Portsmouth	27	11	See Table 5-39	$38 + (4 \times 5a)_{\text{facility}}$
RFETS	110	19	See Table 5-39	$129 + (4 \times 5a)_{\text{facility}}$
SNL-NM	320	18	See Table 5-39	$338 + (4 \times 5a)_{\text{facility}}$
SRS	21	3	See Table 5-39	$24 + (4 \times 5a)_{\text{facility}}$
WIPP	3	2	See Table 5-39	$5 + (4 \times 5a)_{\text{facility}}$
WVDP	60	3	See Table 5-39	$63 + (4 \times 5a)_{\text{facility}}$
Y-12	60	25	See Table 5-39	$85 + (4 \times 5a)_{\text{facility}}$

a. ANL—Argonne National Laboratory, BNL—Brookhaven National Laboratory, ETEC—Energy Technology Engineering Center, FEMP—Fernald Environmental Management Project, INEL—Idaho National Engineering Laboratory, KAPL-K—Knolls Atomic Power Laboratory—Kessel ring, KCP—Kansas City Plant, LANL—Los Alamos National Laboratory, LBL—Lawrence Berkeley Laboratory, LLNL—Lawrence Livermore National Laboratory, MSP—Middlesex Sampling Plant, NTS—Nevada Test Station, ORNL—Oak Ridge National Laboratory, PGDP—Paducah Gaseous Diffusion Plant, RFETS—Rocky Flats Environmental Technology Site, SNL-NM—Sandia National Laboratory-New Mexico, SRS—Savannah River Site, WIPP—Waste Isolation Pilot Plant, WVDP—West Valley Demonstration Project.

b. Includes the additional factor of 1/3, to calibrate the SRM risk predictions to person-rem.

c. Includes the factor of 1/3, to account for site personnel being at the site 8 h per day.

d. Values listed are for airborne releases. For groundwater releases, multiply by $(1E-4) T/(K_1 \times R_1)$.

Table 5-39. Lookup table of recommended values for combined Element $(4 \times 5a)_{\text{facility}}$ for airborne releases.

Type of facility or process	Size of facility or process	Number of involved workers ^a	Number of support personnel ^b	Recommended value of Elements $(4 \times 5a)_{\text{facility}}$ ^{c,f}
Berm or trench storage	Small	1 ^c	3	1
	Medium	3 ^c	7	3
	Large	6 ^c	10	6
Storage	Small	3 ^d	6	4
	Medium	6 ^d	14	10
	Large	10 ^d	20	17
Disposal	Small	0	10	1
	Medium	0	30	3
	Large	0	50	6

a. Assumed to be 10 m from contaminant 50% of working hours, unless otherwise indicated. The remaining 50% of working hours are at 100 m.

b. Assumed to be 100 m from contaminant 100% of working hours, unless otherwise indicated.

c. Assumed to be 10 m from contaminant 6.25% of working hours (for inspection).

d. Assumed to be 10 m from contaminant 12.5% of working hours (for inspection).

e. Includes the additional factor of 1/3, to calibrate the SRM risk predictions to person-rem.

f. Includes the factor of 1/3, to account for site personnel being at the site 8 h per day.

5.5.3.1 Lookup Tables – Combined Element 4 × (5a + 5b). The recommended values are subdivided into three contributions:

- Elements 4 × 5b for the public surrounding a given DOE site
- Elements $(4 \times 5a)_{site}$ for DOE site workers not directly associated with the facility being considered
- Elements $(4 \times 5a)_{facility}$ for workers and support personnel directly involved with the storage or disposal facility being considered.

The first two contributions are covered in Table 5-38; the last is covered in Table 5-39.

5.5.3.2 Basis for Values in Lookup Tables. To develop simplified recommendations for the combined Elements 4 × (5a + 5b), the storage or disposal facility was considered to be located approximately at the center of the DOE site. Given the population distribution information for DOE sites presented in ORNL (1995), the combined Elements 4 × 5a site and 4 × 5b were calculated for each site using the models for Elements 4 and 5 discussed previously. The relative air transportabilities from Table 5-17 were used for Element 4. Results are presented in Table 5-40.

The recommended values for 4 × (5a + 5b) listed in Tables 5-38 (and 5-39) are from Table 5-40, but have been divided by three and rounded. The division by three calibrates the risk model results with person-rem. This allows the accident risk results, from Sections 5 and 6 in this report, to be added to the normal, incident-free exposure risks (person-rem for radiological sources) in Section 7 of this report.

In order to calibrate the risk model predictions with person-rem, unit Ci dispersion results (for the public) were compared with SRM predictions for the INEL. If 1.0 Ci of Pu-239 is dispersed into the atmosphere at the INEL, the predicted public exposure is 630 person-rem (DOE, 1995d). The SRM risk result is the following:

$$(1a) (1b) (2a) (2b) (3a + 3b) (4 \times 5b) (6) = \text{SRM risk}$$

$$(1) (129) (1) (1) (1) (15) (1) = 1935 \text{ (no units).}$$

Therefore, if the SRM result is divided by three, the prediction matches the person-rem result. This factor of three division is included in the recommended values for 4 × 5.

For groundwater modeling, the recommended values in Tables 5-38 and 5-39 should be multiplied by the factor:

$$(1E-4) T/(K_d \times R_w),$$

as explained in Section 5.4.4.3.

Table 5-40. Elements 4 x 5a and 4 x 5b for airborne releases at DOE sites.

DOE site ^a	Onsite population	Calculated value for Element 4 x 5a ^b	Offsite population	Calculated value for Element 4 x 5b
ANL-East	5.6E+3	28	7.9E+6	1090
BNL	3.5E+3	18	5.7E+6	750
ETEC	1.3E+2	1.3	1.1E+7	1160
FEMP	2.5E+3	25	2.8E+6	380
Hanford	8.7E+3	4	3.8E+5	38
INEL	8.5E+3	9	1.5E+5	15
KAPL-K	3.9E+3	39	1.3E+6	1100
KCP	4.4E+3	44	1.7E+6	840
K-25	3.8E+3	31	8.7E+5	110
LANL	1.2E+4	18	1.6E+5	32
LBL	3.9E+3	39	5.9E+6	2980
LLNL	9.5E+3	95	6.3E+6	820
Mound	1.7E+3	17	3.0E+6	740
MSP	0	0	1.7E+7	2480
NTS	3.8E+3	7	1.4E+4	1.4
ORNL	3.8E+3	37	8.8E+5	110
Pantex	2.8E+3	17	2.7E+5	28
PGDP	2.0E+3	20	5.0E+5	69
Pinellas	1.2E+3	12	2.5E+6	1080
Portsmouth	3.2E+3	32	6.4E+5	81
RFETS	7.0E+3	58	2.2E+6	320
SNL-NM	1.1E+4	55	6.1E+5	970
SRS	1.6E+4	10	6.2E+5	64
WIPP	7.7E+3	77	9.0E+5	180
WVDP	1.1E+3	6	1.0E+5	10
Y-12	9.6E+2	10	1.7E+6	180

a. ANL—Argonne National Laboratory, BNL—Brookhaven National Laboratory, ETEC—Energy Technology Engineering Center, FEMP—Fernald Environmental Management Project, INEL—Idaho National Engineering Laboratory, KAPL-K—Knolls Atomic Power Laboratory—Kessel ring, KCP—Kansas City Plant, LANL—Los Alamos National Laboratory, LBL—Lawrence Berkeley Laboratory, LLNL—Lawrence Livermore National Laboratory, MSP—Middlesex Sampling Plant, NTS—Nevada Test Station, ORNL—Oak Ridge National Laboratory, PGDP—Paducah Gaseous Diffusion Plant, RFETS—Rocky Flats Environmental Technology Site, SNL-NM—Sandia National Laboratory-New Mexico, SRS—Savannah River Site, WIPP—Waste Isolation Pilot Plant, WVDP—West Valley Demonstration Project.

b. Includes the factor of 1/3, to account for site personnel being at the site 8 h per day.

If the storage or disposal facility to be modeled will be located close to a site boundary, then the recommended values may not be appropriate. Also, the recommended values do not account for evacuation or sheltering of the offsite population.

5.6 Element 6—Length of Time for which Waste Type is in the Rest State

5.6.1 Brief Description of Element

Element 6 is the length of time, in years, for which the waste type is assumed to be in the rest state. The relative risk value is assumed to be linearly proportional to the length of time in the rest state. Other risk elements address phenomena such as radioactive decay and the time-dependent degradation of confinement barriers.

Rest-state durations of 500 years or less are typical for storage states or for interim disposal states. In these cases, the appropriate value of the time in the state is determined in a straightforward manner based on programmatic assumptions.

The last state in the sequence of operations for each waste type, however, is generally a long-term disposal state with no intention of future action. The waste type is left in the rest state for an unlimited period of time.

The question arises as to what maximum time period should be used in Element 6 for long-term disposal states. The use of an unlimited time in the relative risk calculation is not practical mathematically nor is it realistic because of the impossibility of foreseeing conditions many thousands of years into the future. The guidance in the following sections addresses this question.

5.6.2 General Approach for Developing Lookup Table

The general approach for developing the maximum time value to be used for Element 6 in calculating the relative risk of long-term rest states was as follows:

- Examine corresponding times used in detailed HSRAs. Recommended or required values are listed in several bodies of regulation or sets of guidelines, often under the term time of compliance. This term represents the simulated time for which transport models that project future consequences of waste type disposal must be exercised to demonstrate that the disposal system will comply with the regulatory requirements.
- Compare these compliance times and arrive at a recommended maximum value for use in the simplified evaluation of relative risk.

5.6.3 Lookup Table—Element 6

Use the number of years for which the waste type will be in the rest state, up to a recommended maximum value of 1,000 years. The user may select a different maximum value if desired.

5.6.4 Basis for Values in Lookup Table

Much of the following discussion is based on the comparison of long-term compliance times in Wood et al. (1994b). Wood et al. found no scientific basis for selecting any particular time of compliance and, therefore, focused on the regulatory and legal history.

The various types of detailed HSRAs deal with long-term time of compliance in different ways. Safety analysis reports seldom deal with long-term (e.g., > 100 years) risks. Because of the objective of these documents, they focus instead on the near-term risks associated with operations. Even the SARs for disposal facilities generally do not address long-term risk, deferring that topic to other risk assessments. Most EISs and environmental assessments similarly focus on the short-term (< 100 years) impacts.

The detailed HSRAs that most commonly deal with long-term risk are called performance assessments. For both DOE and commercial disposal of LLW, performance assessments must demonstrate that the proposed long-term confinement will limit doses to potential future receptors to values below the limits specified in regulations. Performance assessments are also required to demonstrate the future performance of repositories such as those for disposing of SNF, HLW, and TRU waste. Different bodies of regulation with different requirements govern each type of long-term disposal.

The NRC standards for a repository for HLW and SNF are found in 10 CFR 60. Confinement of the waste type must be substantially complete for a period of 300 to 1,000 years. No specific time of long-term compliance is given, but the following requirement provides insight:

The release rate of any radionuclide from the engineered barrier system following the confinement period shall not exceed one part in 100,000 per year of the inventory of that radionuclide calculated to be present at 1,000 years ...

Thus, the risk is not stated in terms of a cumulative risk over a long time period, but rather in terms of one factor (the release rate) related to the annual risk.

The EPA standards for a repository for SNF, HLW, or TRU waste are found in 40 CFR 191. The time of compliance is 10,000 years.

The NRC standards for commercial disposal of LLW are found in 10 CFR 61. No time of compliance is specified, although there is a requirement to protect against intrusion for at least 500 years for Class C LLW.

The DOE standards for LLW disposal are found in DOE Order 5820.2A. No time of compliance is given. Wood et al. (1994b) recommends that 10,000 years be used as the time of compliance in DOE performance assessments for LLW disposal.

The EPA standards for mill tailings are in 40 CFR 192. The time of compliance is 1,000 years.

The EPA standards for no-migration petitions in connection with hazardous waste injection are given in 40 CFR 148. The time of compliance is 10,000 years.

The other type of detailed HSRA that often deals with long-term time compliance is the risk assessments prepared under CERCLA. The guidance manual (EPA 1989) for BRAs under CERCLA gives no standard for the time to be covered. The times are established case-by-case. In the BRA for the INEL Radioactive Waste Management Complex Subsurface Disposal Area, the plan is to evaluate the risk over a period of 10,000 years. The risks projected in a BRA are the risks to a single individual of various lifestyle categories (e.g., residential or industrial) over the person's lifetime, not the cumulative risk to all persons over the entire time that the waste poses a hazard.

The conclusions drawn from the above regulatory sources and practices are as follows:

- Some types of detailed HSRAs deal only with short-term risks and do not address a long-term time of compliance.
- Most of the regulatory sources specify a time period of 10,000 years. The time is limited by the ability to project future conditions with some degree of confidence, rather than by the duration of the toxicity of the waste type. (Many of the actinides remain highly toxic for hundreds of thousands of years or more.)
- Some regulatory sources specify compliance times of 500 or 1,000 years.

An upper-limit time of compliance of 10,000 years appears to be the consensus from the regulatory sources. If desired, that maximum value can be used in the simplified method to calculate relative risks of long-term disposal. However, an upper-limit time of 1,000 years is recommended for normal use of the method on all waste types because

- Calculated disposal risks may be unjustifiably increased relative to calculated treatment and shipping risks if excessive times of compliance are used. For example, if the time of compliance is increased by a factor of 10 to 10,000 years, the calculated relative risk of disposal will increase by a factor of almost 10 because the activity of the actinides decreases extremely slowly. Another factor of 10 increase in the time to 100,000 years would again increase the calculated disposal risk by almost a factor of 10. These calculated increases in risk may bias the overall analysis toward (excessively) large risks associated with long-term disposal. In turn, this may bias the analysis in favor of performing additional waste treatment to reduce the artificially inflated long-term disposal risk. To be conservative and avoid potential overemphasis on enhanced waste treatment for the reduction of long-term disposal risk, the smaller value of 1,000 years is recommended for time of compliance.
- The longer the time of compliance, the more uncertain the results for relative risk because of unpredictable conditions at times many thousands of years into the future.

6. HOW TO ESTIMATE THE RISK OF A TRANSITION STATE— LOOKUP TABLES

This section explains how to select the most appropriate value of each risk element for transition states in Equation (4-3). Sections 6.1 through 6.5 either (a) provide a lookup table for each risk element and discuss the bases for the values or (b) refer the user back to the identical lookup table for the same risk element for rest states in Section 5.

6.1 Element 1—Waste Characteristics

Elements 1a, contaminant quantities, and 1b, specific toxicity, are identical for transition states and rest states. The lookup tables in Section 5.1 should be used.

6.2 Element 2—Susceptibility of Contaminants to Movement

6.2.1 Element 2a—Mobility of Waste Form

Element 2a, the mobility of the waste form, is identical for transition states and rest states.

Transition states generally are subject only to airborne releases. Exceptions, such as an accidental release during waste shipment while passing over or beside a body of water, are rare. Therefore, the mobility values for transition states should normally be taken from the airborne column of the Element 2a lookup table.

If the transition state changes the characteristics of the waste, the value chosen for Element 2a should represent the waste form that exists *during* the transition process. For example, if a transition state involves solidifying a slurry, the waste form during most of the treatment steps is the slurry, not the solidified waste form.

6.2.2 Element 2b—Confinement Capability

Element 2b, confinement capability, is identical for transition (nontransportation) states and rest states. For transportation, additional guidance is needed. The lookup values in Table 6-1 should be used.

For transportation accidents, elements 2a, 2b, and 3b are closely interrelated. Typical accident modeling of transportation accidents involves eight categories of severity, ranging from I (least severe) to VIII (most severe). Respirable release fraction results for transportation of TRU waste in Type B TRUPACT-II or NuPac 72B containers are presented in Table 6-2. Given a truck accident, the total respirable release fraction for all eight accident categories is $4.6E-7$. Assuming $2a = 1.0E-3$ for most TRU waste, element 2b must equal $4.6E-4$ in order for the product $2a \times 2b$ to represent the total respirable release fraction. Rounding off, $5E-4$ is recommended for element 2b for TRU waste transportation using Type B containers.

Table 6-1. Lookup table for Element 2b.

Type of facility or process	Confinement	Value
Transition (non-transportation)	No engineered confinement or flimsy engineered barriers (e.g., cardboard boxes) or severely degraded engineered barriers (e.g., badly rusted drums)	1
	Single engineered barrier in good condition ^a	1E-1 ^a
	Two engineered barriers in good condition ^a	1E-2 ^a
	Three engineered barriers in good condition ^a	3E-3 ^a
Transportation	Type B (TRUPACT-II or NuPac 72B, assumes 2a = 1E-3)	5E-4
	Type B (vitrified HLW, assumes 2a = 1E-5)	1
	Type A (assumes 2a = 1E-3)	1
	SNF shipping cask (assumes 2a = 1E-5)	1E-1

a. Additional credit (reduction by a factor of 3 to 10) can be taken if the barrier is massive.

Similarly, Table 6-2 presents the results for transportation of vitrified HLW in Type B containers. The total respirable release fraction is 6.3E-5. Assuming 2a = 1.0E-5 for vitrified HLW, 2b is then 6.3. However, 2a cannot physically be greater than 1.0, so 2b = 1.0 is assumed.

For transportation of waste in Type A containers, Table 6-2 indicates a total respirable release fraction of 3.1E-3 to 3.1E-4. Again assuming 2a = 1E-3, then 2b ranges from 3.1 to 0.31. Because 2b cannot be greater than 1.0, 2b = 1.0 is assumed.

Finally, for transportation of SNF in shipping casks, DOE (1995b) lists release fractions of 1E-3 to 1E-9 (assuming a respirable fraction of 1E-1 to 1E-2), depending on the radionuclide. Using an average of 1E-6 and assuming 2a = 1E-5, then 2b = 1E-1.

6.3 Element 3—Severity and Likelihood of Challenges to Contaminant Confinement

For Element 3a, the transition state lookup table for environmental challenges to confinement is almost identical to the corresponding table for rest states.

For Element 3b, operational challenges to confinement, the approach to develop the lookup table is almost identical to that for rest states. Additional challenges to confinement are nuclear criticality events, transportation accidents, and handling accidents.

Table 6-2. Transportation accident effective release fractions.

Truck accident category	Type B container (TRU)			Type B container (Vitrified HLW)			Type A container		
	Category fractional occurrence ^a	Respirable release fraction ^a	Product of fractional occurrence and release fraction	Respirable release fraction ^b	Product of fractional occurrence and release fraction	Respirable release fraction ^c	Product of fractional occurrence and release fraction	Respirable release fraction ^c	Product of fractional occurrence and release fraction
I	5.5E-1	0	0	0	0	0	0	0	0
II	3.6E-1	0	0	0	0	1E-3 to 1E-4	3.6E-4 to 3.6E-5	1E-3 to 1E-4	3.6E-4 to 3.6E-5
III	7.0E-2	8E-9	5.6E-10	1E-4	7.0E-6	1E-2 to 1E-3	7.0E-4 to 7.0E-5	1E-2 to 1E-3	7.0E-4 to 7.0E-5
IV	1.6E-2	2E-7	3.2E-9	1E-3	1.6E-5	1E-1 to 1E-2	1.6E-3 to 1.6E-4	1E-1 to 1E-2	1.6E-3 to 1.6E-4
V	2.8E-3	8E-5	2.2E-7	1E-2	2.8E-5	1E-1 to 1E-2	2.8E-4 to 2.8E-5	1E-1 to 1E-2	2.8E-4 to 2.8E-5
VI	1.1E-3	2E-4	2.2E-7	1E-2	1.1E-5	1E-1 to 1E-2	1.1E-4 to 1.1E-5	1E-1 to 1E-2	1.1E-4 to 1.1E-5
VII	8.5E-5	2E-4	1.7E-8	1E-2	8.5E-7	1E-1 to 1E-2	8.5E-6 to 8.5E-7	1E-1 to 1E-2	8.5E-6 to 8.5E-7
VIII	1.5E-5	2E-4	3.0E-9	1E-2	1.5E-7	1E-1 to 1E-2	1.5E-6 to 1.5E-7	1E-1 to 1E-2	1.5E-6 to 1.5E-7
Total =	1.0	Total =	4.6E-7	Total =	6.3E-5	Total =	3.1E-3 to 3.1E-4	Total =	3.1E-3 to 3.1E-4

a. Source is DOE (1995d).

b. Source is DOE (1995d), multiplied by 1E-2 for respirable fraction.

c. Source is DOE (1995d), multiplied by 1E-1 to 1E-2 for respirable fraction.

6.3.1 Element 3a—Confinement Challenges from Environmental Events

The NPH challenges to confinement for transition states and the resulting lookup table values are similar to those developed for surface structures in Section 5.3.2. The lookup table for environmental challenges to confinement for nonshipping transition states is Table 6-3.

For shipping states, the value of Element 3a is zero.

6.3.2 Element 3b—Confinement Challenges from Operational Events

6.3.2.1 General Approach for Developing Lookup Tables. For transition states, the major operational challenges to contaminant confinement are generally criticalities, fires, explosions, material handling accidents (including crane accidents), and transportation accidents. The following sections develop the frequency-severity values for these challenges to contaminant confinement.

Table 6-3. Element 3a lookup table—environmental challenges to confinement (nonshipping states).

NPH event	Frequency (1/yr)	Severity	Frequency-severity value: Element 3a ^{a,b}	Selection criteria
Seismic (beyond design basis)	1E-4	High	1E-4	Facility not meeting NPH design criteria
	1E-4	Moderate	1E-5	Modern PC 2 (Hazard Category 3) facility or process
	1E-4	Low	1E-6	Modern PC 3 (Hazard Category 2) facility or process
Strong wind/tornado (beyond design basis)	1E-4	High	1E-4	Facility not meeting NPH design criteria
	1E-4	Moderate	1E-5	PC 2 (Hazard Category 3) facility or process
	1E-4	Low	1E-6	PC 3 (Hazard Category 2) facility or process
Flood (beyond design basis)	1E-4	Moderate	1E-5	Facility not meeting NPH design criteria
	1E-4	Low	1E-6	PC 2 (Hazard Category 3) facility or process
	1E-4	Negligible	1E-7	PC 3 (Hazard Category 2) facility or process

a. The total for Element 3a is the sum of the frequency-severity values from seismic events, strong winds and tornadoes, and floods, as applicable.

b. The frequency-severity values have been transformed to unitless values by assuming each transition state lasts 1 year. This transformation is appropriate because the risk from each transition state is based on the entire inventory to be processed during the transition state. See Section A-5 of Appendix A for a more detailed discussion of this transformation of units.

6.3.2.2 Lookup Tables. Table 6-4 lists the frequency-severity values for Element 3b for nonshipping transition states. To use Table 6-4, determine the operational confinement challenges that apply to the subject operation. Sum the frequency-severity values for each applicable type of challenge. Then use this aggregated value for Element 3b for the transition state.

Table 6-5 lists the frequency-severity values for Element 3b for shipping states.

6.3.2.3 Bases for Values in Lookup Table. The following sections describe the bases for the relative values of Element 3b for transition states.

6.3.2.3.1 Criticality—To determine appropriate criticality frequencies for DOE facilities and processes, several DOE EISs (DOE 1995b,d) and SARs (LITCO 1995d,e,f) were reviewed. DOE (1995b) indicates a criticality frequency range of 1E-3/yr to 5E-7/yr for various INEL SNF facilities. DOE (1995d) discusses criticalities for WM facilities and processes and concludes that, in most cases, the frequency would be less than 1E-6/yr. Finally, the SARs indicate a range of criticality frequencies of 1E-5/yr to less than 1E-6/yr. Factors influencing the criticality frequency are the following: amount of fissile material present, frequency of activities that could result in a criticality, degree of difficulty in controlling processes that could result in criticalities, and the types and numbers of barriers preventing a criticality.

Based on the above information, a base case criticality frequency of 1E-5/yr was chosen. This frequency is increased to 1E-3/yr for cases in which the barriers are ineffective, the process is difficult to control, or there is a large potential for criticality. If there is very little potential for criticality or there are effective passive barriers, then the frequency is 1E-7/yr. These frequencies are summarized in Table 6-4.

The severity of a criticality event is conceptually different from the severity of other types of events. Typically, the severity refers to the fraction of the radionuclide inventory that may be affected by the accident in question. That fraction of the inventory is then dispersed through the atmosphere or transported by groundwater to receptors. However, a criticality results in an extremely large but highly localized radiation field that can affect nearby workers. Effects on other workers and the public are typically very small. To preserve the potentially large impact on nearby workers, an intermediate severity level of Moderate is used for criticality accidents.

6.3.2.3.2 Fires—The fire frequency range discussed for rest states in Section 5.3.3 is appropriate for transition states. However, transition states have additional factors affecting the fire frequency: the existence of high-temperature or high-pressure processes, the existence of welding or torch cutting processes, and the type of process and waste form. A base frequency for an unmitigated fire is 1E-3/yr. This value is increased to 1E-2/yr for energetic processes such as incineration or torch cutting processes. For benign processes or waste forms that are difficult to combust, the frequency is 1E-4/yr. These frequencies are summarized in Table 6-4. Similarly to rest states, the severity level of unmitigated fires is assumed to be Moderate.

Table 6-4. Element 3b lookup table—operational challenges to confinement: nonshipping states.

Operational event	Frequency (1/yr) ^a	Severity	Frequency-severity value-Element 3b ^{b,c}	Selection criteria
Criticality	1E-3	Moderate	1E-4	Large potential for criticality (frequent activities or large amounts of material); process difficult to control; or ineffective barriers
	1E-5	Moderate	1E-6	Potential for criticality; process easy to control; or effective administrative barriers
	1E-7	Moderate	1E-8	Little potential for criticality (infrequent activities or small amounts of material); or effective passive barriers
Fire (unmitigated)	1E-2	Moderate	1E-3	Energetic process (high temperature and/or pressure) such as incineration or welding/torch cutting; large amount of combustibles and inadequate fire suppression; retrieval of poorly characterized waste that could contain flammables or pyrophorics
	1E-3	Moderate	1E-4	Moderately energetic process such as thermal desorption; moderate amounts of combustibles and adequate fire suppression
	1E-4	Moderate	1E-5	Benign process such as grouting or cementation; waste form difficult to combust
Facility/process explosion	1E-2	Moderate	1E-3	Energetic process such as rotary kiln incinerator
	1E-4	Moderate	1E-5	Moderately energetic process such as thermal desorption with natural gas or fuel sources present
	1E-6	Moderate	1E-7	Benign process such as grouting or cementation with no natural gas or fuel sources present
Container explosion	1E-2	Low	1E-4	Poorly characterized waste in unvented containers; retrieval of poorly characterized waste
	1E-4	Low	1E-6	Waste in vented containers; movement of waste in vented containers
Handling accident (forklift/crane)	1	Negligible	1E-3	Movement of waste containers under suboptimal conditions (unwieldy containers, uneven ground, poor visibility, etc.)
	1E-1	Negligible	1E-4	Movement of waste containers under optimal conditions (standardized waste containers, cement floor, good weather/visibility, spotter present)

a. For operations that involve technologies that are not proven in full-scale applications, increase the frequency and the frequency-severity by a factor of 3, based on limited data in Thomas (1981)

b. The total for Element 3b is the sum of the frequency-severity values from criticality, fire, facility and process explosion, container explosion, and handling accident, as applicable.

c. The frequency-severity values have been transformed to unitless values by assuming each transition state lasts 1 year. This transformation is appropriate because the risk from each transition state is based on the entire inventory to be processed during the transition state in question. See Appendix A for a more detailed discussion of this unit's transformation.

Table 6-5. Element 3b lookup table—frequency-severity values for operational challenges to confinement: shipping states.

Truck shipment	$4E-7 \times \text{route length}^a$
Rail shipment	$1E-7 \times \text{route length}$

a. The route length is the one-way travel distance in miles.

6.3.2.3.3 Facility and Process Explosions—Facility and process explosion frequencies were estimated by reviewing two DOE EISs (DOE 1995b,d). DOE (1995d) lists an explosion frequency of $1.5E-2/\text{yr}$ for rotary kiln incinerators. Other types of processes have significantly lower explosion frequencies. DOE (1995b) lists explosion frequencies ranging from $2E-4/\text{yr}$ to $3E-6/\text{yr}$ for various INEL WM and ER facilities and processes. Factors affecting the explosion frequency include the type of process and the presence of natural gas or fuel lines or tanks.

A base frequency is $1E-4/\text{yr}$ is used for typical processes with natural gas or fuel sources present. For very energetic processes, such as rotary kiln incinerators, a frequency of $1E-2/\text{yr}$ is used. For benign processes with little or no natural gas or fuel sources, the frequency is $1E-6/\text{yr}$. The severity of an explosion is assumed to be Moderate, as was assumed for rest states. These results for facility and process explosions are summarized in Table 6-4.

6.3.2.3.4 Container Explosions—The information presented in Section 5.3.3.4.3 for waste container explosions for rest states is applicable for transition states. The results are summarized in Table 6-4.

6.3.2.3.5 Handling Accidents—Handling accidents include forklift and crane drops of waste containers, vehicle impacts against waste containers, and other types of handling drops and impacts. DOE (1995d) lists a range of frequencies of $1/\text{yr}$ to $2E-2/\text{yr}$ for such accidents for WM facilities and processes. DOE (1995b) lists a frequency of $1E-2/\text{yr}$ for a SNF handling accident. Two container breach incidents have occurred during waste handling for storage at the INEL Radioactive Management Complex in an operational period of 25 years. The annual rate is $8E-02/\text{yr}$ (LITCO 1995d).

Based on the above information, two frequencies for handling accidents are used. For handling of waste under suboptimal conditions (e.g., unwieldy containers, uneven ground, and poor visibility), a frequency of $1E-1/\text{yr}$ is used. For handling of waste under optimal conditions (e.g., standardized containers, spotter present, and good visibility), a frequency of $1E-1/\text{yr}$ is used.

Handling accidents typically affect only one or several waste containers. Therefore, a severity level of Negligible is assumed.

The results for handling accidents are summarized in Table 6-4.

6.3.2.3.6 Transportation Events—DOE waste shipments are usually made by truck or rail. The risks associated with both shipping modes are reviewed in this section to develop the relative frequency-severity values in the Element 3b lookup table.

Background and Approach—The risks associated with shipping a waste type include risk to the workers (transportation crews) and the public from accidents and incident-free shipments (normal external radiation dose). The detailed evaluation of these risks is highly complex and beyond the scope of this simplified method. For example, in detailed risk evaluations, shipping accidents are typically divided into eight categories of uniformly increasing severity based on the fire duration and either the crush force or the impact speed associated with the accident. Each category of accident occurs with different frequencies and consequences and is evaluated separately.

For the SRM, Elements 2a and 2b have been defined for transportation to model the total or effective respirable release fraction for all eight accident categories. Therefore, 3b for transportation should represent the frequency of all types of accidents covered in the eight accident categories. DOE (1995d) lists an average truck accident rate of $3.9E-7/mi$ and $9.0E-8/mi$ for railcar accidents. These values were rounded to $4.0E-7/mi$ and $1.0E-7/mi$, as shown in Table 6-5.

6.4 Element 4—Environmental Transport Effectiveness

The relative transportability values of the airborne pathway for transient states are identical to those for rest states in lookup Table 5-17. The groundwater pathway is generally not applicable for transition states.

As was done in Section 5.5.3 for rest states, recommended values for the combined Elements $4 \times (5a + 5b)$ for airborne transport for transition states are presented in Section 6.5.5.

6.5 Element 5—Presence of Human Receptors

Most transition states involve activities that take place in facilities, even if the facility is in the open air. For facility-based transition states, Elements 5a and 5b, the proximity of the workers and the public to the waste is the same as for rest states, except as described in Sections 6.5.1 through 6.5.5.

See Sections 6.5.1 and 6.5.2 for values of Elements 5a and 5b for nonshipment transition states.

For transition states that involve waste shipment, the methods described in Sections 6.5.3 and 6.5.4 are used to calculate the value of Elements 5a and 5b. The method is a modification of that used for rest states, discussed in Section 5.5. For shipment activities, one difference between the methods is that the workers are generally transportation personnel such as truck drivers and train brakemen. For offsite shipment, another difference is that members of the public are located along a fixed route that extends many miles in length, rather being located at fixed distances away from a fixed facility.

Section 6.5.5 includes recommended values for the combined Elements $4 \times (5a + 5b)$ for airborne transport for transition states. The recommended values can be used as a time-saving measure.

The industrial hazards associated with shipping are addressed in Section 10. The risks evaluated in Section 10 include those associated with shipping accidents in which no release of contaminants occurs.

6.5.1 Element 5a for Nonshipment Transition States—Workers

For nonshipment transition states, the value of Element 5a is determined by the same method used for rest states (see Section 5.5.1.3).

6.5.2 Element 5b for Nonshipment Transition States—Public

For nonshipment transition states, the value of Element 5b is determined by the same method used for rest states (see Section 5.5.2.3).

6.5.3 Element 5a for Shipment—Workers

6.5.3.1 Brief Description of Element. This element represents the same basic parameters as the corresponding element for a rest state or a facility-based transition state.

6.5.3.2 General Approach for Developing Lookup Table. The approach is nearly identical to that for rest states and facility-based transition states. The same equation is used, but the factors in the equation are selected based on the route used for the onsite transfer or the offsite shipment. The only exposure routes to the workers are assumed to be direct radiation and inhalation.

6.5.3.3 Lookup Table. The value of Element 5a for each group of workers is determined from Equation (5-4), which is presented in Section 5.5.1.3.

$$\text{Element } 5a_i = \frac{N_i \times F_i}{WAP_i \times PPE_i} \quad (6-1)$$

The recommended values for calculating the product of Element 4 and Element 5a for generic offsite shipment are as follows:

- $i = 1$ (transportation crew is only worker group)
- $N = 3$ people in crew
- $F = 1$ (assuming multiple crews operate the transport vehicle 24 hr/day)
- $PPE = WAP = 1$.

If the crew is located at a distance of 100 m during the accident exposure, the value of Element 4 is 1 (see Table 5-18). This produces a value of 3 for the product of Element 4 and Element 5a.

6.5.3.4 Basis for Values in Lookup Table. The basis for the values in the lookup is essentially the same as those for the rest states and nonshipment transition states. Insights gained from existing, in-depth studies of shipping risks have been added.

6.5.4 Element 5b for Shipment—Public

6.5.4.1 Brief Description of Element. This element represents the same basic parameters as the corresponding element for a rest state or a facility-based transition state.

6.5.4.2 General Approach for Developing Lookup Table. For onsite transfer, the approach is nearly identical to that for rest states and facility-based transition states. The same equation is used. For onsite transfer, the distance factor in Element 4 is selected based on the nature of the transfer route.

For offsite shipment, the approach is similar, but the fact that the shipping route passes through areas of varying population density needs to be included and has been addressed below.

6.5.4.3 Lookup Table. For each public population group k along the shipping route, a value should be selected for Element 5b _{k} for use in Equation (4-6). The value is simply the number of people in group k .

The recommended value for the product of Elements 4 and 5b for generic offsite shipment by truck or rail is 200.

For risk calculations that focus on specific shipping routes, route-specific values can be developed. The same method described for developing the generic values should be used.

6.5.4.4 Basis for Values in Lookup Table. For onsite transfer, the basis for the values in the lookup table is essentially the same as that for the rest states and nonshipment transition states.

To simplify the calculation of $\sum_k (V_{4_k} \times V_{5b_k})$ for offsite shipping routes, Table 6-6 was used.

For offsite shipment, the basis for the values representing the proximity of the public is as follows. Risk assessments of offsite shipping typically divide the route into three types of population density areas: (1) urban areas, (2) suburban areas, and (3) rural areas. Every route has different percentages of the mileage in the three types of areas. DOE (1995b) presents the percentage of the three types of areas along several hundred potential routes for shipping SNF. The average percentage breakdown is approximately 3% urban, 17% suburban, and 80% rural. Those values were used in developing values for this report as an average for all offsite waste shipments. For specific routes, case-by-case values can be calculated.