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SAND86—2994 • DOE/HWP—26 • UC—69
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Printed May 1988

SRS: Site Ranking System for Hazardous Chemical and Radioactive Waste

Rob P. Rechard, Margaret S. Y. Chu, Stephen L. Brown

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

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SF2900Q(8-81)

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A13
Microfiche copy: A01

SAND86-2994
DOE/HWP-26
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Prepared March 1987
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Sponsored by the
U.S. DOE Hazardous Waste Remedial Actions Program
through the
Support Contractor Office
Oak Ridge, Tennessee 37831
operated by
Martin Marietta Energy Systems, Inc.

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*ENVIRON Corporation, Washington, DC

PREVIOUS DOCUMENT IN SERIES

Chu, M. S. Y., J. V. Rodricks, C. St. Hilaire, and R. L. Bras, 1986. Risk assessment and ranking methodologies for hazardous chemical defense waste: A state-of-the-art review and evaluation, Task 1 Report, SAND86-0530, Sandia National Laboratories, Albuquerque, NM 87185.

ACKNOWLEDGEMENTS

We appreciate the time and suggestions supplied by the technical reviewers: R. L. Hunter, R. M. Ostmeyer, and D. Tomasko of Sandia National Laboratories and J. Vandevan of ENVIRON Corporation. In addition, we acknowledge the help of C. St. Hilaire of Risk Science Institute, J. V. Rodricks of ENVIRON, P. A. Rechard of Western Water Consultants, and J. C. Helton of Arizona State University in the early stages of this report. Development of SRS was funded by the Hazardous Waste Remedial Action Program (HAZWRAP) of the Department of Energy (DOE). We thank H. F. Bauman and J. Petty of Martin Marietta Energy Systems, Inc, Oak Ridge, TN for their managerial support.

ABSTRACT

This report describes the rationale and presents instructions for a site ranking system (SRS). SRS ranks hazardous chemical and radioactive waste sites by scoring important and readily available factors that influence risk to human health. Using SRS, sites can be ranked for purposes of detailed site investigations. SRS evaluates the relative risk as a combination of potentially exposed population, chemical toxicity, and potential exposure of release from a waste site; hence, SRS uses the same concepts found in a detailed assessment of health risk. Basing SRS on the concepts of risk assessment tends to reduce the distortion of results found in other ranking schemes. More importantly, a clear logic helps ensure the successful application of the ranking procedure and increases its versatility when modifications are necessary for unique situations. Although one can rank sites using a detailed risk assessment, it is potentially costly because of data and resources required. SRS is an efficient approach to provide an order-of-magnitude ranking, requiring only readily available data (often only descriptive) and hand calculations. Worksheets are included to make the system easier to understand and use.

CONTENTS

		Page
1.	SUMMARY	13
2.	INTRODUCTION	19
	Organization of Report	19
	Using this Report	19
	Objective of SRS	20
	Background on DOE Hazardous Waste Program	21
	Relationship of SRS to Risk Assessment and Risk Management	22
	Juxtaposition of SRS to other Waste Site Decisions	24
	SNLA Proposed Risk Methodology	27
	Review of Ranking Methods	30
	Incidents from Waste Disposal Sites	35
3.	GENERAL ASPECTS OF SRS	37
	Overview of SRS	37
	Principles Guiding Development of SRS	40
	Scoring Concept of SRS	42
	Scoring Individual Factors	45
	Sensitivity/Uncertainty Analysis	47
	Sensitivity of Variables in SRS	48
	Uncertainty Analysis in SRS	50
	Using Monitoring Data	53
	Summary of SRS Assumptions	54
4.	POPULATION AND TOXICITY SCORES	55
	Population	55
	Chronic Toxicity	56
5.	GROUND-WATER SCORE	61
	Idealized Ground-Water Pathway	61
	Method of Scoring	62
	Derivation of Scoring Model	64
	Model Equation	73
	Model Sensitivity	75
6.	SURFACE-WATER SCORE	78
	Idealized Surface-Water Pathway	78
	Method of Scoring	79
	Derivation of Scoring Model	82
7.	AIR SCORE	88
	Idealized Air Pathway	88
	Method of Scoring	88
	Derivation of Scoring Model	91

CONTENTS (continued)

Page

8. SITE RANKING SYSTEM (SRS) INSTRUCTIONS 99

Conventions Observed in the Instructions 99
Overview of SRS. 99
General Scoring Guidelines 102
Site Ranking Procedure 102

Step 1: Collect data on waste properties 104
Step 2: Score and rank chemicals found at site 105
Step 3: Describe release pathways. 111
Step 4: Evaluate engineered features 115
Step 5: Identify target populations. 119
Step 6: Score site factors 121

Step 6.G1: Score ground-water dilution. 122
Step 6.G2: Score ground-water mass adjustment 129
Step 6.S1: Calculate dilution for surface water . . . 134
Step 6.S2: Score surface-water mass adjustment. . . . 138
Step 6.S3: Score surface-water sediment yield 141
Step 6.A1: Assume mass-release adjustment 146
Step 6.A2: Calculate mass-release adjustment. 147

Step 7: Combine chemical scores. 151
Step 8: Construct ranked list of waste sites 152

9. COMPARISON OF SRS WITH OTHER ASSESSMENT SCHEMES. 153

Three Hypothetical Sites Contaminating Ground Water. 153
Hypothetical Site Affecting Air Quality. 160
Comparison of SRS with EPA Rapid Assessment Technique. 162

10. APPENDIX A--SRS Worksheets 169

11. APPENDIX B--SRS Applied to a Superfund Site. 189

12. APPENDIX C--Chemical Properties of Waste 231

13. APPENDIX D--Data Required. 273

14. APPENDIX E--Nomenclature 279

15. REFERENCES 287

ILLUSTRATIONS

Figure		Page
2.1	Juxtaposition of SRS ranking with other waste site decisions	25
2.2	SNLA's modular method of assessing risks from hazardous waste disposal	28
2.3	Potential contaminant movement that could be important to simulate in consequence modeling	29
3.1	The three simplified pathways examined in SRS	38
3.2	Diagram of SRS Procedure	39
5.1	Conceptual model for ground-water pathway	62
5.2	Variation of dispersivity with distance	71
6.1	Conceptual model for surface-water pathway	79
7.1	Conceptual model for air pathway	89
8.1	General pathways examined in SRS	101
8.2	Diagram of SRS procedure	103
8.3	Conceptual model and definition of terms for ground-water pathway	113
8.4	Conceptual model and definition of terms for surface-water pathway	114
8.5	Conceptual model and definition of terms for air pathway	114
8.6	Mean annual rainfall in United States	126
8.7	Mean annual rainfall-erosivity factor in United States	144
8.8	Length-slope topographic factor	145
8.9	Map of PE index for United States	150
8.10	Juxtaposition of SRS ranking with other waste site decisions	152

TABLES

Table		Page
2.1	Pathway by which industrial disposal sites caused environmental hazard	36
4.1	Target population scores	55
4.2	Chemical/radionuclide chronic toxicity	60
5.1	Dispersivities reported in the literature	73
5.2	Influence of variables as represented by power [b_i] in ground-water equation	77
8.1	Scores for waste quantity	108
8.2	Volumes of common waste containers	108
8.3	Chemical/radionuclide chronic toxicity	109
8.4	Scores for source decay	109
8.5	Qualitative descriptions of decay rates	110
8.6	Scores for solubility	110
8.7	Waste placement scores for all routes	116
8.8	Leachate reduction for ground-water route	117
8.9	Leachate collection system for ground-water route	117
8.10	Protection of waste from surface runoff	118
8.11	Target-population scores	119
8.12	Score for distance to population for ground-water route	120
8.13	Score for distance to population for air route	120
8.14	Fraction of precipitation percolating into waste	124
8.15	Hydraulic conductivity for various rock types	125
8.16	Range of porosity for various rock types	125
8.17	Scores for aquifer fluid velocity in pores	127
8.18	Scores for aquifer thickness	127
8.19	Ground-water route dilution scores	128

TABLES (continued)

Table		Page
8.20	Mass-release adjustment scores for ground-water route	130
8.21	Scores for retardation in ground-water	133
8.22	Fraction of organic matter of soil in several areas of the United States	133
8.23	Definition of SCS hydrologic soil groups	136
8.24	Scores for runoff	136
8.25	Surface-water route	136
8.26	Runoff curve numbers for selected agricultural, suburban, and urban land use	137
8.27	Mass-release adjustment for surface-water route	139
8.28	Scores for runoff dissolution	140
8.29	Control-practice factor [CP] for pasture, rangeland, and woodland	142
8.30	Sediment yield from drainage area of 100 mi^2 ($2.6x10^8$ m^2) or less in the United States	143
8.31	Scores for surface-water sediment yield	143
8.32	Mass-release adjustment of air route	149
9.1	Data general to three hypothetical sites	154
9.2	Data specific to site 3	155
9.3	SRS chemical score for sites 1, 2, and 3	156
9.4	Scores unaffected by chemical type at three sites	157
9.5	Ground-water scores for sites 1, 2, and 3	158
9.6	Relative health risks as scored by SRS, RAPS, HRS, and mHRS	159
9.7	SRS chemical score for PCB site	161
9.8	Scoring of PCB site	161
9.9	Comparison of SRS with rapid assessment technique for air pathway	162
9.10	Data for CCl_4 site	163

TABLES (continued)

Table		Page
9.11	SRS chemical score for CCl_4 site	164
9.12	Scores for CCl_4 site unaffected by chemical type	165
9.13	Ground-water scores for CCl_4 site	166
9.14	Comparison of SRS with rapid assessment technique for ground-water pathway	167
C.1	UCR toxicity data for radionuclides	239
C.2	Physical, chemical, and fate data for hazardous wastes	241
C.3	Half-lives of waste in various media	247
C.4	ADI toxicity data for noncarcinogens	253
C.5	UCR toxicity data for chemical carcinogens	261
C.6	EPA categories for potential carcinogens	263
C.7	Estimated carcinogenic potency factors (CPFs)	264

1. SUMMARY

Purpose of SRS

The site ranking system (SRS) is a method for ranking waste sites containing hazardous chemicals and radionuclides using readily available site data. SRS ranks each individual site by scoring factors that influence the human health risk. Using SRS, one can group waste sites into those that need more detailed study of risk for remedial action and those that do not. In addition, one finds the approximate order to begin investigating sites for detailed risk assessments, remedial investigations (RI), and feasibility studies (FS). In short,

- The purpose of SRS is to rank hazardous waste sites according to the relative human health risk they pose. Combining this technical ranking with other risk management criteria, a manager can decide on the best order to begin site investigations and/or actions.

The Need for SRS

In the United States, many waste sites exist, yet the hazards they pose may differ by orders of magnitude. Although one can select sites that pose the greatest public health risk using detailed risk assessment or extensive site monitoring, these approaches are quite costly. Consequently, there is the need for a simple, low-cost approach to provide an order-of-magnitude ranking of sites (similar to that obtained with a detailed risk assessment). SRS satisfies this need. With SRS, the sites with the greatest health risk should appear near the top and those with the least risk near the bottom of the list.

Currently, the most widely used ranking scheme, the Hazard Ranking System (HRS) used by the U.S. Environmental Protection Agency (EPA), has drawbacks (Chu et al., 1986), many of which SRS corrects. In contrast to HRS, SRS

- uses a more accurate measure of chemical toxicity
- handles both chemical and radioactive hazardous wastes

- evaluates the health hazard from the quantity of each constituent comprising the waste
- more adequately evaluates the risk from surface-water runoff
- considers ground-water-flow direction and distance
- evaluates the potential hazard from the air pathway even without observed releases
- does not use arbitrary maximum distances to targets of concern
- accounts for environmental attenuation of the hazardous material
- separates risk assessment from risk management

The reauthorization of Superfund in October 1986 (SARA, 1986) has required EPA to address several of the above problems with HRS. Thus, developing an improved ranking system such as SRS is also a legislative requirement.

Method for Scoring Sites

The SRS procedure described in this report scores important and readily available factors that influence the risk to humans. Specifically, SRS measures the risk of a release from a waste site as a combination of the potentially exposed population, the average amount of exposure to the waste, and the toxicity of the waste:

$$\text{Health Risk} \propto \text{Population} \cdot \text{Exposure} \cdot \text{Toxicity}$$

Both the population and the toxicity of each hazardous substance are easily indexed with single scores. Only exposure must be subdivided further into component factors.

In SRS, the specific factors used to evaluate exposure vary with the manner of release. Yet generally, the amount of exposure is evaluated from the mass of material initially deposited at the site [W_o], a factor indexing the effectiveness of engineered barriers [f_{eng}], and a factor indexing the ability of site features [f_{site}] to reduce the amount of hazardous material reaching the potentially exposed population:

$$\text{Exposure} \propto W_o \cdot f_{eng} \cdot f_{site}$$

When scoring a site, the various factors will likely be known within only a factor of ten; consequently, SRS is simplified by using the logarithms of the parameters rounded to the nearest integer, which become the "scores." Combining these scores produces the overall site score.

Rationale for SRS

Several principles and goals guided our development of SRS: SRS was to

- approximate the ranking obtained with a detailed risk assessment,
- have a logic easy to understand and use,
- use readily available site data,
- require only data that have an order-of-magnitude effect on the health risk (consistent with the uncertainty of preliminary data),
- be applicable to most waste sites.

The approach described under "Method of Scoring" is based on the techniques used in detailed assessment of health risk. For this reason, SRS provides an approximation of the ranking obtained with a detailed risk assessment, yet uses preliminary data (often only descriptive) and simple models, permiting hand calculations. This logical basis in risk methodology helps reduce the distortion of the scores--an advantage over many other ranking schemes. More importantly, the clear logic helps in successfully applying SRS in normal and unique situations. For example, if the analyst understands the framework, he can confidently modify SRS for unique situations.

In addition, although a ranking system based on risk assessment could incorporate relatively detailed models (for example, a detailed transport model), the uncertainty of preliminary data (for example, uncertainty in amount of hazardous material) easily swamps the added precision of the model. Furthermore, the more precise model usually requires more data. Thus, we used simple models that captured the most important effects consistent with the accuracy of preliminary site and waste data.

Assumptions of the Ranking System

Although numerous assumptions were made in developing SRS, eight assumptions greatly influenced its development. These are as follows:

- Human health risk is the most important risk to evaluate. Sensitive biological habitats or economic institutions at risk are noted in the narrative accompanying the SRS ranking but are not scored.
- The health risk of a hazardous material is adequately determined by scoring its toxicity, the population exposed, and the level of exposure. Acute hazards from flammable and explosive chemicals are described but are not scored.
- Scores based on the exposed population rather than an exposed individual are more useful for ranking. (However, the individual exposure is easily evaluated by omitting the population score.)
- The health risk posed by a site is best evaluated by chronic (long-term) risks. Although the health risk is a combination of both chronic and acute risks, SRS only evaluates chronic risk because acute risks usually involve emergency rather than remedial response.
- The scores for toxicity, population, and exposure are based on best estimates of parameters, not worst-case estimates.
- With preliminary site data, only an order-of-magnitude approximation of the health risk and resulting ranking is possible.
- The level of exposure can be represented by three generic release pathways: ground water, surface water, and air.
- Hazards from direct contact are sufficiently estimated by air pathway.

Synopsis of Instructions

Ranking hazardous waste sites involves the following eight steps. These steps are presented in detail in Chapter 8.

1. **Collect data on material present at the site.** The quantity and toxicity of the hazardous material placed at the waste site directly influences potential health risk; consequently, the chemicals present and their properties are important data. The challenging and time-consuming portion of SRS is the collection of these data.
2. **Rank material found at site.** This step identifies the substances that are likely to dominate the health risk score. Although in principle the analyst should investigate every substance present, chemicals present in very small quantities, chemicals with very low toxicity, and chemicals that degrade very rapidly may not appreciably affect the overall site risk and thus may be neglected.

3. **Describe release pathways.** SRS uses three generic pathways: air, surface water, or ground water; however, SRS also briefly documents the presumed real pathways at the site as part of the ranking procedure. Unusual pathways or conditions that are not treated by SRS can at least be noted in an accompanying narrative.

Steps 4 and 5 score factors pertinent to each pathway.

4. **Identify target populations for selected pathways.**

5. **Evaluate engineered barriers at the site.** The engineered design of the site is evaluated specifically for each pathway in this step. Engineered barriers serve to extend the containment of the chemical, lower the release rate, and minimize access to the chemical. They do not, however, provide indefinite isolation.

The instructions for step 6 are specific to each pathway. But, in general, the instructions break the step into two parts: (1) scoring characteristics applicable to all wastes at the site, and (2) scoring characteristics specific to each waste. As an example, the steps for the ground-water pathway (G1 and G2) are listed.

6.G1 **Score ground-water dilution, aquifer velocity, and aquifer thickness.**

6.G2 **Score ground-water quantity, decay, and retardation adjustments.**

7. **Evaluate site score.** Evaluating the site score consists of first evaluating each pathway score and then combining the pathway scores.

8. **Construct ranked list of waste sites.** Ordering the sites on the basis of their rank (roughly estimated health risk) is straightforward; however, circumstances such as lack of high quality data may need to be taken into account to differentiate between sites with nearly identical scores.

Background on Risk Assessment Project

SRS was developed for use by the Hazardous Waste Remedial Actions Program (HAZWRAP) on hazardous defense waste generated by the U.S. Department of Energy (DOE). DOE, through the HAZWRAP Support Contractor Office, Martin Marietta Energy Systems, Oak Ridge, TN, contracted with Sandia National Laboratories, Albuquerque (SNLA) to develop tools and procedures (a "methodology") for performing risk assessment. The methodology should assist DOE in identifying problems and evaluating solutions for existing and future waste sites; in other words, it should effectively allocate cleanup resources.

SNLA divided the risk-assessment development task into four subtasks:

1. Evaluation of current techniques for ranking waste disposal sites (reported by Chu et al., 1986);

2. Development of a scheme, based on risk methodology, that ranks DOE hazardous chemical and radioactive waste sites (reported herein);

3. Development of tools and procedures for a comprehensive risk assessment of DOE disposal sites;

4. Demonstration and transfer of the methodology to DOE.

Subtasks 3 and 4 were proposed but postponed indefinitely because the DOE HAZWRAP program is now oriented toward demonstrating innovative clean-up techniques.

Suggested Future Work

Scoring schemes, by nature, are imperfect tools. Although SRS has a sound logical basis, it undoubtedly has hidden faults that need to be corrected. Consequently, SRS needs to be tested to ensure a good scoring scheme. We recommend

- testing the feasibility and credibility of the SRS scoring with at least five real sites--preferably sites that had been thoroughly studied and possibly ranked using another scheme.

- performing an analysis of the SRS ranking scheme to examine the sensitivity of the ranking to various input factors and to identify specific improvements needed in SRS,

After carrying out these recommendations, SRS will be ready to rank hazardous waste sites; however, to make SRS even easier to apply, we also recommend

- compiling pertinent chemical property data to construct a data base for use with SRS,

- placing SRS on a personal computer,

- incorporating sensitivity/uncertainty techniques in a computer version.

Suggested related work includes

- developing separate ranking scheme for evaluating environmental risks (based primarily on risk indicies)

- developing risk-based decision scheme for RCRA-type problems

2. INTRODUCTION

Organization of Report

This report is divided into two major sections: The first section describes the rationale behind the site ranking system (SRS); the second, its use. The first section includes

- background information and motivation for developing SRS (remainder of Chapter 2, Introduction),
- general principles observed in SRS (Chapter 3, Scoring Concept),
- chapters dealing with the specific models for scoring the three generic pathways: ground water, surface water, and air pathway (Chapter 4, Population and Toxicity Scores; Chapter 5, Ground-Water Score; Chapter 6, Surface-Water Score; Chapter 7, Air-Pathway Score),
- comparison of SRS with other assessment schemes, Chapter 9.

The second section, printed on colored sheets, discusses the use of SRS. It includes

- instructions for using SRS, including a brief description of SRS (Chapter 8, Site Ranking System Instructions),
- SRS worksheets (Appendix A),
- scoring worksheets for an actual Superfund site (Appendix B),
- physical and chemical data on common hazardous wastes (Appendix C),

Using this report

To more fully understand the motivation behind SRS, the background on the DOE program of which this report is a part, and background on existing ranking schemes continue with this introduction.

To understand the theory of SRS, read Chapter 3, General Aspects of SRS.

To determine the data requirements of SRS or how easy SRS is to use (in general whether SRS will meet your needs), thumb through the second section (colored sheets), especially, the example problem. If you have questions

about certain aspects, refer to the instructions or theory. (Mathematical symbols and acronyms are defined in Appendix E.)

If you will be using SRS, are familar with problems at hazardous waste sites, and are familar with general procedures for assessing risks, you can skip to the second section and begin. However, we strongly urge you to read the entire report at some point to understand the framework and assumptions. This background information points out vital features and their purpose so that you, the analyst, can make sensible modifications to SRS if necessary.

Objective of SRS

Purpose. The objective of SRS is to rank sites containing hazardous waste according to the potential human health risk they pose, primarily using information that already exists on the site. SRS ranks each individual site by scoring factors that influence the human health risk. Using SRS, a risk manager can group waste sites into those that need more detailed study of risk and those that do not. In addition, the manager can determine the approximate order in which to begin detailed investigations for site data, perform remedial investigations (RI), and perform feasibility studies (FS).

The Resource Conservation and Recovery Act (RCRA, 1976) defines a hazardous waste as material that may cause or significantly contribute to serious illness or death in humans or poses a substantial threat to the environment when improperly managed. Hazardous waste typically possesses one or more of the following four characteristics: toxicity, ignitability, corrosivity, or reactivity. SRS specifically scores toxic material, a broad subset of hazardous wastes, because they largely determine long-term potential risk. Hazards from the other three categories (ignitability, corrosivity, or reactivity) are noted in an accompanying narrative of the site but not scored because of the usual need to respond immediately to these threats rather than sometime in the future.

Need for site ranking. SRS was developed to help decision makers direct investigative funds toward sites with the greatest potential health risk. Many waste sites exist in the United States, many need remedial action to protect public health, but the hazards differ by orders of magnitude among

these sites. Although a manager can select sites posing the greatest health risk using detailed risk assessment or extensive field monitoring, it is quite costly in both data and time required. SRS is a simple, low-cost approach to provide an order-of-magnitude ranking of sites similar to that obtained with a detailed risk assessment. Although the sites with the greatest potential health risk appear near the top of the list, SRS provides only a relative comparison of risk, not an absolute measure.

Summary. In summary, SRS ranks hazardous waste sites according to relative human health risk. Two indirect benefits of SRS are that (1) the analyst evaluates the quality of and identifies any gaps in existing data; and (2) because SRS parallels the risk assessment method, SRS suggests important release mechanisms and, thereby, identifies remedial possibilities to explore in later investigations. SRS cannot pinpoint with accuracy the absolute health risk or remedial solutions at a waste site because, unlike a comprehensive risk assessment, simplified models and sparse data are used.

Background on DOE Hazardous Waste Program

General. The U.S. Department of Energy (DOE) operates about 30 facilities (research laboratories, uranium enrichment plants, and nuclear weapon production plants) for the nation's defense. These facilities generate about 10 million tons of waste a year, including radioactive or hazardous and radioactive waste combined ("mixed" waste). Although the Atomic Energy Act (AEA, 1954) exempted DOE from many environmental and human health laws, a 1984 court ruling (LEAF v. Hodell) required that DOE comply with regulations of the U.S. Environmental Protection Agency (EPA) concerning the Clean Water Act (CWA, 1977) and either RCRA (1976) for active sites or CERCLA (1980) and SARA (1986) for inactive sites.

DOE established the Hazardous Waste Remedial Actions Program (HAZWRAP) to internally implement RCRA requirements. In addition to programs to examine remedial techniques, HAZWRAP chose to examine tools and procedures (a "methodology") for performing probabilistic risk assessments from postulated and actual releases at their facilities.

SNLA program. In FY 1986 DOE, through the HAZWRAP support contractor office at Martin Marietta Energy Systems, Inc., Oak Ridge, TN, contracted with Sandia National Laboratories, Albuquerque (SNLA) to develop a risk methodology for evaluating hazardous waste sites, designated "Technical Task 4: Risk Assessment/Evaluation for Hazardous Chemical Wastes." SNLA divided Task 4 into four subtasks:

1. Evaluate current techniques for ranking and the state of the art in assessing risk at waste sites,
2. Based on outcome of subtask 1 possibly develop an appropriate ranking scheme for DOE hazardous chemical and radioactive waste sites,
3. Develop tools and procedures for a comprehensive assessment of risk at DOE waste sites,
4. Demonstrate and transfer the methodology to DOE.

This report describes subtask 2, the improved site ranking scheme (SRS) SNLA developed for DOE. Results from subtask 1 were reported by Chu et al. (1986). The final two subtasks (3 and 4) have been delayed indefinitely because of a reorientation of HAZWRAP toward demonstrating innovative clean-up techniques at several DOE waste sites.

Relationship of SRS to Risk Assessment and Risk Management

SRS is directly related to risk assessments and purposely omits risk management decisions. This relationship is clearly evident from the definitions of these risk assessment terms. However, definitions do vary somewhat; hence, for this report the following definitions are used:

Risk. Risk is defined as the product of the probability of an event or process times the effect or consequence of that event or process. In this report the time scale of interest for events are short, making the probability of all but one or two scenarios highly unlikely and, thereby, eliminating the need to formally estimate probabilities.

Risk Assessments. In general, risk assessments estimate (usually quantitatively but sometimes qualitatively) probabilities and effects or consequences (usually health but sometimes economic consequences) of a substance or process on an individual or population (usually human but

sometimes entire environment population) (Risk Assessment, 1983). For this report, a risk assessment means a quantitative assessment of the human health risk from the release of a hazardous material.

Risk assessments provide technical input to a decision-making process. A risk assessment is useful for

- determining the suitability of potential waste sites
- determining whether remedial action is necessary at existing sites
- selecting appropriate remedial solutions at a site by identifying the source of the risk
- assigning priorities in upgrading sites and/or handling practices

Risk assessments are necessary to wisely direct public funds and other resources to eliminate hazards that pose the greatest risk to human health, biologic systems, and/or economic institutions. When used as a decision-making tool, the logic and results of a risk assessment are easily defended whenever decisions are questioned by other government agencies or the courts. Finally, EPA regulations for hazardous waste sites imply (but do not require) a simplified risk assessment for hazardous waste sites (EPA, 1986a, 1986b; 40CFR267). Similarly, EPA regulations for high-level radioactive waste repositories are risk based. Although not requiring a risk assessment, they suggest estimating consequences and probabilities of scenarios for demonstrating compilance (40CFR191).

Risk management. Risk management is the process of evaluating and selecting alternative courses of actions. A primary component of the decision criteria is the factual input provided by a risk assessment but regulations, public issues, feasibility, and costs are also important. Ideally, risk assessments would be completely separated from risk management decisions (Risk Assessment, 1983).

Risk assessment policy. Risk assessment policy establishes the philosophy used to select among analysis choices. Because risk assessments are frequently most useful when data is sparse, professional judgement, experience, intuition, and consensus must bridge the gaps in knowledge that invariably exist. Risk assessment policy establishes the degree of

conservatism in a risk assessment if there is no decisive way to make the choice between several analysis options. An example, is choosing to use best-estimate models rather than conservative models. Although seemingly containing aspects of risk management, risk assessment policy is always subservient to scientific fact (Risk Assessment, 1983).

Juxtapostion of SRS to Other Waste Site Decisions

Figure 2.1 shows the suggested relationship of the SRS ranking to the overall program to reduce hazards at waste sites. The headings of Figure 2.1 are described below.

Emergency checklist/action. After discovery, a site evaluation begins by quickly evaluting the acute hazards (B. Murphy, prsnl. comm., 1987). If acute hazards are present and no barriers protect the public, then immediate action must be taken. An emergency checklist might include the following questions and suggested emergency action:

- Can the public directly contact any hazardous materials (especially acutely hazardous materials)? Control access to the site.
- Is drinking water contaminated at the tap? Find an alternate drinking water source.
- Is there a serious threat from flammable or explosive materials? Neutralize or remove the material.
- Are acutely hazardous materials stored in weak bulk containers or present at or very near the soil surface or can wind or water easily disperse the material? Remove or thoroughly cover and protect the material.

SRS screening. The second major step of a site evaluation involves scoring with SRS. Ranking the sites of concern is an integral part of the overall assessment and management of risk; thus, the basis of the ranking scheme must be similar to risk assessment methodology to ensure a consistent ranking. Because currently existing ranking schemes did not have this basis, we developed SRS.

Because SRS is risk based, the information gleaned from the ranking can guide further data collection efforts; hence some interaction may occur between screening and collection of readily available data (Figure 2.1).

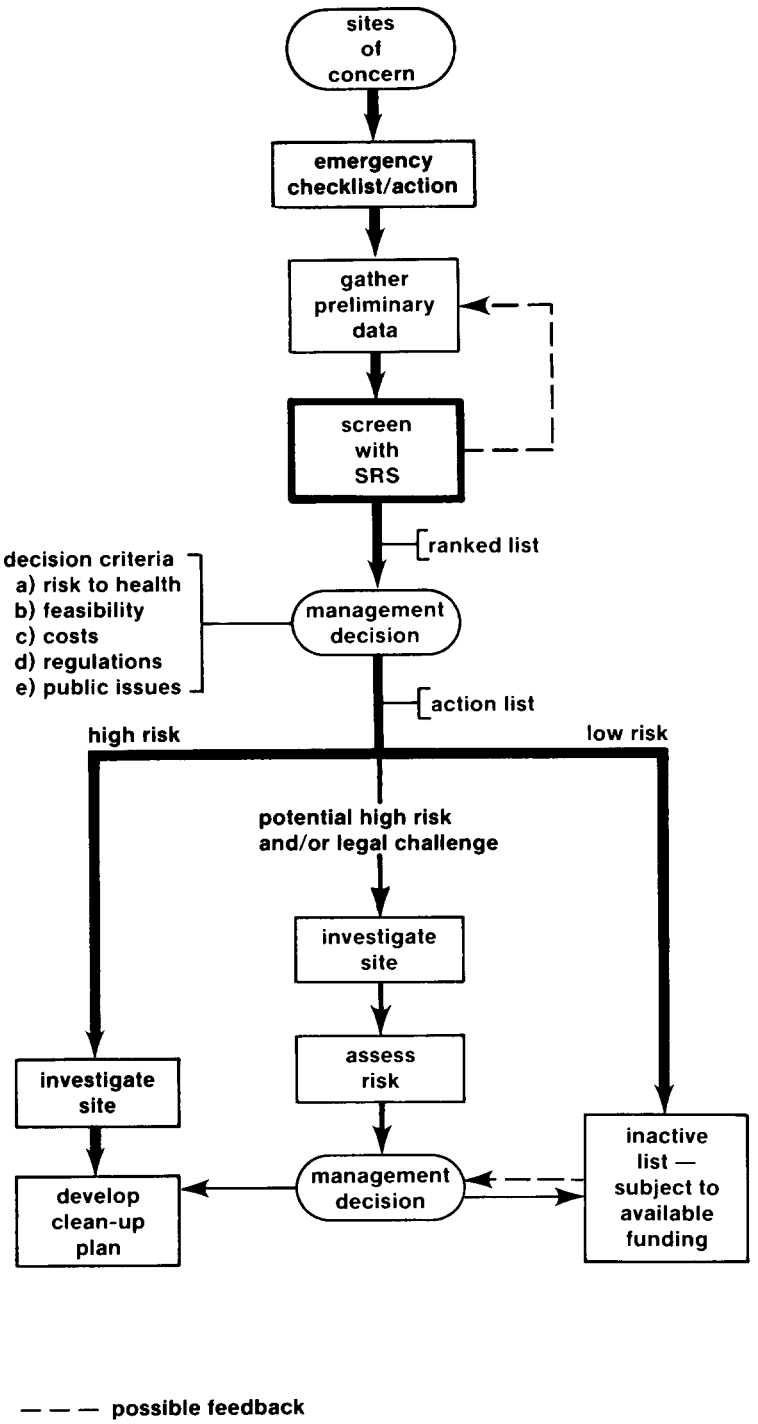


Figure 2.1 Juxtaposition of SRS ranking with other waste site decisions

Management decision. Considerations such as ecologic hazards, cost to clean up a site, technical feasibility, public concerns, or risk-management policies of a regulatory agency have been omitted in SRS; consequently, the ranked list is not necessarily a final action list; the ranked list provides only technical input on human health risk. The final action list is a result of risk management decisions (Risk Assessment, 1983) based on the technical input of SRS and these other factors.

Many ranking schemes combine aspects of both risk assessment and risk management. There are instances when the risk management decision criteria are rigid enough to incorporate into a ranking scheme, but in general the decision criteria are not and, thus, this practice is not recommended (Risk Assessment, 1983). Combining risk assessment and risk management can frequently confuse industry and the public over decisions based on the ranking scheme. It also reduces the portability between governmental agencies with different decision criteria. Furthermore, it also reduces the flexibility of the risk manager to manage. For example, some sites are easier to clean up; thus, a grouping (portfolio) that includes easily cleaned up sites, not necessarily the worst sites, may reduce overall health risks more for the money spent.

Site groupings. Following the management decision step, sites will be set into three groups: high risk, potentially high, and low risk sites. The high risk sites will undergo detailed RI/FSstudies, highest SRS scores first, and then cleanup. The potentially high risk sites will undergo detailed site investigations (highest SRS scores first), detailed risk assessment, and then through another risk management decision step. Nothing more will be done for sites in the low risk group unless additional cleanup fundings are available. The number of sites in each group will depend upon management decisions. An agency may decide to group most sites into the high or low risk groups, requiring only a few undergo a detailed risk assessment. Alternatively, an agency may require most sites undergo a detailed risk assessment while only a few are automatically set in the high and low risk groups.

Before summarizing conclusions from Chu et al. concerning existing ranking methods, we present a very brief description of SNLA's proposed risk

methodology as background to help explain what "detailed risk assessment" entails.

SNLA Proposed Risk Methodology

To perform probabilistic risk assessments, one must evaluate both the probabilities and consequences of events that could lead to release of contaminants from a waste site and then transport to a specific target of concern. The five steps in the assessment usually are

- disposal system characterization (waste properties, site characteristics, and facility design);
- scenario development, probability estimates, and screening;
- consequence modeling;
- risk calculations and/or comparison with government regulations; and
- sensitivity/uncertainty analysis.

SNLA's modular approach to risk assessment, based on extensive experience for high-level radioactive waste repositories (Cranwell et al., 1987), is shown in Figure 2.2. The five components of the methodology are represented by the various modular blocks. This modular approach has several advantages for the analyst:

- The analyst, by examining intermediate results, gains insight into physical processes and important parameters affecting risk.
- The analyst can use intermediate results directly in determining compliance with regulatory standards (for example, 40CFR264)
- The analyst can more easily modify the methodology, if necessary.

Because a large portion of the methodology consists of simulating physical processes to estimate consequences from waste release (consequence modeling), Figure 2.3 illustrates a classical, detailed breakdown of the numerous pathways that would have to be examined.

Even if all the necessary data were available, analyzing every intricate pathway would be time consuming. Hence, in addition to consequence modeling, an important part of a risk assessment is sensitivity and uncertainty

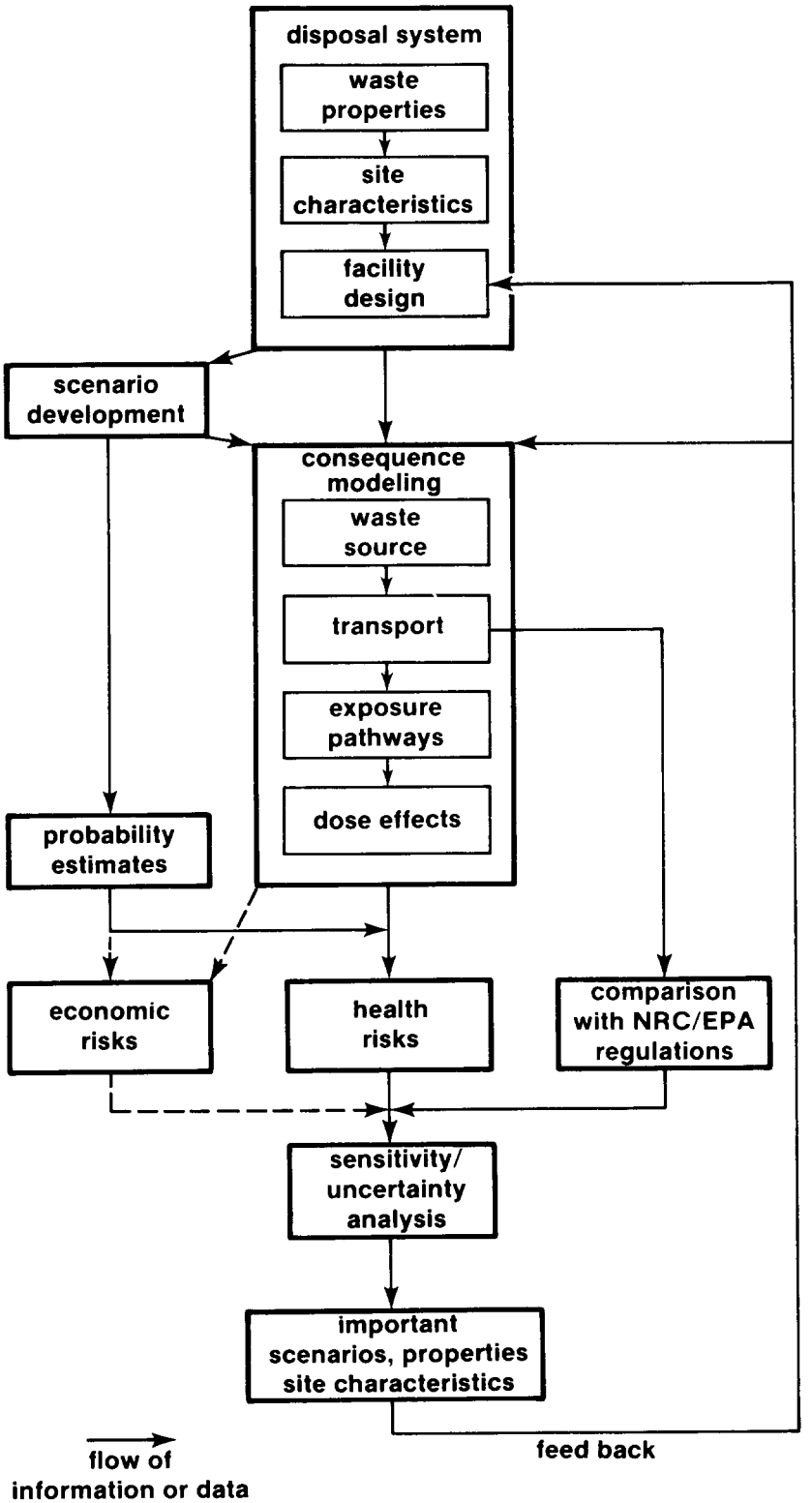


Figure 2.2 SNLA's modular method of assessing risks from hazardous waste disposal

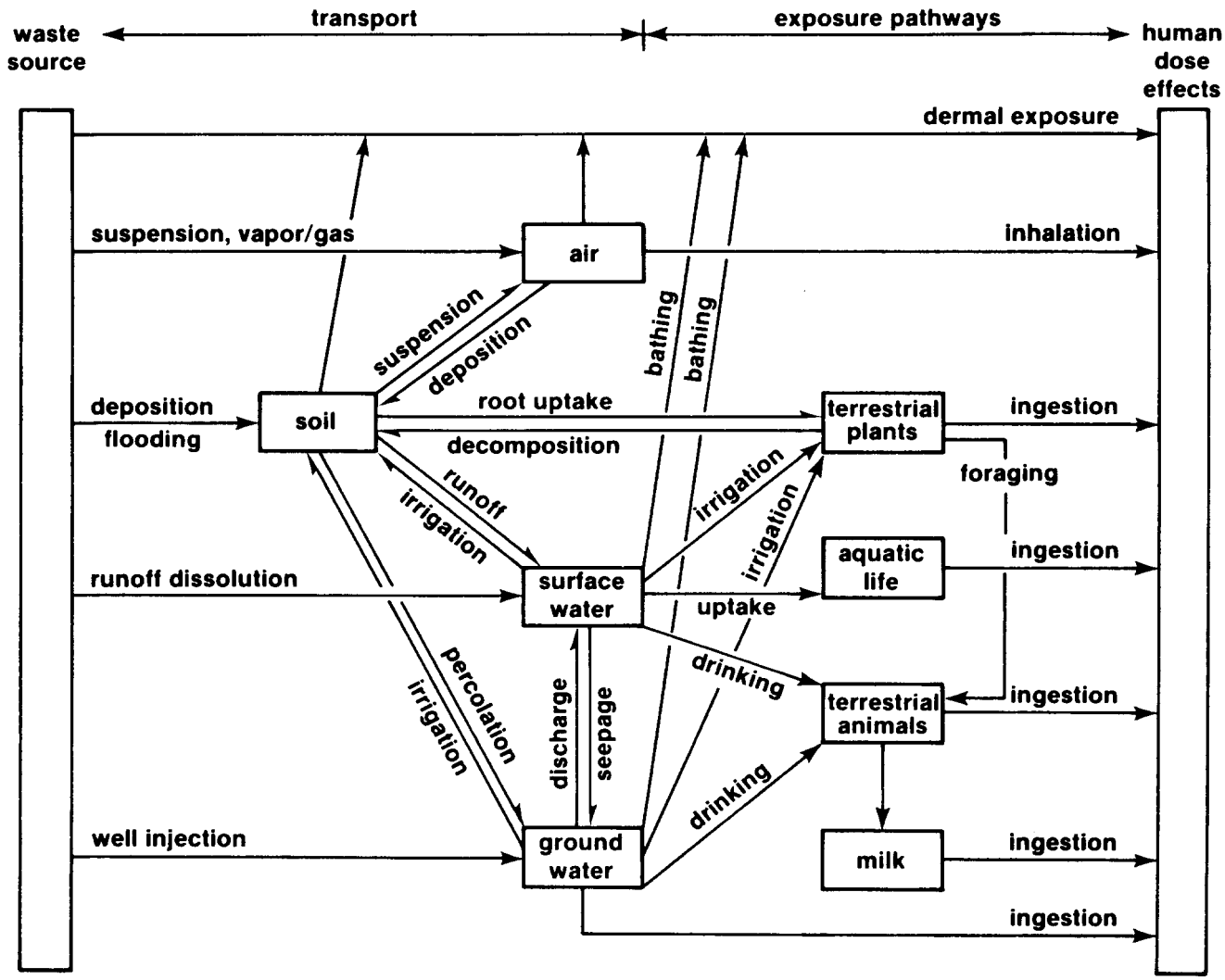


Figure 2.3 Potential contaminant movement that could be important to simulate in consequence modeling

analysis (Figure 2.2). Sensitivity analysis identifies those parameters that most influence the total risk. Uncertainty analysis identifies uncertainty in the results because of uncertainty in models and input parameters.

Obviously from Figures 2.2 and 2.3, a detailed assessment of health risk at a site is time consuming and expensive. Consequently, sites of concern must be ranked to identify sites that are more likely sources of contamination and, thus, hazards to the public. Before developing SRS, we reviewed the current ranking methods available.

Review of Ranking Methods

Chu et al. (1986) reviewed ranking and screening procedures created for a variety of purposes. Although most were only marginally relevant for DOE, three of the procedures surveyed were examined in detail. These were the Hazard Ranking System (HRS), developed by MITRE Corporation for EPA (HRS Workshop, 1982); the modified Hazard Ranking System (mHRS), a modification of HRS by Battelle Pacific Northwest Laboratory (PNL) to include radioactive wastes (Hawley and Napier, 1985); and the Hazard Assessment Rating Methodology (HARM), created by the U.S. Air Force for its installation restoration program (USAF, 1983). A fourth detailed ranking scheme under development, RAPS (Whelan et al., 1986), is also discussed. Because of drawbacks in the currently available schemes (HRS, mHRS, and HARM) and because they lacked a risk basis, SNLA strongly recommended developing a new site ranking system (SRS) for DOE hazardous waste sites.

Hazard Ranking System (HRS). HRS, requiring limited data, is simple to use. By virtue of its use in selecting almost 900 hazardous sites for listing on the National Priorities List (NPL) (40CFR300), HRS is the standard method for ranking hazardous waste sites.

Although it does not quantify the probability or magnitude of harm that could result from a waste site, HRS ranks sites by scoring factors that influence these elements of risk. HRS scores

- the manner in which hazardous wastes are contained,
- the pathway by which they could be released,
- the characteristics and total amount of harmful substances,
- the likely targets (receptors) harmed.

Specifically, HRS assigns three scores to a hazardous waste site:

- The migration score [F_M] indexes the potential harm to humans or sensitive environments because of the waste migrating away from the site along a ground-water, surface-water, or air pathway. F_M is the geometric average of separate scores for each of these three pathways.
- The flammable and explosive score [F_{FE}] indexes the potential harm from flammable or explosive material.
- The direct-contact score [F_{DC}] indexes the potential harm from direct exposure (no migration) to a human intruding into the site.

EPA usually uses F_{FE} and F_{DC} to identify sites requiring emergency attention; thus, the migration score F_M is the primary score for ranking. Three major factors comprise the migration score [F_M]: waste, pathway, and target characteristics. The pathway factor is given the maximum score if any release of a hazardous substance has occurred. EPA ranks and places sites on the NPL if the final score is above 28.5 (HRS Workshop, 1982).

HRS has several strengths (HRS Workshop, 1982):

- It is simple to use. Once the value of a parameter is known, one looks up its score in a table.
- It does not require extensive data.
- The parameters selected affect risk and are not redundant.
- It gives a wide range of scores.
- The three major migration pathways are considered, and the geometric averaging of the individual pathway scores does not severely dilute one important pathway when the other two are unimportant.

Yet, HRS has drawbacks. First, HRS ignores several properties of the hazardous wastes that directly influence the human health hazard. Although HRS scores waste properties (persistence, toxicity, and quantity), the manner in which they are scored distorts the results:

- The score for toxicity is based on only the most hazardous substance, rather than a composite of the entire waste inventory. In contrast, total mass of all substances is used to quantify the magnitude of this hazard--quantity is not linked to each (or a category of) chemical.

- Only the severity of effect (regardless of required dose) is considered when rating the chemical toxicity using SAX scores (Sax, 1975); consequently, radionuclides, which may cause cancer, automatically receive the highest toxicity score regardless of dose.

- Only the initial quantity of waste is considered, even though similar quantities over markedly different areas pose different threats.

Second, problems exist with scoring the population:

- HRS does not address the elapsed time before exposure.

- Distance is used as a weighting factor in situations where release has already occurred. This may or may not be appropriate, depending on where the release is observed.

Third, HRS ignores several important characteristics of the pathway:

- HRS does not account for the direction of the hydraulic gradient.

- HRS does not score the air pathway unless release has been observed.

- HRS uses an arbitrary 3-mile radius for the ground-water pathway regardless of the hydrogeologic conditions.

- Sorption properties of the soil are not considered in the ground-water or surface-water pathways.

- HRS gives no guidance on what monitoring data are acceptable and what defines a "significant" release--important because observed releases overwhelm the HRS score, especially for the air pathway.

Finally, several general criticisms of HRS have also been raised:

- HRS, being highly subjective, sometimes has problems in ranking sites because the score can be manipulated too easily by the analyst, especially by choosing whether or not to collect data for "evidence of contamination."

- HRS sometimes adds scores, sometimes multiplies them, and finally finds the geometric average of the scores for the different pathways (air, surface water, and ground water)--combining rules that have little connection with the comprehensive tools and procedures of risk assessment.

- Sites posing only risks to sensitive environments usually rank low; HRS heavily weighs sites posing human health risks.

- Hazards from food chains are not considered.
- HRS combines both risk assessment and risk management decisions.

The new authorization of Superfund that passed in October 1986 [Superfund Amendments and Reauthorization Act (SARA, 1986)] requires EPA to correct and/or comment on many of these specific problems in HRS within 2 years. Because the logic for HRS was not readily apparent, we could not confidently understand the implication of any changes we made ourselves. Thus, we chose to develop an entirely new ranking system.

Modified Hazard Ranking System (mHRS). Battelle Pacific Northwest Laboratories (PNL) (Hawley and Napier, 1985) modified HRS for the DOE Office of Operations Safety to rank sites that contained both chemical and radioactive hazardous wastes (that is, mixed-waste sites), as occurs at DOE facilities. This was necessary because HRS was not developed for radioactive wastes and had a severe, albeit possibly unintentional, bias against them. Yet, EPA required DOE to rank their current and abandoned waste sites for possible listing on the NPL. The mHRS is identical to HRS except that mHRS splits the waste characteristics scoring into two parts--one for chemical wastes and one for radioactive wastes. The highest score from the two parts is used in further calculations for scoring the site. Although alleviating a limitation, mHRS still suffers from the other drawbacks of HRS.

Hazard Assessment Rating Methodology (HARM). The Department of Defense (DOD) has established a program to identify and control problems at its hazardous waste sites to comply with the intent of RCRA (1976), similar to the purpose of the DOE HAZWRAP program. The U.S. Air Force uses HARM for ranking sites under its control. It is a highly modified version of the ranking model developed for EPA by JRB Associates (Kufs et al., 1980). Because the JRB model was also the starting point for HRS, it is somewhat similar. HARM scores hazards of the waste by considering both toxicity and quantity--a more realistic approach. However, HARM inappropriately scores persistence by using the most persistent chemical in the waste inventory.

Remedial Action Priority System (RAPS). PNL has been developing since FY 1983 a computer-based ranking system called RAPS for the Office of Environmental Guidance and Compliance, also at DOE (Whelan et al., 1986).

Like SRS, RAPS is based on risk methodology; hence, they can work together in tandem--SRS for screening and RAPS for more detailed risk assessment.

Using empirical, analytic, and semianalytic algorithms, RAPS addresses many limitations of HRS. It considers

- more site and waste characteristics,
- both chemical and radioactive wastes,
- waste dispersion and decay,
- individual chemical toxicity
- population distributions,
- three exposure routes: external, inhalation, ingestion,
- duration of exposure,
- time until population exposed.

RAPS outputs a hazard potential index (HPI) (not an absolute but a relative measure of risk) that can be used to rank the site relative to other sites. To obtain the HPI, RAPS considers four major pathways: ground water, overland, surface water, and air.

RAPS is not entirely operational. Currently, PNL is working on a version of RAPS for the personal computer. A preliminary PC version should be completed by September 1987. The entire RAPS system should be ready by September 1988 (G. Whelan, persl. comm., 1986).

Ranking system modifications. During the development of SRS, the previously discussed ranking systems were undergoing modifications (sometimes extensive) (B. Madison, EPA, prsnl. comm., 1987): the State of New York developed the New York System from HRS; ORNL developed the Defensive Prioritization System (DPM) for the U.S. Air Force by extensively modifying HARM; and EPA began revamping HRS. Perhaps all the ranking scheme will converge toward the same philosophy, but reports are currently unavailable; thus, we have not evaluated their theory or improvements.

Incidents from Waste Disposal Sites

As background information for the reader, we present data on incidents of contamination from the 1970s that influenced the development of SRS. A frequently cited paper, Lazar et al. (1976), describes and tabulates 421 incidents of damage from land disposal of industrial hazardous wastes (Table 2.1). The hazardous wastes harm humans or biologic systems by five general mechanisms (in order of importance):

- contaminating ground water,
- contaminating surface water,
- being accessible to direct human contact,
- contaminating the air around the site.
- causing a fire and/or explosion

Of the five mechanisms, exposure to the waste via ground water is the most prevalent (roughly 60% of cases in the EPA survey); hence, a ranking system should be strongest in evaluating the potential human risk via this pathway. Paradoxically, information on the ground-water pathway is frequently unknown, perhaps because it is simply not visible and thus expensive to discern.

The most frequent contamination of surface water resulted from haphazard disposal on vacant property (41%). (In addition, Table 2.1 shows that most incidents of direct contact poisoning came from haphazard disposal.) Surface-water contamination from landfills and lagoons accounted for 29 and 25% of the incidents, respectively. RCRA (1976) and supporting EPA regulations (40CFR264) have attempted to reduce surface-water contamination significantly at engineered sites by requiring hydraulic structures to prevent storm flow onto and off the waste sites. The interim regulations for active sites require structures capable of handling storms of 24-hr duration and a return period of 25 yr or less (40CFR264). (A storm with a return period of 25 yr means that, on average, an event of this magnitude, or greater, is not expected to occur more often than once in 25 yr.)

The air pathway was significant in only 4% of the contamination cases reported in the preliminary study, implying that the air pathway will

frequently not be important. Unfortunately, rarely have emission of volatile substances, other than methane, been considered (Thibodeaux, 1981); thus, the incidence is undoubtedly underreported.

Table 2.1 Pathways by which industrial disposal sites caused environmental hazard (Lazar et al., 1976)

Damage mechanism (no. of cases)[a]	Disposal method (Total no. of cases--421) Surface impoundments (89)	Landfills dumps (99)	Haphazard[b] disposal (203)	Storage of wastes (15)	Slag, mine tailings (15)
Ground water (259)	57	64	117	10	11
Surface water (170)	42	49	71	-	8
Direct contact (52)	1	6	40	5	-
Air (17)	3	5	9	-	-
Fires,explosion (14)	-	11	3	-	-
wells affected (140)	32	28	74	4	2

[a]The numbers in the table exceed 421 because several incidents involved more than one mechanism.
[b]Haphazard disposal on vacant property, on farmland, agriculture spray, etc.

3. GENERAL ASPECTS OF SRS

This chapter discusses the basis and general framework of SRS. The next four chapters (4, 5, 6, and 7) describe in more detail the factors selected for scoring.

Overview of SRS

Before delving into the justification of the scoring concept of SRS, we briefly present (1) the simplified pathways used and the overall scoring procedure, and (2) the principles that guided the development of SRS.

The complex movement of contaminants in the environment depicted in Figure 2.3 is greatly simplified for SRS. Intricate exposure pathways involving food chains are not considered. Instead, the exposure route involves only direct ingestion of surface or ground water or inhalation of air. Furthermore, recycling of contaminant between surface water, ground water, surface soil, and air is assumed to comprise a minor component of health risk. Figure 3.1 shows these and several other simplifying assumptions used for modeling the consequences of contaminant release from a site.

The ranking technique involves (Figure 3.2)

- collecting data on waste properties, site characteristics, and facility design;
- ranking the wastes found at the site by quantity and toxicity to screen out relatively minor waste components;
- describing the release pathways of concern for the site;
- evaluating engineered features at the facility;
- identifying target populations along these pathways;
- scoring site characteristics based on the manner waste escapes from the site (ground-water, surface-water, and air pathways);
- combining individual waste scores to arrive first at a pathway score and finally at a site score;
- ranking the site in relation to other scored sites.

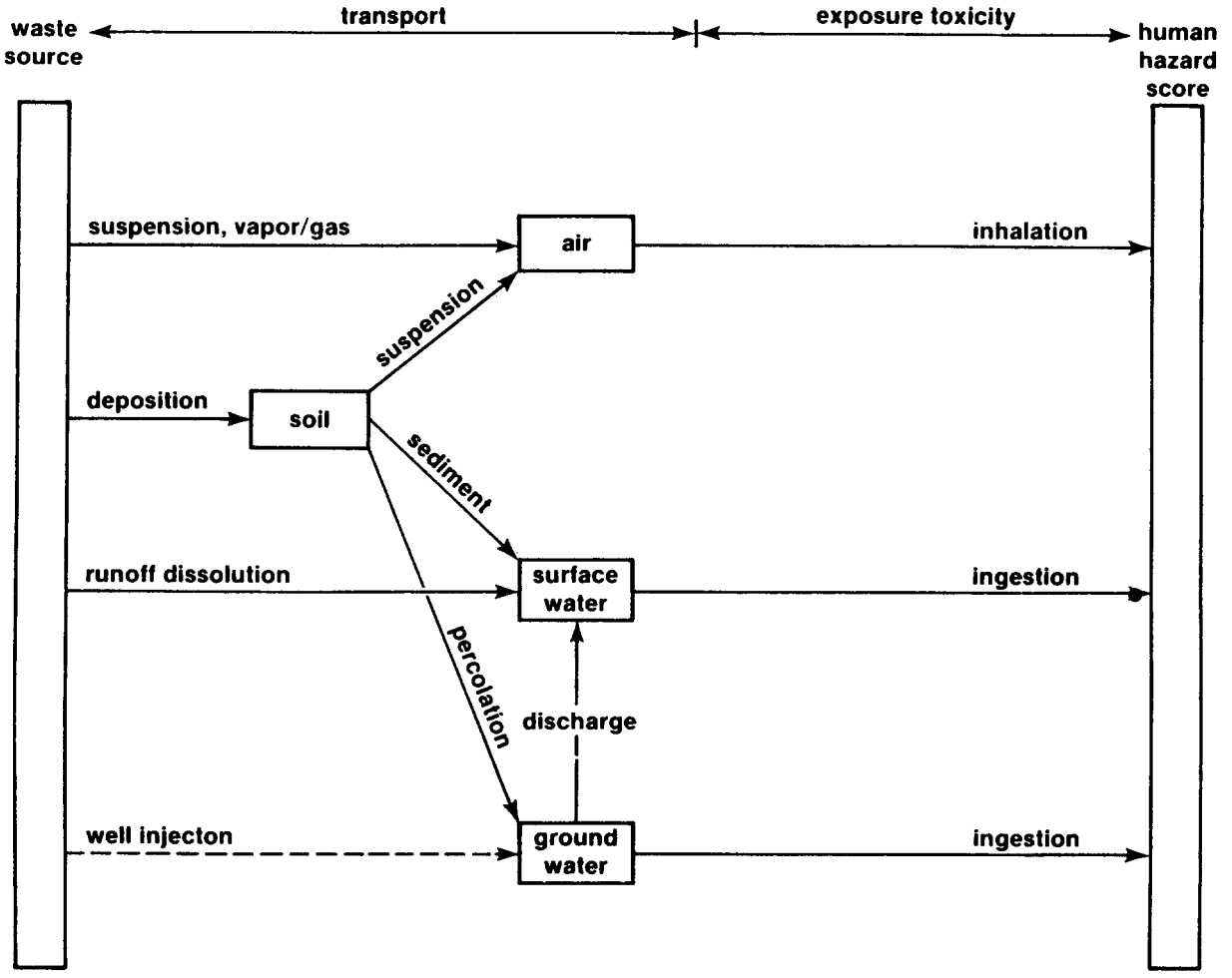


Figure 3.1 The three simplified pathways examined in SRS

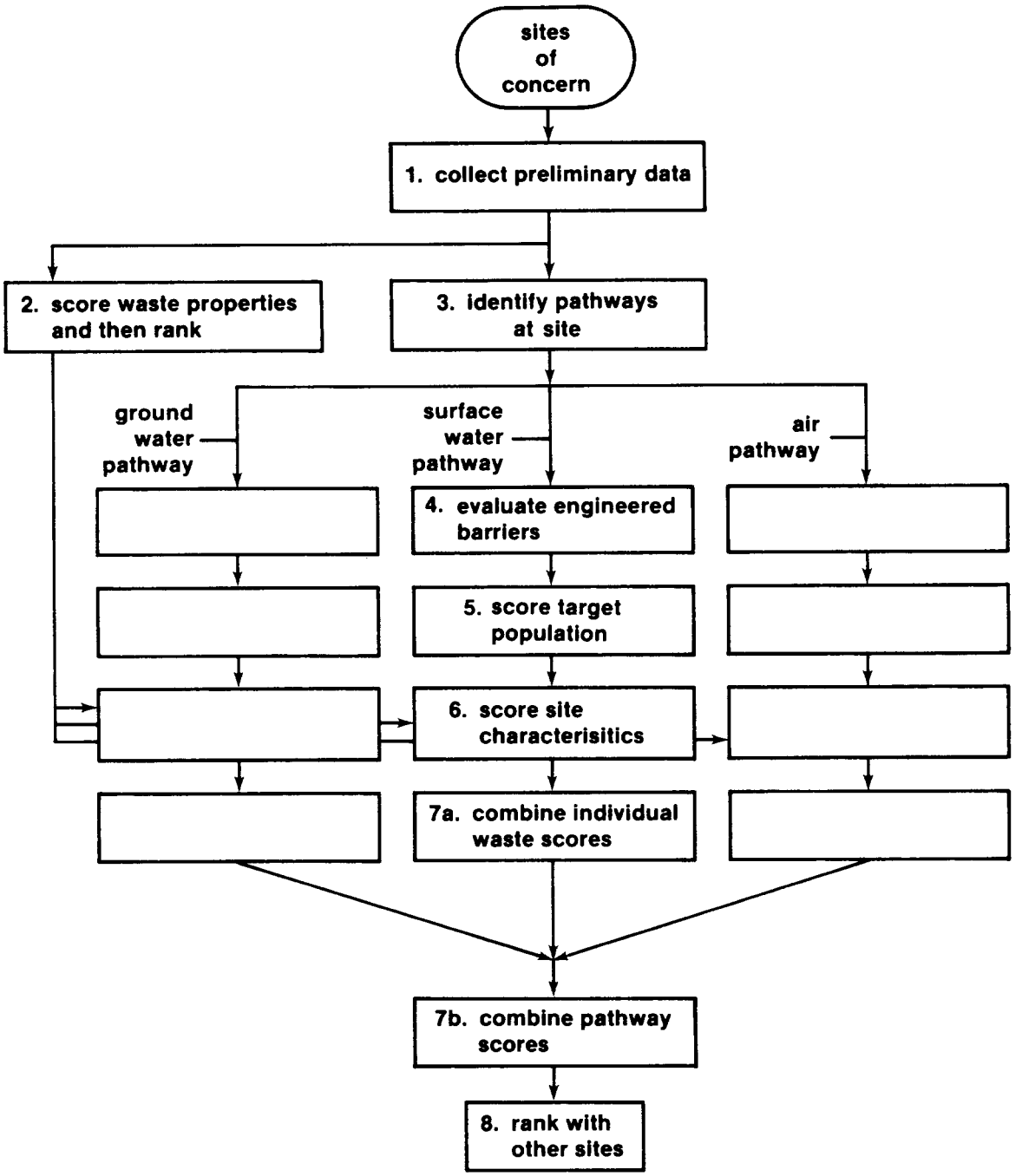


Figure 3.2 Diagram of SRS Procedure

Principles Guiding Development of SRS

Although listing factors that could influence the ranking of a hazardous waste site is easy, developing a credible, scientifically defensible, ranking methodology is difficult. Furthermore for the ranking scheme to be useful in the risk evaluation proposed by SNLA (Figure 2.1), the choice of parameters, scales for scores, and rules for combining scores must be consistent with the detailed risk assessment methodology. Our review of completed ranking systems (Chu et al., 1986) concluded that, although plausible, they failed tests for consistency.

Several principles and goals guided our development of SRS: SRS was to

- approximate the ranking obtained with a detailed risk assessment, and thereby, improve upon HRS;
- have a logic easy to understand and use;
- work with preliminary site data;
- require only data that have an order-of-magnitude effect on the health risk, to be consistent with the uncertainty of preliminary data;
- be applicable to most waste sites.

These principles and the reasons for incorporating them into SRS are discussed in the next few paragraphs.

Risk assessment basis. The basis of SRS is risk assessment methodology. Specifically, in the SRS scoring system, the score is an approximation of a risk assessment calculation. This rationale was used to ensure that the number of false positives (innocuous sites ranked among those felt to be dangerous) and false negatives (dangerous sites ranked among those felt to be innocuous) would be small. In addition, with this approach the parameters and the manner in which they contribute to the risk can be easily identified. For example, if two factors such as exposure and toxicity combine multiplicatively in the risk assessment, then they combine multiplicatively in the ranking scheme also. A scoring system thus derived likely includes the most important parameters and combines them in a consistent manner, so that distortions are minimized. We have attempted to ensure this consistency in SRS. Indeed, it is an advantage over many other ranking schemes.

Of course, if we could devise a scoring system that accurately mimicked a detailed risk assessment, an analyst would not need the latter. Numerous compromises are necessary. But these simplifications are not always a shortcoming; a simpler and less mathematically rigorous system can be easier to use with preliminary site data that may at times be only descriptive.

Improvement over HRS. By basing SRS on risk methodology, we readily were able to understand how to improve upon HRS. In contrast to HRS, SRS

- uses a more accurate measure of toxicity;
- handles both chemical and radioactive hazardous wastes;
- evaluates the health hazard from the quantity of each constituent comprising the waste;
- more adequately evaluates the risk from surface-water runoff;
- considers ground-water flow direction and distance;
- evaluates the potential hazard from the air pathway even without observed releases;
- does not use arbitrary maximum distances to targets of concern;
- accounts for environmental attenuation of the hazardous material;
- separates risk assessment from risk management decisions.

Several of these improvements were required by SARA (1986), others are improvements under consideration by EPA (Caldwell, 1986).

Understandable logic. Although using a risk assessment approach, SRS is easily understood and simple to score. Ease of use is important because SRS is a preliminary screening tool, not a replacement for detailed risk assessment or field monitoring. A clear logic is important because it helps ensure the successful application and versatility of the ranking procedure.

Use with readily available data. The ease with which scores are assigned is influenced by the data required. For example, even complex computer systems can be easy to use, but the amount of data required may, in turn, require massive amounts of time and money to collect. We assumed the most difficult and expensive part of ranking a waste site was collecting

data, especially for the many abandoned sites that have little information available. Compared to scoring systems such as HRS, the major change in required data concerned collecting more detailed information on type, properties, and amount of hazardous waste stored.

Data uncertainty. Preliminary data gathered at a site is likely to have large uncertainty. For example, the identity and amount of hazardous material disposed of at an abandoned site is often unknown. Accordingly, even though a complex model might exist for ground-water transport of a material, the added precision contributed by this model does not improve the certainty of the prediction because the source term is so uncertain; the added data requirements for the precise model are not justified. Therefore, we only used models (and thereby factors) that had a major effect on the result. In summary, our premise was that when large data uncertainty exists, a simple model involving the major processes is as adequate as a complex one and, thus, does not hamper predictions.

General applicability. Finally, although SRS was specifically developed for DOE, we kept it general such that one could apply it, possibly with minor modifications, to the whole spectrum of land-based waste sites currently existing [for example, chemical or sanitary landfills and lagoons, leaking surface or underground storage tanks, mill tailings and other waste piles, injection wells, accidental spills, and roadside (or vacant land) contamination from illegal dumping]. SRS may even be useful for selecting future disposal sites; however, we strongly caution that bounding calculations from simple analytical models (as used in SRS) can possibly eliminate many good sites.

Scoring Concept of SRS

Because SRS is risk-based, an important starting point is the measure of risk. Several measures of risk are possible: risk to human health [$\hat{R}_h$], risk to other ecosystems [$\hat{R}_e$], and risk to economic institutions [$\hat{R}_\$$]. In principle, all could be included to obtain total risk [$\hat{R}$]. Normally, however, subjective weights [γ, φ] would be assigned to the ecosystem and economic risk components (Symbol definitions are repeated in Appendix E):

$$\hat{R} = \hat{R}_h + \gamma\hat{R}_e + \varphi\hat{R}_\$$$

SRS uses only human health risks [$\hat{R}_h$]; other risks are described but not scored. The latter risks can be brought into the decision process when the risk manager is selecting the priority sites.

Risk [$\hat{R}_h$] is the product of the probability [P] of a scenario and the consequence [ψ] of that scenario. Here, a scenario is a sequence of events that could lead to release and transport of hazardous chemicals from a waste site to some target (receptor) that could be endangered. Usually, a large number of scenarios can be developed; health risk is the sum of these individual risks:

$$\hat{R}_h = \Sigma\ P_i\psi_i \qquad i = 1, \text{ number of scenarios}$$

The risk can be subdivided into chronic risks, which occur over long periods of time, and acute risks, which occur suddenly. Chronic risks are approximated by annualized health effects at steady-state conditions. Acute risks are irregular occurrences associated with brief increases in risk. According to the public's disposition toward risk aversion, a risk modeler may need to subjectively weigh (γ) acute risk more:

$$\hat{R}_h = \Sigma\ P_i\psi_i + \Sigma\ \gamma_j P_j\psi_j \qquad i = \text{chronic scenarios, } j = \text{acute scenarios}$$

SRS considers only the potential risk to humans [$\hat{R}_h$] from chronic scenarios. Acute risks from fire, explosion, or direct contact are noted in the narrative accompanying the ranking. These types of problems require rapid response (for example, separating certain chemicals or building a security fence around the site) as opposed to long-term remedial response (for example, stabilizing lagoon wastes) as scored in SRS.

In SRS, risk is measured by summing consequences [ψ] from three generic pathways. The generic pathways are identified by the manner in which hazardous waste leaves the site: either through an air, surface-water, or ground-water route. For initially screening waste sites, it is impractical to develop numerous mutually exclusive scenarios and estimate their probabilities of occurrence. Hence, the complicated contaminant pathways

depicted in Figure 2.3 are replaced with three greatly simplified pathways (Figure 3.1). These three generic migration pathways comprise the release scenario, which has a probability of one of occuring. (Release is not necessarily simultaneous or equal along all pathways.)

$$\hat{R}_h = \Sigma\, \psi_k \qquad k = \text{number of pathways};\ P_k = 1 \qquad [3.1]$$

SRS assumes that the consequence [ψ] (for example, chronic illness or cancer death) of any pathway is influenced by three factors: the size of the population at risk [N], the exposure [E] of that population to the hazardous material, and the toxicity of hazardous material [T]. Let toxicity be expressed as age-adjusted annual risk per rate of exposure, assuming an average 70-yr life [for example, (1/70) (lifetime risk per mg/kg/day)]. Further, assume that the risk to an average population, not a sensitive subset such as children, is the ranking index of interest. Finally, let exposure be expressed as a daily rate (for example, mg/kg/day). Then the annual number of instances of chronic illness or cancer deaths, which is the consequence [ψ], is

$$\psi \propto N \cdot E \cdot T \qquad [3.2]$$

Furthermore, the consequence [ψ] of any pathway for all chemicals is the sum of the consequences from each hazardous chemical or radionuclide of the inventory at the waste site; hence, the risk is proportional to

$$\hat{R}_h \propto \sum_k \sum_\ell N_{\ell k} \cdot E_{\ell k} \cdot T_{\ell k} \qquad \ell = \text{chemical},\ k = \text{pathway} \qquad [3.3]$$

Of these three factors, two--population and toxicity--are easily characterized by single "scores" in a ranking system and discussed in Chapter 4. Only exposure [E] must be disaggregated further into component factors.

The specific component factors of E, which vary with each pathway, are discussed in detail in Chapters 5, 6, and 7, but generally the amount of exposure is evaluated from the quantity of material initially deposited at the site [W_o] and the factors indexing the effectiveness of the engineered barrier [f_{eng}] (for instance, waste package or facility design) and site

features [f_{site}] in reducing the amount of hazardous substance reaching the potentially exposed population:

$$E \propto W_o \cdot f_{eng} \cdot f_{site} \qquad [3.4]$$

Substituting equation [3.4] into [3.3] yields (assuming the population [N] does not change with the chemical)

$$\hat{R}_h \propto \sum_k N_k \sum_\ell T_{\ell k} \left[W_o \, f_{eng} \, f_{site} \right]_{\ell k} \quad \ell = \text{chemical},\ k = \text{pathway} \qquad [3.5]$$

In a detailed risk assessment, the mass of waste [W_o] should be divided among the various pathways; however, SRS only roughly estimates the health risk, thus, this minor adjustment in equation [3.5] is unnecessary. The abstractness of equation [3.5] belies the relative simplicity of SRS revealed in Figure 3.2.

Scoring Individual Factors

We made SRS easier for hand calculations by tabulating "scores" for the individual factors as done with most hand ranking systems. We selected the appropriate scores by simply using the logarithms of the factors in the basic ranking equation [3.2]. These individual scores can then be added (subtracted) rather than multiplied (divided) to arrive at the overall score. For example, the logarithm of the expression for exposure, equation [3.4] is as follows:

$$\log (E) \propto \log W_o + \log f_{eng} + \log f_{site} \qquad [3.6]$$

Furthermore, because the various site parameters that influence E will likely be known within only a factor of ten, using preliminary data, we used only the logarithm to the nearest integer (the characteristic).

To substitute equation [3.6] into [3.5], one must first take the antilogarithm. Yet, the score has already been based on the assumption that the preliminary data are not better than a factor of 10; thus, we can approximate the addition by taking the largest of the logarithm scores. For

instance, a score of 1 for one chemical along a pathway added to a score of 3 for another chemical results in a pathway score of 3 ($10^1 + 10^3 \approx 10^3$).

However, if several chemicals have the same large score, the score should be increased. A simple rule such as

$$F_t \simeq F_a + 0.1\ n_a + 0.01\ n_b + \ldots \qquad [3.7]$$

where

F_t = total score; e.g., $F_t = \log\ (\Sigma\ E_\ell T_\ell)$
F_a = highest individual score; e.g., $F_a = \log\ E_\ell T_\ell$
n_a = number of chemicals with score F_a
n_b = number of chemicals with score one unit less F_b
F_b = next highest individual score

suffices for hand calculations. For instance, suppose 10 chemicals all had a score of 8. Using equation [3.7] we would assign a score of 9, which on a logarithm scale is 10 times as bad as a score of 8. To be consistent with data inaccuracies, one should round equation [3.7]. For example, if more than 3 chemicals have the same score, increase it by a full unit.

There are several advantages to selecting the logarithm, rounded to the nearest integer, as the score for SRS:

- It simplifies the hand calculations; only order-of-magnitude effects are scored.
- It automatically restricts the sensitivity of the ranking system to order-of-magnitude effects.
- It makes SRS similar to other ranking systems, yet selection of scores is easily understood if modifications are necessary; furthermore, the scores are not excessively large or small.

We must acknowledge a disadvantage, best demonstrated with an example, that often exists with other hand ranking systems as well. If SRS scores two different sites as 20 and 25, then SRS has measured a five order-of-magnitude difference between them; however, this difference is not readily conveyed to an analyst with only a 5-point spread in the scores. We feel the advantages outweigh this disadvantage; however, the analyst is by no means restricted to the logarithmic scoring system. The analyst can record the actual numerical

value of each factor on the worksheets and multiply, divide, add, and subtract as required by the models on which SRS is based.

Programming the basic SRS equation (equation [3.7] along with the expressions for exposure discussed in Chapters 5, 6, and 7) on a personal computer could eliminate the need for logarithmic approximations. Indeed, we plan to do this; however, we also wanted SRS to be workable with hand calculations to maintain its versatility while developing and checking its feasibility.

Sensitivity/Uncertainty Analysis

SRS was developed to effectively allocate resources towards those sites with the greatest potential risk. However, SRS is most necessary when little information on sites is available; therefore, a risk manager also must know the important data to collect based on the potential impact of that data. This knowledge in turn, requires understanding the ranking system.

The SRS model equations developed in Chapters 5, 6, and 7 list the variables to measure or index to evaluate consequences of hazardous waste release along the three pathways (for example, fluid pore velocity [V_{gw}] and waste quantity [W_o]). Yet, we can glean more understanding from these equations through sensitivity/uncertainty techniques (Iman et al., 1981a, 1981b).

A detailed sensitivity/uncertainty analysis was not within the scope of the first phase of developing SRS. Hence, we do not present results from a detailed analysis but rather describe here the added insight the analysis provides and how we incorporated the concepts into SRS.

General definitions. With sensitivity/uncertainty analysis we evaluate the potential variation of variables and their relative importance on the results. Specifically, the SRS ranking model is a function $\hat{R}(X_1,...X_k)$ of variables $X_1,...,X_k$. Because $X_1,...,X_k$ have ranges and distributions, $\hat{R}(X_1,...,X_k)$ will also have a range and distribution. Uncertainty analysis involves determining properties of the distribution of $\hat{R}$. These properties include the distribution, expected value, and variance of $\hat{R}$. Sensitivity

analysis involves determining the importance of an individual X_i in influencing $\hat{R}$ and its uncertainty (Helton et al., 1986).

Sensitivity of Variables in SRS

Measures of variable importance. One approach to sensitivity analysis (especially useful for analytic models such as used in SRS) is differentiation of the model with respect to the independent variables X_i. Specifically, the model can be approximated by a Taylor series

$$\hat{R} \simeq \hat{R}(\mathbf{X}_0) + \Sigma_i \frac{\partial \hat{R}(\mathbf{X}_0)}{\partial X_i} \{X_i - X_{i0}\} \qquad [3.8]$$

where

$\mathbf{X}$ = vector of variable values X_i

$\mathbf{X}_0$ = vector of "base case" variable values X_{i0}

Because the partial derivatives of [3.8] are dependent on units, they are typically normalized to either

$$\frac{\partial \hat{R}(\mathbf{X}_0)}{\partial X_i} \frac{X_{i0}}{R(\mathbf{X}_0)} \qquad [3.9]$$

or

$$\frac{\partial \hat{R}(\mathbf{X}_0)}{\partial X_i} \frac{S(X_i)}{S(R)} \qquad [3.10]$$

where

$S(X_i)$ = standard deviation of X_i distribution

$S(\hat{R})$ = standard deviation of $\hat{R}$ distribution

Depending on the analyst's preference, an ordering of the absolute values of either [3.9] or [3.10] can be used to measure and rank variable importance $[I_i]$. Using equation [3.9],

$$I_i = \left| b_i \frac{X_{i0}}{R(\mathbf{X}_0)} \right| \qquad [3.11]$$

otherwise using equation [3.10]

$$I_i = \left| b_i \frac{S(X_i)}{S(R)} \right| \qquad [3.12]$$

where

$$b_i = \frac{\partial \hat{R}(X_0)}{\partial X_i}$$

Equation [3.9] ranks variable importance based on the effects of equal percentage changes from the base case values X_{i0} [the traditional sensitivity analysis first introduced by Tomovic (1963)]. The normalization in equation [3.10] ranks variable importance based on the effects of equal percentage changes of the standard deviation $S(X_i)$. Hence, [3.10] folds in the likelihood that a variable X_i will vary enough to potentially influence the result $\hat{R}$ while [3.9] does not.

Numerical sensitivity analysis. The normalization expressed by [3.10] is especially useful because, conceptually, [3.10] is equivalent to standardized regression coefficients (SRCs) $[b_i S(X_i)/S(\hat{R})]$ where here b_i denotes a model regression constant (Helton et al., 1986). The absolute values of SRCs (and the mathematically related partial correlations coefficients, PCCs) are frequently used for ranking variable importance when complex computer codes describe the model (numerical sensitivity analysis). The method involves constructing a regression model between the variables and the observed response $\hat{R}_{ob}$ (Iman and Helton, 1985) in conjunction with a Monte Carlo approach [such as Latin hypercube constrained sampling (McKay et al., 1979)].

Sensitivity variation with distribution. The measure of importance expressed by equation [3.10] is very useful for environmental models were variables may vary over several orders of magnitude because an important purpose of a sensitiviy analysis is to allocate data collection resources towards those variables that most influence $\hat{R}$ based on what is already know about the site. When a variable is precisely known, we may not want to allocate more resources towards evaluating it even though the variable could potentially effect results if it varied.

In general, two steps can occur with sensitivity analysis when using sensitivity measures influenced by the variable distributions; the information gleaned at each step can differ slightly. We can

1) examine function behavior ($\hat{R}$) as the independent variables, $X_1, \ldots X_k$, vary over their global range of uncertainty (range over all sites)

2) evaluate influence of independent variables, $X_1, \ldots, X_k$, on $\hat{R}$ over a specific subset of their range (for example, a specific site),

In the first case, we evaluate the potential importance of each variable in differentiating between sites, in the second case, the importance of each variable at a specific site.

Sensitivity of linear SRS model. Often the pathway models in SRS reduce to a multiplicative equation (or linear equation with a logarithmic transformation),

$$R = N \cdot (W_o f_{eng} f_{site}) \cdot T \qquad [3.13]$$

when the exponential term of f_{eng} and f_{site} drop out. Indeed, we purposely reduced the models to this multiplicative form (often with coarse approximations) for hand calculations. (A computerized version of SRS would incorporate a more rigorous sensitivity analysis of the simple but complete model.) Consequently, an analyst can more easily discern the importance [I_i] of a site score to a variable. The controlling factors are the power on the variable [b_i] (or leading coefficient after a logarithmic transformation) and either its base case value [X_{i0}] or its standard deviation $S(X_i)$.

For example, if base case values for W_o, f_{site}, f_{eng}, T, and N of equation [3.13] were 10^3, 1, 1, 15, and 10^4, respectively, a ranking of variable importance by equation [3.11] would indicate that $N > W_o > T > f_{site} = f_{eng}$ (importance influenced by base case values). However, if the expected range of W_o varied by a factor of 100, f_{site} by a factor of 10, f_{eng} by a factor of 5, T by a factor of 2, and N by a factor of 1.2, an analyst reaches a different conclusion if equation [3.12] is the measure of importance. The order of variable importance would be $W_o > f_{site} > f_{eng} > T > N$ (importance influenced by distribution) (Hoffman and Gardner, 1983).

Uncertainty Analysis in SRS

As implied when defining uncertainty analysis, the final risk score assigned to a site is made up of numerous individual scores, each with varying degrees of uncertainty. Some site scores will undoubtedly be more

certain than others, if only because a more complete data set is available. For these sites, the ranking might be relatively firm. However, if the uncertainty is high in some individual scores, less confidence should be placed on the total score.

Sources of uncertainty. Errors in model predictions of real-world phenomena will result from

- improper parameter estimation,
- biased models.

An analyst evaluates improper parameter estimation either by incorporating variable uncertainty directly when formulating the problem (stochastic approach) or by combining a Monte Carlo sampling with a deterministic formulation of the problem. Because SRS is based on a deterministic formulation, we will discuss parameter uncertainty analysis from this latter point of view.

However, the utility of the parameter uncertainty analysis depends on having a relatively unbiased model of the system, that is, the model adequately represents the system (model validation). Validating a model requires site specific experimental data. Certainly for a initial site screening, validation of the simple models in SRS will not occur. Nevertheless, qualitative judgments about the ability of the scoring system to capture unique features should be noted in any accompanying narrative. The information may be especially useful when attempting to rank sites with similar scores.

Best estimate of variable used for scoring. When using an uncertainty analysis approach, the analyst should assign a score based on the best estimate, not a highly conservative estimate, regardless of the degree of uncertainty in a parameter's value. Otherwise, (1) distortions in the score and ultimate ranking occur and (2) the meaning of the uncertainty is unclear. (We discuss at the end of this section an alternate technique for identifying uncertainty in the score using conservative estimates.)

Uncertainty estimates. As mentioned above, for complex models uncertainty estimates using deterministic models are made using Monte Carlo sampling. (Because analytic equations are used in SRS, a computerized version could perform an uncertainty analysis each time a site was scored.) Because SRS has been reduced to linear combination of groupings of parameters for hand scoring, the uncertainty can also be evaluated fairly easily by associating a tolerance or standard deviation [$\pm$ $S(X_i)$] about the expected value of X_i (best estimate) and combining these standard deviations to obtain an overall score uncertainty as follows (assuming no correlation between X_is) (Hoffman and Gardner, 1983):

$$S(\hat{R}) = \left[\sum_i^n S(X_i)^2\right]^{1/2} \qquad [3.14]$$

Although engineering judgement is reasonable for estimating individual $S(X_i)$ in SRS, standard deviations based on optimistic and pessimistic values for a parameter could be assigned as in estimating completion times for project management (Wiest and Levy, 1977):

$$S(X_i) = (F_{ip} - F_{io})/6 \qquad [3.15]$$

where

F_{ip} = pessimistic score estimate for variable X_i
F_{io} = optimistic score estimate for variable X_i

We recommended uncertainty estimates by equation [3.14]; however, an important purpose of an uncertainty analysis is to pinpoint variables and/or pathways that significantly contribute to uncertainty and, thereby, need more precise evaluation either to confidently score a site or to help direct detailed RI/FS studies. This latter purpose (pinpointing highly uncertain variables and/or pathways) can be accomplished to a limited extent by providing a worse-case estimate.

Worst-case estimate. Unless a standard deviation is required, for hand calculations one can carry along another "score," in addition to the score for the best estimate to flag highly uncertain variables and pathways. This "score" is a pessimistic, worst case, or highly conservative estimate of the score. If the score uncertainty is high because of variable uncertainty, this fact should be reflected in the disparity between the best-estimate site score and the pessimistic "score." A large disparity suggests the need

to examine the site in more detail, specifically, parameters with large disparity between best-estimate and pessimistic scores.

Missing data. A problem also arises when data are completely missing. Our fundamental premise is that lack of data on a specific site means, in essence, that the site is not known to differ from a typical site (within the group of sites being ranked). Therefore, one should assign a score that is typical for the group. Of course, the uncertainty in such an assignment is large and should be indicated by a large variance or pessimistic score.

Although we recommend that default values should be typical (neutral), not extreme, as a risk policy decision an agency may decide to specify low scores (or conversely, high scores) when data to support a score assignment are fragmentary or entirely missing. However, we caution this approach ensures that sites will rank low (or high) if data are sparse. In addition, this policy may (1) allow the analyst to more easily influence site rank by deciding whether or not to look for data (an important practical consideration) and (2), cause greater variation in scores assuming that between individuals estimates of a bounding or conservative value for a variable differ more than estimates of a mean value.

Using Monitoring Data

SRS uses monitoring data to make or check estimates of chemical quantity [W_o] (by using the measured areal extent, thickness, and concentrations, assuming that the concentrations are steady-state values--see Appendix B). In addition, if monitored data suggest that an urgent response is needed, this information is noted in the narrative of the site.

However, SRS does not directly score the monitoring data (for example, whether release is observed or its areal extent). If a few sites have detailed monitoring data, a few have sporatic observations, and the rest have no direct observations of release, using monitoring data directly is difficult. Monitoring data at a site may suggest, on the one hand, lower risks or, on the other hand, greater risks than predicted by SRS. An analyst has limited means to discern between these two possibilities without using calibrated models to interpret where he is in the development of a pollution plume (maybe the peak concentration has passed, maybe it is yet to come); and

building and calibrating models is not justified for determining a preliminary site rank. Furthermore, even after analyzing the monitoring data, there is the question of how to rank monitored with unmonitored sites.

Although SRS does not require monitoring data, as a policy decision, an agency may require monitoring data to reduce uncertainty in the ranking. For example, for old sites without disposal records, the uncertainty of waste quantity estimates may be very large; monitoring might reduce this uncertainty. Monitoring would also help answer risk management questions about cleanup cost and technical feasibility. Furthermore, RCRA regulations require monitoring if the site is to remain active.

Summary of SRS Assumptions

Because of assumptions made in its development, SRS

- assumes health risk is the most important risk to evaluate;
- makes only an order-of-magnitude estimate of the health risk;
- evaluates only chronic risks during the mean life of an individual;
- evaluates only risks along three generic pathways;
- assumes health risk [$\hat{R}_h$] of a hazardous material at a site is proportional to amount of exposure [E], substance toxicity [T], and population exposed [N] (which implies population risk is more important than individual risk for ranking);
- uses the best estimate of a factor influencing the health risk, not a worst case or highly conservative estimate, except as a measure of uncertainty in the score;
- uses monitoring data for calculating W_o and i_r, for breaking ties, or for independently ranking sites, depending on number of sites with monitoring data.

4. POPULATION AND TOXICITY SCORES

SRS assumes the consequence [ψ] of exposure to a toxic substance is proportional to the product of population [N], exposure [E], and toxicity [T]: $\psi \propto N \cdot E \cdot T$. The following section first demonstrates how to score the population [N] using a logarithm-based table, then describes how to characterize and score toxicity [T]. The underlying theoretical models used to evaluate the exposure factor [E] for the ground-water, surface-water, and air pathways are described in Chapters 5, 6 and 7.

Population Score

The population score [F_{pop}] is simply the logarithm of the population [N] at risk rounded to the nearest integer (Table 4.1). Specifically, the score for a population of 300 is $2.477 \simeq 2$. This score [F_{pop}] of 2 for N would be added to the score [F_{tox}] for toxicity [T] and the score [F_{exp}] for exposure [E] to obtain the pathway score for one specific hazardous material.

Table 4.1 Target population scores

Population [N]	Score[a]
<3	0
3-30[b]	1
30-300	2
300-3,000	{3}[c]
3,000-30,000	4
30,000-300,000	5
...	

[a]Score = log(population)
[b]Log(3) through log(30)≃ 1
[c]Score chosen by default

The default score (3 in Table 4.1) should be typical of the group (for example, the mode) of waste sites being ranked; therefore, the value can change.

Clearly, the scoring is similar to other ranking schemes: It consists primarily of looking up values in tables. Yet, the theoretical basis of SRS allows it to interweave with the overall goals of risk assessment. The real difficulty in SRS (or any ranking system) is selecting the parameter value (that is, collecting and interpreting the data).

The instructions provide guidelines for selecting parameter values, but these are stated primarily to provide consistency in estimating values from sparse data--important because many individuals will likely help rank the sites. (Presumably in needing SRS you have too many sites and too little time to do detailed investigations of every site, which usually implies that the task of ranking the sites is too large for one or a few specially trained individuals to complete in a reasonable amount of time.)

Consistency, however, does not always imply the most accurate technique is used. For example, the instructions specify the current population potentially exposed. Yet, one may correctly argue that for rapidly expanding areas the current population may be misleading. The projected population in 10 years may better estimate the population exposed over the "long-term." Provided data exist to estimate the future population, the analyst may choose to ignore the guidelines to better estimate health risks.

We note that although both the health risk to an individual and the risk to the entire population can be important, we assume that for ranking a site the risk to the entire population is more important. This is a risk policy decision. (However, SRS does use the individual score, the score ignoring the population, as a tie-breaker in Chapter 8)

Chronic Toxicity

The human health effect of a unit dose exposure to a chemical is evaluated from the chemical toxicity [T]. Two bases of chronic toxicity are used:

- acceptable daily intake (ADI) for noncarcinogens, and
- unit cancer risk (UCR) for carcinogens and radionuclides.

These toxicity measures are also used by EPA for the detailed RI/FS studies.

The acceptable daily intake (ADI) as defined in this report means the highest human intake of a chemical, expressed as mass of chemical per individual body mass per day, that does not cause adverse effects when exposed for a lifetime. (EPA uses the alternate term, reference dose [RfD] for ADI.) Although, many early ADIs were originally developed for assessing acute toxicity, the practical application of ADIs over the past 20 years has been in setting food and drinking water standards (chronic toxicity) (CWA, 1977). Health Effects Assessment (HEA) documents by the EPA Office of Research and Development are the recognized sources for ADIs on hazardous materials (Appendix C).

Toxicologists evaluate the ADI for a chemical by applying a safety factor (to account for species differences and interspecies variation) to the experimentally estimated threshold dose (NOAEL). [Traditionally, noncarcinogenic chemicals are thought to have a threshold dose below which a toxic effect will not occur, the no-observed-adverse-effect level (NOAEL).] The safety factors vary: a 10-fold safety factor for long term human experiments; a 100-fold safety factor for well-conducted, chronic, animal experiments; and a 1000-fold safety factor for subchronic animal or lower-quality experiments (FSC, 1980).

The unit cancer risk (UCR) is the upper bound on lifetime risk of cancer per unit of dose, expressed as risk per mass of substance per individual body mass per day. (EPA uses the alternate term, carcinogenic potency factor [CPF] for UCR.) For carcinogens, toxicologists generally assume there is no threshold dose below which the substance will not cause cancer: any exposure level poses some risk of cancer. To estimate the cancer risk, toxicologists extrapolate from studies on animals at high doses to humans at low doses using a mathematical model, frequently linear (BEIR, 1980) [although much controversy surrounds the amount of conservatism in this approach (Runkle et al., 1981)].

Although for chemical carcinogens, the UCR is often reported in HEA documents, cancer risk from radionuclides is usually reported by dose factors (ICRP, 1979; BEIR, 1980). We calculated equivalent UCRs (Appendix C) on the basis of these dose factors for use with SRS as follows.

Calculation of radionuclide UCR. Provided that the cancer risk [CR] per rem and the dose factor for either ingestion [DF_{oral}] or inhalation [DF_{air}] are known, the calculation of an equivalent UCR is straightforward:

$$UCR = CR \cdot DF_{oral} \cdot Z \qquad [4.1]$$

where

CR = cancer risk per rem (cancer risk/rem)

DF_{oral} = dose factor from ingestion (rem per μCi/day)

Z = weight (70 kg)

Normally for radionuclides, the quantity [W_o] is expressed in terms of its activity (Ci) rather than its mass (kg). For this case, Z converts UCR toxicity [T] expressed in units of $(\mu Ci/day)^{-1}$ to $(\mu Ci/kg\ body\ mass/day)^{-1}$ to be consistent with ADI toxicity.

Runkle et al. (1981) tabulate dose factors for ingestion [DF_{oral}] and inhalation [DF_{air}], assuming lifetime (70 yr) intake for numerous radioisotopes and the latent cancer risk per rem for several types of cancer. From these tables we calculated the ingestion or inhalation UCR listed in Appendix C by selecting an organ [b] (including the whole body) with the largest product of DF and CR.

Comparing ADI and UCR. As explained when defining ADI and UCR, the assumptions toxicologists use to evaluate these measures of toxicity differ. However, they both attempt to evaluate chemical hazards. For use in SRS, the scales for the two measures of toxicity, UCR and ADI, must align such that a carcinogen (UCR) receiving a score of -5, for example, represents roughly the same risk as a noncarcinogen (ADI) receiving a score of -5. Aligning the scales requires finding the points representing acceptable risks for the two scales. This alignment is a policy choice, however, not a scientific one.

Acceptable cancer risk. Although not entirely consistent, regulations of the Food and Drug Administration (FDA) and Environmental Protection Agency (EPA) have generally considered lifetime cancer risks from individual chemicals of less than 10^{-6} as insignificant and risks between 10^{-6} and 10^{-4} as possibly significant but acceptable if technically infeasible or too costly to reduce further (for example, polychlorinated biphenyls (PCBs) and dioxin) (Rodricks et al., 1987). Consistent with this generality, EPA policy

permits the aggregate cancer risks after cleanup at Superfund sites to range anywhere from 10^{-4} to 10^{-7} (EPA, 1986b). We chose 10^{-5} as representing a "very small" aggregate cancer risk from a waste site (Rodricks, 1984). [An incremental increase of 10^{-5} is very small because a person currently has between a 0.2 to 0.3 chance of dying from cancer in the United States (Almanac, 1986)].

A 10^{-5} chance of contracting cancer approximates the middle ground for involuntary aggregate risks permitted in regulations. For example 10CFR20 (radiation protection standard) limits involuntary, whole-body radiation exposure to the public to 0.5 rem/yr (voluntary occupational exposure is 5 rem/yr) and 10CFR61 and 40CFR190 (low-level nuclear waste and nuclear power regulations) to 0.025 rem/yr. The latent cancer risk over a lifetime per rem of exposure for whole body exposure is about 1.5×10^{-4} (Runkle et al., 1981), thus the regulations correspond to risks of 7.5×10^{-5} and 3.75×10^{-6}, respectively, for involuntary exposure (and 10^{-3} for voluntary exposure).

Acceptable noncancer risk. We assumed that the health risk from a lifetime ADI exposure is also 10^{-5}. An ADI for a noncarcinogen is established such that the allowable dose poses no more than a very small risk of adverse effects. Unfortunately, we have no means of quantifying this "very small" risk. If one assumes that noncarcinogenic materials have a threshold dose below which the toxic effect will not occur, the no-observed-adverse-effect level (NOAEL), the risk is very small indeed.

However, we present the following two arguments to support our assumption of 10^{-5}. First, we simply argue that regulators have established 10^{-5} as an acceptable risk and ADI levels are defined as acceptable. Second, (although admittedly more conservative than the threshold concept) we heuristically argue as follows. If, as an example, an animal study includes 1000 animals in the test group and at a certain extrapolated dose 1 animal is adversely affected in comparison to a control group; then there is a 0.1% risk near the NOAEL level. If a 100-fold safety factor is applied to the NOAEL, the risk is indeed 10^{-5} (assuming a 1 to 1 dose response curve).

Aligning scales. If the assumptions concerning UCR and ADI health risks are accepted, one can align the UCR and ADI scales (Table 4.2). For example,

a mild carcinogen with a UCR of 10^{-5} cancer risk per mg/kg body weight/day has an equivalent allowable daily intake (ADI) of 1 mg/kg/day if a cancer risk of 10^{-5} is acceptable; UCR•ADI = 10^{-5} cancer risk. In principle, Table 4.2 is unbounded, but in practice most substances fall within the ranges shown.

Table 4.2 Chemical/radionuclide chronic toxicity[a]

Chronic Toxicity [T]		
UCR (mg or μCi/kg/day)$^{-1}$	ADI[b] (mg or μCi/kg/day)	Score[c]
$3\times10^{-6} < 10^{-5} \leq 3\times10^{-4}$	$3\times10^{0} > 1 \geq 3\times10^{-1}$	-5
10^{-4}	10^{-1}	-4
10^{-3}	10^{-2}	-3
10^{-2}	10^{-3}	-2
10^{-1}	10^{-4}	-1
10^{0}	10^{-5}	{0}[d]
10^{1}	10^{-6}	1
10^{2}	10^{-7}	2
10^{3}	10^{-8}	3

[a]Toxicity to average cross-section of population
[b]UCR and ADI scales aligned assuming similar severity of effects; divide 10^{-5} by ADI for UCR
[c]Score = log(UCR toxicity)
[d]Score chosen by default

Table 4.2 also shows the score (logarithm) that SRS assigns to the toxicity factor. Toxicity [T] should be converted from toxicity per body mass per day (mg/kg/day)$^{-1}$ to toxic risk for an average individual for a lifetime (kg^{-1}) by converting from mg to kg and multiplying by average body mass [w = 70 kg] and life expectancy [$t_\ell = 2.56\times10^{4}$ day] to be consistent with exposure [E]. However, because the conversion is similar for all chemicals and because the conversion is $0.556 \simeq 1$, it was omitted.

5. GROUND-WATER SCORE

This chapter discusses the method used to evaluate the ground-water exposure score [E_{gw}]. It starts by describing the idealized ground-water pathway and follows with the model underlying the SRS scoring. Subsequent sections discuss the derivation and justification of this simple model, which you may wish to defer reading until later.

The ground-water pathway rarely can be ignored; it is frequently the most important contamination route. As shown by Table 2.1, ground-water contamination accounted for roughly 60% of the cases in the EPA survey (Lazar et al., 1976). The EPA also reported that nearly one-third of large, public ground-water systems in the United States show signs of chemical contamination, frequently from landfills (EPA, 1984a).

Idealized Ground-Water Pathway

The idealized ground-water pathway begins at a landfill (lagoons or injection wells involve simple modifications). Trapped moisture and precipitation vertically seeping into the landfill (no lateral seepage) react with the waste to form a leachate. This leachate escapes from the landfill by seeping through any degraded container and/or liner or fills and overflows the edges. It percolates vertically downward through the unsaturated zone to an aquifer (both assumed porous media). The chemical is transported through the aquifer either to a well down gradient from the landfill, where it is withdrawn, or to a stream that supplies drinking water (Figure 5.1).

Understandably, actual sites may vary from this conceptual model. Unfortunately for the ground-water pathway, variations are not easily recognized without extensive site investigation. Furthermore, leakage of leachates into the potable aquifer may take years or decades to become apparent: First, leaching of the soluble and suspended waste is slow and often intermittent. Second, flow rates in the unsaturated zone and aquifer are slow, ranging from meters per day to meters per year. Consequently, an aquifer presumed isolated from waste in an initial scoring may later be polluted, for example, through an abandoned well. Herein lies the difficulty in scoring the ground-water pathway.

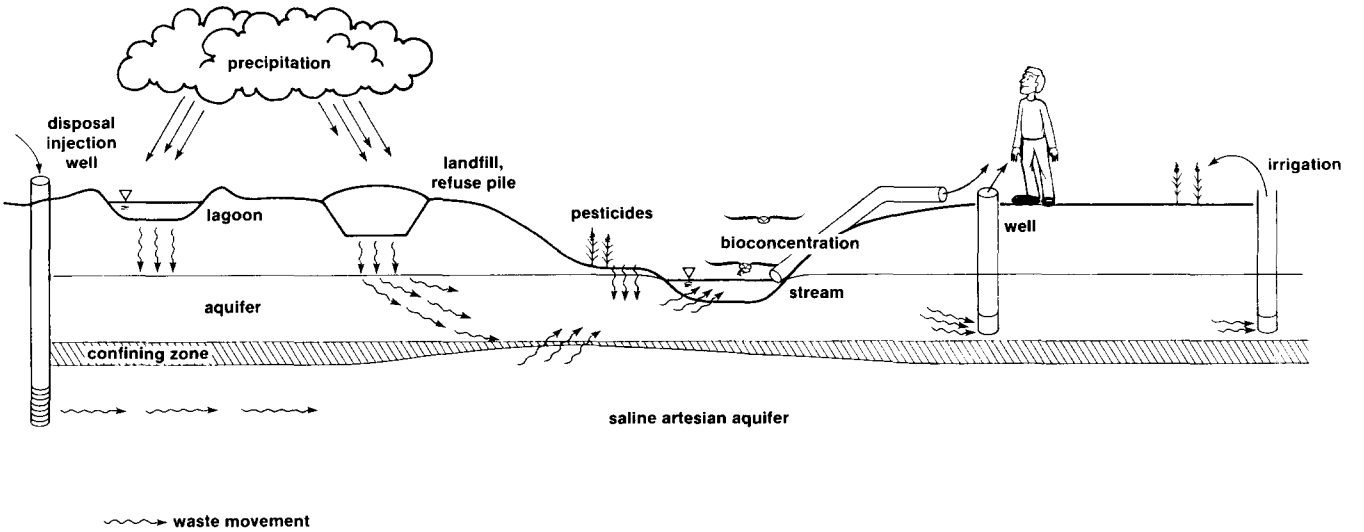


Figure 5.1 Conceptual model for ground-water pathway

Method of Scoring

Generally, the exposure is evaluated as

$$E \propto W_o \cdot f_{eng} \cdot f_{site}$$

where

W_o = mass of hazardous material initially left at site (kg or Ci)
f_{eng} = factor indexing effectiveness of engineered barriers
f_{site} = reduction factor indexing effectiveness of site features

The mass of material [W_o] is determined directly from preliminary data. The engineered-barrier reduction factor [f_{eng}] is evaluated from

$$f_{eng} \simeq \frac{1 - \exp(-\lambda_s t_\ell)}{\lambda_s t_\ell} \cdot f_{put} \cdot f_{cllct} \cdot f_{rtrd} \qquad [5.1]$$

where

f_{put} = subjective factor evaluating method of waste placement
f_{cllct} = subjective factor evaluating leachate collection practices
f_{rtrd} = subjective factor for evaluating chemical retardation
t_ℓ = time frame of interest (day)
λ_s = decay rate while at site $(day)^{-1}$

The site reduction factor [f_{site}] is evaluated as follows (units are given as assumed in SRS but any consistent units can be used; square brackets enclose dimensionless groups):

$$f_{site} \simeq \left[\Gamma_{gw} \cdot \frac{1}{m} \cdot \frac{1}{x_{gw}^{1/2}} \cdot \frac{1}{V_{gw}} \right] \cdot \delta_{gw} \cdot g_{gw} \cdot \exp\left[-d\frac{\lambda_u}{V_u}\right] \cdot \exp\left[-x_{gw}\left(\frac{\lambda_{gw}}{\alpha_{gw} V_{gw}}\right)^{1/2}\right] \qquad [5.2]$$

where

d = vertical distance from base of waste to aquifer (m)

g_{gw} = $1-\exp(-i_r t_\ell S/W_i)$ = mass-release adjustment

- i_r = leachate flow rate from waste site (m^3/day)
- t_ℓ = average life expectancy (2.56×10^4 day)
- S = chemical solubility (kg/m^3)
- W_i = quantity released (kg or Ci) = $W_o \cdot \dfrac{1 - \exp(-\lambda_s t_\ell)}{\lambda_s t_\ell}$
  - t_ℓ = time frame of interest (day)
  - W_o = quantity originally deposited at site (kg or Ci)
  - λ_s = decay rate while at site (day^{-1})

m = aquifer thickness (m)

x_{gw} = horizontal pathway distance from waste site to target (m)

V_{gw} = average aquifer interstitial pore water velocity (m/day)

V_u = unsaturated average interstitial water velocity (m/day)

α_{gw}, α_u = dispersivity ({0.1x if x ≤ 200 m; 20 m if x> 200 m}

Γ_{gw} = $B_w / [\phi\ (\pi\alpha)^{1/2}]$ ($m^3/m^{1/2}$/day)

- B_w = average water ingestion rate (2×10^{-3} m^3/day; 2 ℓ/day}
- ϕ = average aquifer porosity {0.3}

δ_{gw} = $i_r/(i_r + Q_a + Q_w + Q_r)$ = dilution of waste along pathway

- i_r = leachate flow rate from waste site (m^3/day)
- Q_a = additional uncontaminated water (m^3/day)
- Q_w = well withdrawal rate (or seepage from aquifer to river)
- Q_r = discharge in intervening river if $x_{riv} \geq \ell_m$; otherwise
  = $\left[\dfrac{x_{riv}}{\ell_m}\right]^{1/2}$ • river discharge (m^3/day); $\ell_m = \dfrac{w_{riv}^2 \cdot 15}{d_{riv}}$
  - d_{riv} = depth of river (m)
  - x_{riv} = distance traveled in river (m)
  - w_{riv} = width of river (m)

λ_u = average decay rate of waste in unsaturated zone (day^{-1})

λ_{gw} = average decay rate of waste in aquifer (day^{-1})

Nine major assumptions used to arrive at equation [5.2] are as follows:

- Steady-state conditions appropriate for ranking chronic risks.
- Degradation of the toxic waste is represented by first-order decay.
- A mixing cell appropriately represents leaching of the waste.
- 1-D, vertical, saturated, waste transport occurs in unsaturated zone.
- 2-D, horizontal transport applies (vertical mixing occurs rapidly).
- An individual's life expectancy (70 yr) is time frame of interest.
- Solubility [S] of the chemical indexes initial concentration [C_o].
- Hydrodynamic dispersion [D] approximated by αV; D^* unimportant.
- Constant concentration injected into aquifer.

The SRS scores for the multiplicative factors of equation [5.2] are simply the logarithms of those factors rounded to the nearest integer. The instructions in Chapter 8 describe how to estimate these various parameters and provide tables for scoring. In addition, worksheets in Appendix A help an analyst organize data and properly combine scores. These scoring tables and worksheets make use of SRS much more straightforward than might initially appear from equations [5.1] and [5.2].

EPA has developed methods for assessing, in emergencies, exposure from accidental contamination of ground water or air (Cowherd et al., 1985; Donigian et al., 1983). Ideally, an assessor can gather information and evaluate one pathway in less than 24 hr. The formulas are similar to [5.1] and [5.2] and those described in the next two chapters, but they incorporate more detail on transport phenomenon. However, the rapid assessment methods are readily adapted to SRS, should an analyst wish more detail.

Derivation of Scoring Model

The ground-water migration of contaminants from a waste site to a downgradient target is conveniently divided into several segments. The following sections describe these segments (source term, unsaturated zone transport, aquifer transport, and withdrawal) in more detail. The end results are formulas [5.1] and [5.2] that indicate important parameters to score and the way to combine these scores. Because landfills are slightly more prevalent (Table 2.1), the discussion assumes a landfill waste site.

Engineered-barrier factor. Engineered barriers serve to

- extend the containment of the chemical (beneficial if decay occurs),
- lower the release rate,
- minimize human access to waste in the near term.

They do not, however, provide indefinite isolation unless decay is complete, especially for the ground-water route.

The expression for the engineered-barrier reduction factor [f_{eng}], equation [5.2], contains an analytic expression and three subjective factors. Because the quantity of waste escaping from the site can differ from that initially placed [W_o], if the waste can decay while held at the site, we corrected the waste quantity by $(1-\exp(-\lambda_s t_\ell))/\lambda_s t_\ell)$, where λ_s is the decay rate while at the site (day^{-1}) and t_ℓ is the time frame of interest. For many sites and waste material this correction will be minor.

The subjective factors (f_{put} and f_{rtrd}) adjust the score to account for transient effects of waste release. As is described later, SRS is based on steady-state formulas describing waste transport because transient phenomena have little effect on the ultimate risk to the public for surface and near-surface waste sites. As a result, parameters influencing time until exposure, such as retardation properties and waste placement, are not explicitly accounted for. Although these parameters have no influence on the ultimate risk, they do have importance in setting priorities for remedial action. For example, reduced mobility is important in delaying the extent of contamination. Thus, if two sites score identically except that the primary hazard at one site involves a chemical easily retarded, then the other site should have priority in cleanup, even though the ultimate risk is the same and might eventually make cleanup at both sites necessary.

Besides accounting for time to exposure, the placement reduction factor [f_{put}] also partially accounts for the probability of failure. For example, storage of liquid wastes in lagoons is more likely to lead to contamination than storage of stabilized waste in engineered landfills. Consequently, sites with poor waste placement should be penalized.

The subjective reduction factors acknowledge these facts and apply a small reduction in score. The reduction is small because, though the risk may be delayed, the ultimate risk is the same. Because the factors cannot be "derived," they are not defended further here but are adequately described in the instructions, Chapter 8.

Chemical decay rate. In equation [5.2], the decay rate is needed. The average decay rate of the waste is also used in subsequent calculations and is, thus, discussed in general here. The decay rate is

$$\lambda = (\ln 2)/t_{1/2}$$

where

$t_{1/2}$ = half-life of waste (day)

Persistence is a general term describing the length of time a hazardous waste remains in the environment in its toxic form. With radioactive wastes, the persistence is simply described by the radioactive half-life [$t_{1/2}$]. With toxic metals, the persistence is infinite, unless innocuous compounds can form. For inorganic or organic compounds, persistence describes the tendency to degrade into other chemical compounds or species, presumably less toxic. Common processes of degradation are (Verschueren, 1984; Sax, 1975)

- Biodegradation--enzymatic breakdown by microorganisms, typically bacteria, that can extract energy from the waste--occurs primarily in surface water and in upper layers of soil. Rates are a function of metabolic rates and population density which, in turn, are functions of availability of other nutrients, pH, temperature, and sunlight.

- Hydrolysis--addition or substitution by the OH^- radical--may be the primary route of degradation in ground water. It is significant in surface water and a possible method in air. Rates are highly dependent on water pH, yet concentrations of constituents and rate constants are also important.

- Oxidation--attack by various oxygen species--is common in air (ozone or hydroxyl radical) and surface water (alkyl or peroxyl radicals). Reaction rates are controlled by concentration and rate constants.

- Photolysis--breakdown through the action of light, usually sunlight--may include light-catalyzed oxidation (photo-oxidation). It occurs in air, shallow surface waters, and on exposed soil. Rates depend on intensity of various spectral components (photon availability), concentrations, light absorption coefficient, and rate constants.

This cursory review of degradation processes readily indicates that for many non-radioactive materials the persistence is pathway- and media-specific; hence, the analyst must approximate an average degradation rate (or equivalent half-life) for each medium. For example, for the ground-water pathway, an average degradation in the unsaturated zone and aquifer is needed. Under usual conditions this would be the biodegradation half-life in the unsaturated zone and the hydrolysis half-life in the aquifer. Furthermore, for the surface-water route, degradation from oxidation and hydrolysis would be important, and for the air route, photolysis. (However, the air-pathway model does not explicitly assume degradation in air.)

Because quantitative data on decay rates for specific chemicals are sometimes difficult to find, qualitative descriptions are also supplied for scoring. But, as a default, SRS assumes no degradation (or alternatively, the decay products are as toxic as the original waste material).

Leachate source term. The leachate is formed by infiltrating precipitation mixing with the waste. The quantity of leachate depends on the quantity of precipitation reaching the waste, which in turn depends on whether the site is open or closed. Apart from infiltrating precipitation, the initial quantity [W_o] (or concentration [C_o]) and solubility [S] of the waste are the most important factors affecting leachate composition.

To develop a simple analytic model for the chemical source, assume that the lagoon or landfill behaves as a well-mixed chemical reactor with a fixed waste inventory. The release rate as leachate [dM/dt] at any given time is then (Weber, 1972) (units as assumed in the scoring system)

$$dM/dt = C_i i_r \exp(-i_r t / \Omega) \qquad [5.3]$$

where

$C_i = C_o f_{eng}$ = chemical concentration at release (kg/m^3)
- C_o = starting concentration $\simeq$ S (kg/m^3)
- f_{eng} = engineered-barrier reduction factor (equation [5.2])
- S = chemical solubility (kg/m^3)

i_r = flow rate at which leachate leaves the site (m^3/day)

t = time after start of release (day)

Ω = waste cell volume = W_i/S (m^3)

W_i = quantity released (kg or Ci) = $W_o \cdot \frac{1 - \exp(-\lambda_s t_\ell)}{\lambda_s t_\ell}$

t_ℓ = time frame of interest (day)

W_o = quantity originally deposited at site (kg or Ci)

λ_s = decay rate while at site $(day)^{-1}$

Although some liquid pollutants can move independently of the water phase, we assume that human health risk is better indexed by concentrations of soluble pollutants. Yet, except possibly for lagoons (surface impoundments), C_o will likely be unknown. Consequently, solubility [S] becomes the surrogate of starting concentration [C_o].

As used in SRS, the exponential term [$1-\exp(-i_r t_\ell S/W_i)$] (hereafter termed the mass release adjustment [g]) mathematically determines whether the correct average release rate over period t_ℓ is $S \cdot i_r$ or W_i/t_ℓ. This fact is readily seen by noting that for small $i_r S/W_i$, $1-\exp(-i_r t_\ell S/W_i) \simeq i_r t_\ell S/W_i$; and as $S/W_i \rightarrow \infty$, $1-\exp(-i_r t_\ell S/W_i) \rightarrow 1$.

In the above expressions, we assumed the waste container released waste immediately because their life is usually less than 3 years. Accounting for container life could be important, however, in evaluating proposed sites using advanced technology containers. For these long-life containers, W_o would be reduced by $\exp(-\lambda_c L_c)$ where λ_c is the decay rate while in the container (possibly different than normal decay) and L_c is the average life of the container before leaking. This reduction would be in addition to that already accounted for in equation [5.3].

Equation [5.3] can be integrated from start of release, t = 0, to time of interest, $t = t_\ell$ (2.56×10^4 day), assuming i_r independent of time, to evaluate the total mass released [M]:

$$M = C_i \Omega \, [1 - \exp(-i_r t_\ell / \Omega)] \qquad [5.4]$$

For a landfill, i_r is the most difficult term to evaluate in equation [5.4], assuming site-specific percolation data are lacking. The flow rate from the waste site [i_r] equals the surface area of the waste site capturing precipitation [A_s] times the precipitation infiltrating [r_{seep}] into the landfill. Evaluating r_{seep} from site-specific lysimeter data is the most

desirable method, but the data are likely lacking. Thus, a percentage of annual precipitation (or conductivity of a low permeability cover) is used.

Unsaturated-zone transport. Once it escapes from the landfill, the contaminant is assumed to travel vertically downward through the intervening geologic strata to the aquifer. Although possibly occurring only intermittently, transport in a saturated condition is assumed. Furthermore, because SRS evaluates the long-term human health risk, steady-state conditions are assumed to prevail. The partial differential equation describing the transport is (Javandel et al., 1984)

$$\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_i} \right) - \frac{\partial}{\partial x_i} CV_i = \frac{\partial C}{\partial t} \qquad [5.5]$$

where

C = contaminant concentration
D_{ij} = dispersion tensor
V_i = interstitial velocity in ith spatial direction
x_i = spatial coordinate

The one-dimensional, steady-state solution to equation [5.5], with initial condition of $C(x,0) = 0$; far boundary condition of $\partial C(\infty,t)/\partial t = 0$; and input condition of $C(0,t) = C_i$, is then (van Genuchten and Alves, 1982)

$$C_a = C_r \exp\{[1 - (1 + 4D_u\lambda_u/V_u^2)^{1/2}]d(V_u/2D_u)\} \qquad [5.6]$$

where

C_a = concentration injected into aquifer (kg/m^3)
C_r = average release concentration = $M/(t_\ell i_r)$ (kg/m^3)
D_u = saturated hydrodynamic dispersion in unsaturated zone (m^2/day)
d = vertical distance from landfill or lagoon to aquifer (m)
V_u = percolation velocity in pores $\simeq r_{perc}$ (m/day)/ϕ
  r_{perc} = percolation rate
  ϕ = effective porosity in unsaturated zone {0.3}
η = hydraulic gradient {1}
λ_u = average decay rate in unsaturated zone (soil) (day^{-1})

For persistent waste (no decay), there is no reduction in the chemical concentration under steady-state conditions, regardless of distance. Thus, the unsaturated zone, where transport is primarily one dimensional, offers no protection for persistent chemicals in the very long term when seepage is

possible (Piver and Lindstrom, 1984). However, as explained previously, we account for delayed risk by the subjective terms in equation [5.2].

For waste (primarily organic and radioactive) that does degrade, a site sufficiently high above the water table can safely detain the waste. This is the basis for septic tanks and their accompanying drain fields, which depend on aerobic bacteria in the tank and unsaturated zone to degrade the biologic waste. Thus, old empirical rules for locating waste disposal sites weighted the depth-to-water table factor heavily. For example, the LeGrand empirical point system (LeGrand, 1964) for evaluating potential pollution weighted the distance-to-the-water-table factor such that it could contribute up to 27% of the score irrespective of decay rates. Also, HRS (40CFR300) had this factor contribute up to 37% of the maximum exposure score, also irrespective of decay rate (score not including the effect of population).

The influence of the exponential term of equation [5.6] is indexed for the scoring system as follows: First, substitute into equation [5.6] the approximation of the hydrodynamic dispersion, assuming molecular diffusion is unimportant:

$$D = \nu\phi D^{*}/\tau + \alpha V \simeq \alpha V \qquad [5.7]$$

where

D^{*} = molecular diffusion (m^2/day)

V = seepage velocity (m/day)

α = dispersivity (m)

τ = tortuosity {$\sqrt{3}$}

ϕ = average porosity {0.3}

ν = constrictivity {1}

Second, when $4D_u\lambda_u/V_u^2$ ($\sim 4\alpha\lambda_u/V_u$) is much smaller than one (often true in unsaturated zone), equation [5.6] reduces to simple decay for slug flow,

$$C_a \simeq C_r \exp\{-d\lambda_u/V_u\} \qquad [5.8]$$

When $4D_u\lambda/V_u^2$ is much larger than one (often true in the saturated zone), equation [5.6] reduces to

$$C_a \simeq C_r \exp\{-d\,[\lambda_u/(\alpha V_u)]^{1/2}\} \qquad [5.9]$$

Although equations [5.8] and [5.9] are not precise, they are useful for indicating trends for SRS.

Aquifer transport. The contaminant concentration after passing through the unsaturated zone [C_a] is the input concentration for the next segment: transport through the aquifer. As the contaminants reach the unconfined aquifer through the unsaturated zone, a plume will develop downstream. Before the plume fills the entire aquifer thickness [m], the spreading will be three-dimensional (3-D), thereafter it will be two-dimensional (2-D). We have assumed a 2-D model of dilution and plume spreading represents most situations. It is not conservative if 3-D spreading applies, but vertical mixing is usually rapid. For example, mixing usually occurs if $\Phi = m^2/(\alpha x) <$ 3.3 for an instantaneous source (Codell et al., 1982). If $\alpha_x \simeq 0.1x$ for x less than 200 m (Pickens and Grisak, 1981; Figure 5.2) and $\alpha_z \simeq 0.01\alpha_x$ (Walton, 1984), then, even for an extreme case of a 100-m thick aquifer, the contaminant is almost completely mixed for x greater than 550 m.

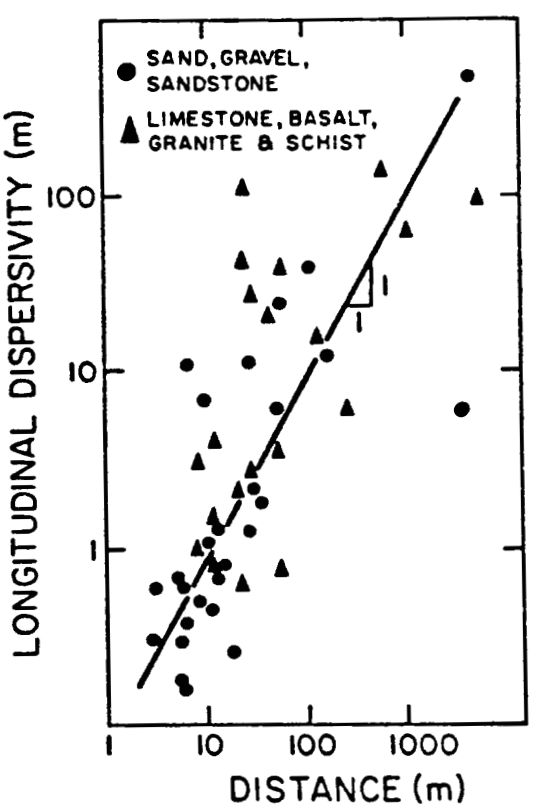


Figure 5.2 Variation of dispersivity with distance (Boutwell et al., 1985)

If one assumes 1) a line source (for example, well injection), 2) two-dimesional geometry, 3) zero lateral distance [y] (directly downgradient from site), and 4) transverse hydrodynamic dispersion [D_y] equals one-fourth longitudinal dispersion [D_x] (Freeze and Cherry, 1979; Table 5.1), then the analytic solution to the advection-dispersion transport equation [5.5] is (Wilson and Miller, 1978),

$$C_p = \frac{\bar{M}_{gw}\exp\{ (x_{gw}V_{gw}/ 2D_{gw})[1 - (1 + 4D_{gw}\lambda_{gw}/ V_{gw}^2)^{1/2}]\}}{\phi\ (\pi D_{gw}V_{gw}x_{gw})^{1/2}(1 + 4D_{gw}\lambda_{gw}/V_{gw}^2)^{1/4}} \qquad [5.10]$$

where

C_p = concentration in plume (kg/m^3)
D_{gw} = hydrodynamic dispersion in aquifer (m^2/day)
$\bar{M}_{gw}$ = average mass injection rate per aquifer thickness [m]
= $C_a i_r/m$ (kg/day/m)
x_{gw} = horizontal distance from site to target population [N] (m)
V_{gw} = aquifer seepage velocity $\approx \eta\ K_{gw}/\phi$ (m/day)
K_{gw} = average hydraulic conductivity through aquifer (m/day)
η = hydraulic gradient
λ_{gw} = average decay rate in aquifer (day^{-1})
ϕ = average porosity {0.3}

Equation [5.9] is similar to the 1-D, steady-state equation [5.6] except for the added terms in the denominator (especially $x^{1/2}$) which describe the added diffusion in two dimensions. Simplifying equation [5.10] using equations [5.7] and [5.9] and omitting the expression to the 1/4 power (when this expression is important, its value in the exponential expression will dominate) results in

$$C_p \simeq \frac{\bar{M}_{gw}\exp\{-x\ (\lambda_{gw}/ \alpha V_{gw})^{1/2}\}}{\phi V_{gw}(\pi\alpha x)^{1/2}} \qquad [5.11]$$

<u>Withdrawal.</u> Equation [5.11] expresses the concentration in the steady-state contaminant plume. The withdrawal of this contaminated water from an aquifer disturbs the plume; hence, the well will likely withdraw both

Table 5.1 Dispersivities [α] reported in the literature (Pettyjohn et al., 1982)

Aquifer type	Location	Dispersivity (m) α_x	α_x/α_y
Local Scale			
Alluvial sediment	Chalk River, Ontario	0.34 - 1	
	Lyons, France	5 - 12	0.34 - 780
	Barstow, CA	15	
	Tucson, AZ	15	
Regional Scale			
Alluvial sediment	Rocky Mt. Arsenal, CO	30	1
	Colorado	30	3
	Sutter Basin, CA	80 - 2000	10
	California	30	3
	Alsace, France	15	15
Glacial deposits	Long Island, NY	21	5
	Alberta, Canada	3 - 61	5
Fractured basalt	Hanford Site, WA	30	
	Idaho	91	
Limestone	Culter area, FL	22	10
	Brunswick, GA	61	3

contaminated and uncontaminated water, which results in some further dilution. This dilution is most easily represented as

$$C_w \simeq C_p i_r/(i_r+Q_w)$$

where

C_w = withdrawal concentration (kg/m^3)

i_r = flow rate of leachate from waste site (m^3/day)

Q_w = the volume rate withdrawn from the aquifer through well (m^3/day)

Other sources of water for dilution also exist. Should the contaminant discharge into a stream that supplies water to a town, rather than discharging directly into a town well, dilution by the stream (stream flow rate, Q_r) will occur. Should other clean water sources [Q_a] also supply water to the town, dilution will also occur; hence, the expression for dilution becomes

$$C_w \simeq C_p i_r/(i_r + Q_w + Q_r + Q_a) \qquad [5.12]$$

Concerning the river dilution [Q_a], SRS assumes complete mixing if the distance downstream is greater than the mixing length [$\ell_m = 15\ w_{riv}^2/d_{riv}$, where d_{riv} is mean river depth and w_{riv} is mean river width (derived in Chapter 6)]. If the distance traveled by the contaminant is less than ℓ_m, SRS reduces the river discharge [Q_a] by the square root of the ratio of x_{riv} to ℓ_m.

Finally, the site reduction factor [f_{site}] is the withdrawal concentration per mass of waste [C_w/W_i] times the daily water consumption specified by EPA [$B_w = 2x10^{-3}\ m^3/day$]:

$$f_{site} = C_w\ B_w\ t_\ell/W_i \qquad [5.13]$$

Model Equation

Combining equations [5.4] and [5.8]-[5.13] results in the following equation describing the ground-water pathway site reduction factor [f_{site}].

$$f_{site} \simeq \frac{(i_r B_w)\ [1-\exp(-i_r t_\ell S/W_i)]\ \exp\{-d\lambda_u/V_u - x(\lambda_{gw}/\alpha V_{gw})^{1/2}\}}{m\ (i_r + Q_w + Q_r + Q_a)\ \phi V_{gw}\ (\pi\alpha x)^{1/2}} \qquad [5.14]$$

Although not rigorous, it identifies factors that influence the site factor [f_{site}] and the proper way to combine these factors. Accordingly, it is more descriptive of the pathway than formulations used in other simple ranking schemes.

For scoring, several of the expressions are grouped together; for instance,

dilution [δ_{gw}] = $i_r/(i_r + Q_w + Q_r + Q_a)$
mass release adjustment [g_{gw}] = $1-\exp(-i_r t_\ell S/W_i)$

Furthermore, to arrive at equation [5.1], the constants [Γ] are grouped together:

$$\Gamma_{gw} = B_w\ /[\phi(\pi\alpha)^{1/2}] \qquad [5.15]$$

Serendipitously, the constant groups of the three pathways (Γ_{gw}, Γ_{sw}, Γ_a) were all on the order of 10^{-3} and could be omitted for ranking sites in SRS.

As a side note, if one assumes 1-D transport in the aquifer, then (Donigian et al., 1983)

$$\Gamma_{gw,1\text{-}D} = B_w / \phi \qquad [5.16]$$

Furthermore, one must multiply equation [5.14] by $x^{1/2} i_r / d_{plume}$ $\simeq x^{1/2} r_{perc}\, w_{plume} / \phi$, where r_{perc} is the leachate percolation rate, and w_{plume} is the width and d_{plume} is the depth of the leaching plume.

Model Sensitivity

Combining equations [5.1] and [5.2] yields an expression for exposure (E). This expression of E is then substituted into the expression for risk, $\hat{R}_h \propto$ NET.

$$\hat{R}_h = N \cdot T \cdot W_o \cdot f_{eng} \cdot \frac{1-\exp(-\lambda_s t_\ell)}{\lambda_s t_\ell} \cdot \Gamma_{gw} \cdot \delta_{gw} \cdot g_{gw} \cdot \frac{1}{m} \cdot \frac{1}{V_{gw}} \cdot \frac{1}{x^{1/2}}$$

$$\cdot \exp\left[-\frac{d\lambda_u}{V_u} - x\left(\frac{\lambda_{gw}}{\alpha_{gw} V_{gw}}\right)^{1/2}\right] \qquad [5.17]$$

This SRS model is multiplicative in many of the variables as suggested in Chapter 3. The variables, N,T,f_{eng},m, are always multiplicative with powers of one ($b_i = 1$). Hence, their importance [I_i] is easily evaluated by either equations [3.11] or [3.12]:

$$I_i = \left| b_i \frac{X_{i0}}{R_h(X_0)} \right| \qquad [3.11]$$

or

$$I_i = \left| b_i \frac{S(X_i)}{S(R_h)} \right| \qquad [3.12]$$

The sensitivity of site risk to other variable groups in equation [5.17] varies somewhat based on variable values. As an example, examine the mass release adjustment [g_{gw}],

$$g_{gw} = 1-\exp(-i_r t_\ell S/W_i)$$

As a way to evaluate the influence of g_{gw}, we examined its importance at its extreme values. At extreme values, g_{gw} acts like a switch (see discussion of equation [5.3]). Provided S and/or i_r are very large, $g_{gw} \simeq 1$; hence, S has no influence. (The influence of i_r will be zero from g_{gw} but its influence on the dilution term [δ_{gw}] could still be important.) On the other hand, if S and/or i_r are very small, then $g_{gw} \simeq -i_r t_\ell S/W_i$. The influence of W_o drops to zero while S and i_r have influence. Table 5.2 examines the influence of other variables at their extremes neglecting the range of uncertainty.

When waste decay [λ] occurs the groupings $d\lambda_u/V_u$ (or $d(\lambda_u/\alpha_u V_u)^{1/2}$ and $x(\lambda_{gw}/\alpha_{gw} V_{gw})^{1/2}$ (or $x\lambda_{gw}/V_{gw}$) become very influential. An analyst has difficulty analytically separating the influence of individual terms in the group except by noting the likelihood that their ranges vary and, thus, these groupings were not included in Table 5.2.

Table 5.2 Influence of variables as represented by power [b_i] in ground-water model

Condition	Factor	Power
None	Population [N]	1
	Toxicity [T]	1
	Engineering factor [f_{eng}]	1
	Aquifer thickness [m]	-1
	Aquifer porosity [ϕ]	-1
S and/or i_r large	Waste quantity [W_o]	1
	Solubility [S]	0
$i_r \gg Q_w, Q_r, Q_a$	Leachate rate [i_r] and	0
	Well discharge [Q_w] or	0
	River discharge [Q_r] or	0
	Additional source [Q_a]	0
$i_r \ll Q_w, Q_r, Q_a$	Leachate rate [i_r] and	1
	Well discharge [Q_w], etc.	-1
S and/or i_r small	Waste quantity [W_o]	0
	Solubility [S]	1
$i_r \gg Q_w, Q_r, Q_a$	Leachate rate [i_r] and	1
	Well discharge [Q_w], etc.	0
$i_r \ll Q_w, Q_r, Q_a$	Leachate rate [i_r] and	2
	Well discharge [Q_w], etc.	-1
$\lambda_s = \lambda_u = \lambda_{gw} = 0$	Pore-water velocity [V_{gw}]	1
	GW travel distance [x_{gw}]	-1/2
	Dispersivity [α_{gw}]	-1/2
	Unsaturated distance [d]	0
	Unsaturated Pore vel. [V_u]	0
$\lambda_s = \lambda_u = \lambda_{gw} \neq 0$		
d/V_u and/or		
$x/(\alpha V_{gw})^{1/2}$ small	Waste decay [λ]	-1

6. SURFACE-WATER SCORE

This chapter discusses the method used to evaluate surface-water exposure [E_{sw}]. It first describes the idealized surface-water pathway. It then presents the underlying model used by SRS for scoring. A subsequent section discusses the derivation of this simple model--a section you may wish to postpone reading.

In the past, risk to humans or other biologic systems from surface-water contamination has been important. The EPA survey in 1977 (Lazar et al., 1976) found about 33% of the incidents involved surface-water contamination. Of these incidents, haphazard disposal on vacant property was the most frequent contaminant source (41%) (Table 2.1). This damage mechanism was assumed in the following development. Table 2.1 shows contamination from landfills and lagoons accounted for 29 and 25%, respectively; thus with past waste sites, engineered disposal methods were also important sources of surface-water contamination. However, RCRA (1976) and supporting EPA regulations (40CFR267) should significantly reduce surface-water contamination at future engineered sites.

Idealized Surface-Water Pathway

The surface-water pathway begins at a site where toxic waste is exposed to the weather in the upper 0.1 m of soil (or entire lagoon). Precipitation falls on the area, dissolving some of the waste and eroding soil particles to which some of the toxic waste has adsorbed. The dissolved and sedimentary waste is transported overland to an intermittent stream, diluted with water from the same rainfall, transported to a graded perennial stream, diluted further, and finally drawn into a drinking water supply (Figure 6.1).

For SRS, no removal of sedimentary or dissolved waste is assumed while transported in the stream except that which can be expressed as a exponential decay. Further, all the adsorbed waste is assumed to have de-adsorbed from sediments before reaching the water-supply intake, consistent with our assumptions of steady state. Dissolved waste, however, may pass through the system more quickly than sedimentary waste, making decay more important in the latter case.

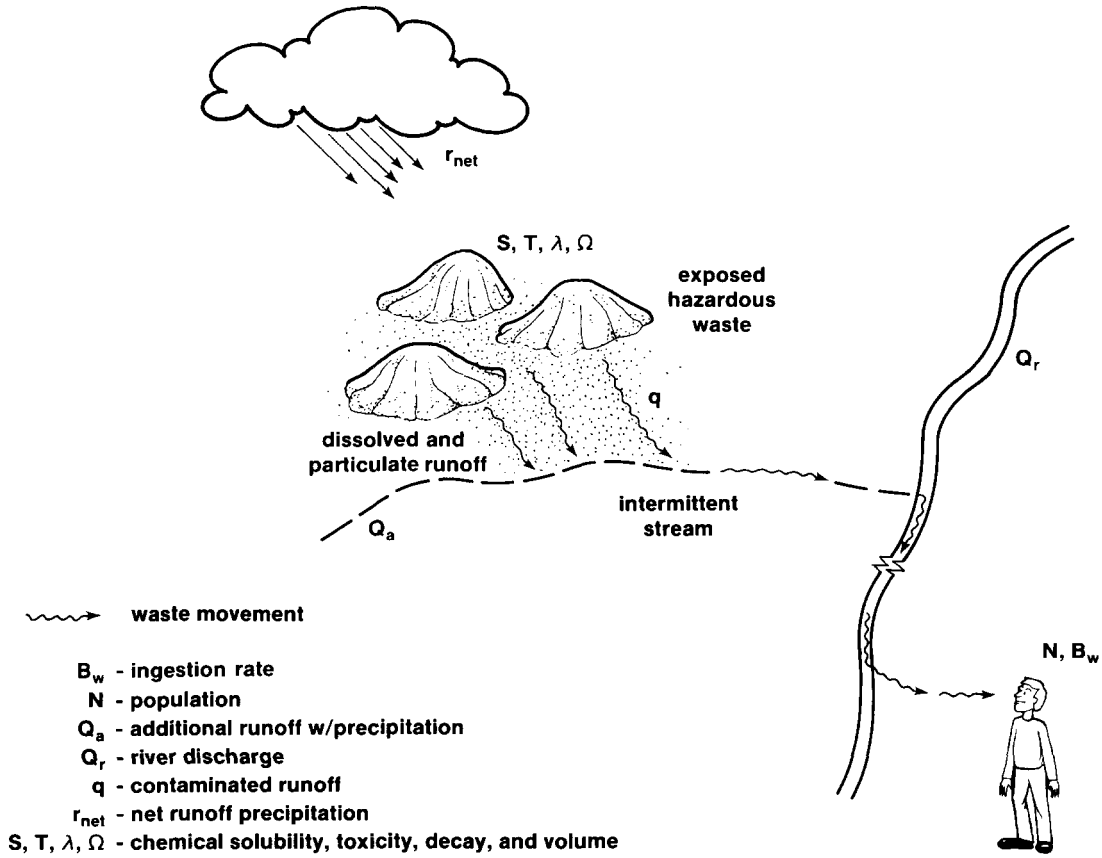


Figure 6.1 Conceptual model for surface-water pathway

Method of Scoring

As for the ground-water pathway, the surface-water exposure [E_{sw}] is $E_{sw} \propto W_o \cdot f_{eng} \cdot f_{site}$, and the engineered-barrier reduction factor [f_{eng}] is evaluated from

$$f_{eng} \simeq \frac{1 - \exp(-\lambda_s t_\ell)}{\lambda_s t_\ell} \cdot f_{put} \cdot f_{strct} \qquad [6.1]$$

where

f_{put} = subjective factor evaluating method of waste placement
f_{strct} = subjective factor evaluating soil cover and hydraulic structures
t_ℓ = time frame of interest (day)
λ_s = decay rate while at site (day^{-1})

Because the subjective factors [f_{put} and f_{strct}] are not derived, their description is found in the instructions (Chapter 8).

The site reduction factor [f_{site}] is evaluated from one of two simple expressions. For many wastes, either the dissolved or sediment transport route described above dominates; specifically, the partition coefficient [K_d] will be either near zero or orders of magnitude greater than one. Furthermore, because K_d is rarely precisely known, SRS considers only two cases: For K_d less than about 0.02 m^3/kg (corresponding to a retardation [R] less than 100), the substance is assumed to leave the site dissolved. For K_d greater than 0.02 m^3/kg, the substance is assumed to leave the site adsorbed on soil particles.

<u>Scoring for small partition coefficient.</u> The hazardous substance is assumed to leave the waste site dissolved when K_d is small (less than 0.02 m^3/kg); this is the default case. For this case, f_{site} is (major groupings dimensionless)

$$f_{site} \simeq \frac{B_w}{q} \cdot g_{sw} \cdot \delta_{sw} \cdot \frac{r_{net}}{r_a} \cdot \exp\left[-x_{riv}\left(\frac{\lambda_{sw}}{\alpha_{sw} V_{sw}}\right)^{1/2}\right] \qquad [6.2]$$

where

B_w = Γ_{sw} = human ingestion rate {2×10^{-3} m^3/day; 2 ℓ/day}

q = annual runoff from waste site = $r_{net} \cdot A_s$ (m^3/day)

A_s = surface area of contamination (m^2)

g_{sw} = $1-\exp(-qt_\ell S/W_i)$ = mass release adjustment

S = waste solubility (kg/m^3 or Ci/m^3)

t_ℓ = average human life expectancy {2.56×10^4 day}

$W_i = W_o \cdot \dfrac{1 - \exp(-\lambda_s t_\ell)}{\lambda_s t_\ell}$

W_o = waste within 0.1 m of surface (kg or Ci)

λ_s = decay rate while at site (day^{-1})

r_a = mean daily precipitation at waste site (m/day)

$r_{net} = (r_a - 0.2S_w)^2 / (r_a + 0.8S_w)$ (m/day)

S_w = a [(1000/CN) -10] = water retention factor

a = conversion constant ({7×10^{-5}} for r_a in m/day)

CN = Soil Conservation Service (SCS) runoff curve number

V_{sw} = surface water velocity (m/day)

x_{riv} = distance traveled in water pathway from site to target (m)

$\alpha_{sw} = 0.6\ d_{riv}^{5/6}$ = dispersivity in surface water {1 m}

d_{riv} = mean depth in river

$\delta_{sw} = q/(q + Q_a + Q_r)$ = surface-water dilution factor

Q_a = flow rate of supplemental clean water (m^3/day)

Q_r = discharge in river if $x_{riv} \geq \ell_m$; otherwise

$= \left[\frac{x_{riv}}{\ell_m}\right]^{1/2}$ • river discharge (m^3/day)

$\ell_m = 15\ w_{riv}^2 / d_{riv}$ = mixing length (m)

w_{riv} = width of river (m)

λ_{sw} = waste decay rate in surface water (day^{-1})

<u>Scoring for large partition coefficient.</u> The hazardous substance is assumed to leave the site adsorbed on soil particles for large K_d (greater than about 0.02 m^3/kg). For this case f_{site} is

$$f_{site} \simeq \frac{B_{sw}}{q} \cdot \delta_{sw} \cdot \frac{Y_s}{\rho_b h} \cdot \exp\left[-x_{riv}\left(\frac{\lambda_{sw}}{\alpha_{sw} V_{sd}}\right)^{1/2}\right] \qquad [6.3]$$

where

h = soil depth subject to erosion each year {0.01 m/yr}

V_{sd} = suspended sediment velocity--default is V_{sw} (m/day)

$Y_s = 5.6\text{x}10^{-2}$ CP LS R_E = annual sediment yield per area (kg/m^2/yr)

CP = SCS control-practice factor

LS = SCS slope factor

R_E = SCS rainfall factor

ρ_b = surface soil bulk density {1500 kg/m^3}

Six major assumptions used to arrive at [6.2] and [6.3] are as follows:

- thorough mixing occurs in the surface water
- degradation is properly represented by first-order decay
- effect of waste decay is similar to that derived for ground water
- partition of waste between adsorbed and dissolved phases is represented by K_d
- Universal Soil Loss Equation (USLE) (Barfield et al., 1981) adequately represents erosion at site
- SCS runoff equation (USBR, 1977) approximates annual site runoff

The scores for SRS for the various multiplicative factors of equations [6.1], [6.2], and [6.3] are the logarithms rounded to the nearest integer. The instructions in Chapter 8 describe how to estimate and score these factors and the worksheets in Appendix A help organize these data to aid in scoring the site.

Derivation of Scoring Model

As with the ground-water pathway, transport along the surface-water pathway is divided into several segments (waste release rate and surface-water transport), which are described by simple formulas.

Waste release rate. The most intensive requirements for data and hand calculations for the surface-water pathway are, as with all the pathways, the estimation of the chemical release rate from the waste site. Estimating the release for the surface-water pathway involves four steps.

The first step is to estimate the amount of annual runoff [q] from annual rainfall [r_a]. The U.S Soil Conservation Service (SCS) method as adapted by the U.S. Bureau of Reclamation (USBR, 1977) was used. The depth of runoff [r_{net}] (m/day) is determined by

$$r_{net} = (r_a - 0.2S_w)^2/(r_a + 0.8S_w) \qquad [6.4]$$

where

r_a = annual rainfall (m/day)

S_w = water retention factor

= a[(1000/CN) - 10]

a = conversion constant ($7x10^{-5}$ for r_a in m/day)

CN = SCS runoff curve number

The curve number (CN) is determined by such factors as the type of soil at the site and the vegetative cover. It indexes the tendency of the soil to absorb and hold precipitation or to allow precipitation to run off.

The annual runoff from the site [q] (m^3/day) is simply

$$q = r_{net} \cdot A_s \qquad [6.5]$$

where

A_s = contaminated area (m^2)

The second step is to evaluate the quantity of toxic waste dissolved annually. The dissolved amount released from the waste site [M] is the ratio of the runoff [r_{net}] and the precipitation [r_a] multiplied by the amount of material available for removal [W_i]. As with the ground-water pathway, the average annual mass of dissolved material in the runoff over period t_ℓ [$\bar{M}_{sw}$] (kg/day) is solubility-dependent and mathematically described as (eq. [5.4])

$$\bar{M}_{sw}/W_i = M/(W_i t_\ell) = (r_{net}/r_a)\ [1-\exp(-q\ t_\ell S/\ W_i)] \qquad [6.6]$$

where

S = solubility of hazardous waste (kg/m^3 or Ci/m^3)

t_ℓ = average human life expectancy (2.56×10^4 day)

W_i = waste available for release = $W_o \cdot \dfrac{1 - \exp(-\lambda_s t_\ell)}{\lambda_s t_\ell}$ (kg or Ci)

W_o = mass of waste originally deposited (kg or Ci)

λ_s = decay rate while at site (day^{-1})

The third step is to evaluate the waste escaping as runoff while adsorbed to soil particles. This release is estimated from the sediment yield [Y_s] (kg/m^2) calculated by the Universal Soil Loss Equation (USLE) developed by U.S. Soil Conservation Service (Barfield et al., 1981). Data on annual soil erosion in the area could also be used if available:

$$Y_s = a \cdot CP \cdot K \cdot R_E \cdot LS \qquad [6.7]$$

where

a = 0.224 for Y_s in kg/m^2

CP = control practice factor (available from local SCS office, but evaluated from graph for ranking)

K = soil erodability factor (available from local SCS office, but set equal to 0.25 for ranking)

R_E = rainfall factor (available from local SCS office, but evaluated from isoerodent map)

LS = length-slope factor (evaluated from graph) = $f(\ell, \theta)$

ℓ = slope length (ft)

θ = angle of slope (%)

The fourth step is to evaluate the fraction of contaminant carried away with sediment annually. This amount is the ratio of the sediment yield [Y_s] to the original amount of soil, $\rho_b h$, where ρ_b is the bulk density of the soil and h is the depth of soil subject to water erosion (assumed to be 0.01 m each year).

The fifth step is to account for decay. A decay expression similar to that used for the ground-water pathway is used (see equation [5.8]). (A similar expression is applicable for the dissolved portion, although V_{sw} replaces V_{sd}.) If $4\alpha_{sw}\lambda_{sw}/V_{sd} < 1$, then

$$Y_d \simeq Y_s \exp[-x_{riv} (\lambda_{sw}/\alpha_{sw}V_{sd})^{1/2}] \qquad [6.8]$$

where

x_{riv} = water course distance traveled by sediment to reach target (m)
V_{sd} = the velocity of sediment (can lag V_{sw}, but V_{sw} is default) (m/day)
α_{sw} = 0.6 $d_{riv}^{5/6}$ = dispersivity in surface water {1 m}
d_{riv} = mean river depth
λ_{sw} = chemical or radioactive decay rate in the surface water (day^{-1})

If $4\alpha_{sw}\lambda_{sw}/V_{sd} > 1$, then simple decay of the contaminant occurs (Delos et al., 1984):

$$Y_d \simeq Y_s \exp[-x_{riv} \lambda_{sw}/ V_{sd}] \qquad [6.9]$$

The expression for surface-water dispersivity [α_{sw}] in equation [6.8] is easily derived from Elder's approximation (Fisher, 1967) to the longitudinal dispersion coefficient [D_x] (m^2/day):

$$D_x = 6\, d_{riv}\, v_* \qquad [6.10]$$

where

d_{riv} = mean river depth (m) ≃ hydraulic radius [b] for natural river
v_* = $(gbs_{riv})^{1/2}$ = shear velocity (m/s) [6.11]
g = acceleration of gravity (m/s^2)
s_{riv} = slope of river bottom (uniform flow) (m/m)

Substituting Manning's equation

$$V_{sw} = \frac{b^{1/6}}{n_m} (bs_{riv})^{1/2} \qquad [6.12]$$

where

n_m = Manning's coefficient (varies between 0.028 to 0.15 for rivers (Chow, 1959)) {0.032 $s/m^{1/3}$}

into equation [6.9], yields

$$D_x = \alpha_{sw} V_{sw}$$

where

$$\alpha_{sw} = 6\ n_m\ g^{1/2}\ d^{5/6} \simeq 0.6\ d^{5/6} \qquad [6.13]$$

Next, we must partition the chemical between dissolved and adsorbed material. This partition is accomplished with the partition (or distribution) coefficient [K_d] (m^3/kg) where

$$K_d = \frac{\text{mass of solute on solid phase per mass of solid phase}}{\text{concentration of solute in solution}}$$

Using K_d,

$$\text{total mass chemical/mass dissolved} = 1 + \rho_b K_d/\phi = R \qquad [6.14]$$

$$\text{total mass chemical/mass adsorbed} = 1 + \phi/\rho_b K_d \qquad [6.15]$$

where

R = retardation factor

ρ_b = soil bulk density {1500 kg/m^3}

ϕ = porosity of near-surface soil {0.3}

Combining relations [6.4] through [6.15] and assuming $4\alpha\lambda/V > 1$ (for illustration) results in an expression of the waste release rate [e_c] for both dissolved and adsorbed components:

$$e_c/W_o \simeq (1/t_\ell) \Big\{ [(Y_s/\rho_b h)/(1+\phi/\rho_b K_d)] \exp[-x(\lambda_{sw}/\alpha V_{sd})^{1/2}]$$

$$+ (r_{net}/r_a)[1-\exp(-q\ t_\ell S/W_i)]/(1+\rho_b K_d/\phi) \exp[-x(\lambda_{sw}/\alpha V_{sw})^{1/2}] \Big\} \qquad [6.16]$$

Surface-water transport. For surface-water transport, toxic waste is assumed to be thoroughly mixed with river water after traveling the mixing length ℓ_m; hence, the main phenomenon occurring with transport of the toxic waste is dilution. The withdrawal concentration [C_w] after dilution of the chemical release is thus

$$C_w \simeq e_c /(q + Q_a + Q_r) \qquad [6.17]$$

where

Q_a = supplemental clean water (usually zero)

Q_r = river discharge if $x_{riv} \geq \ell_m$;

otherwise

$Q_r = \frac{x_{riv}}{\ell_m} \cdot$ river discharge (m^3/day)

$\ell_m = 15 \cdot w_{riv}^2 / d_{riv}$ = mixing length (m)

d_{riv} = mean river depth (m)

w_{riv} = mean river width (m)

If the distance traveled by the contaminant is less than ℓ_m, SRS reduces the river dilution [Q_r] by the square-root of the ratio of x_{riv} to ℓ_m (Codell et al., 1982).

The above expression for mixing length [ℓ_m] is easily approximated as follows.

$$\ell_m = a\, V_{sw} w_{riv}^2 / D_y \qquad [6.18]$$

where

a = {0.3} for river-bank spill or injection (Codell et al., 1982)

= 0.1 for centerline spill (Hubbard et al., 1982)

$D_y = 0.2\, d_{riv} v_*$ = lateral dispersion coefficent (Fisher, 1967) (m^2/day)

V_{sw} = mean surface-water velocity (m/day)

Again using equations [6.10] and [6.11] yields

$$\ell_m = 0.3\, w_{riv}^2 /(0.2\, g^{1/2}\, n_m\, d^{5/6})$$

If Manning's coefficient [n_m] is again set equal to 0.032, then

$$\ell_m = 15\ w_{riv}^2 / d_{riv} \qquad [6.19]$$

Finally, the site reduction factor [f_{site}] is the withdrawal concentration per mass of waste [C_w/W_i] times the average daily water consumption [$B_w = 2\text{x}10^{-3}\ m^3/\text{day}$]:

$$f_{site} = C_w\ B_w\ t_\ell / W_i \qquad [6.20]$$

<u>Model equation.</u> Combining equations [6.16], [6.17], and [6.20] yields the following equation describing the site reduction factor [f_{site}] for the surface-water pathway ($4\alpha\lambda/V > 1$):

$$f_{site} \simeq \frac{B_w}{t_\ell\ (q + Q_a + Q_r)} \cdot \left\{ \frac{CP\ LS\ R_E}{4\rho_b h \left(1+\frac{\phi}{\rho_b K_d}\right)} \exp\left[-x\left(\frac{\lambda_{sw}}{\alpha V_{sd}}\right)^{1/2}\right] \right.$$

$$\left. + \left[1-\exp\left(-qt_\ell \frac{S}{W_i}\right)\right] \frac{r_{net}}{r_a} \frac{1}{1+\frac{\rho_b K_d}{\phi}} \exp\left[-x\left(\frac{\lambda_{sw}}{\alpha V_{sw}}\right)^{1/2}\right]\right\} \qquad [6.21]$$

For SRS scoring, several of the parameters are grouped together:

dilution [δ_{sw}] = $q/(q + Q_a + Q_r)$
mass release adjustment [g_{sw}] = $1-\exp(-qt_\ell S/W_i)$

Furthermore, SRS considers only two cases for K_d: K_d small or K_d very large. For K_d small (less than 0.02 kg/m^3), we omit the sedimentary yield terms from equation [6.21] to obtain equation [6.2], assuming the hazardous material leaves the waste site dissolved in surface runoff. For K_d very large (greater than 0.02 kg/m^3), we omit the dissolution terms from equation [6.21] to obtain equation [6.3], assuming the hazardous material leaves the site adsorbed to soil particles.

7. AIR-PATHWAY SCORE

This chapter discusses the model underlying the air-pathway exposure [E_a]. Specifically, it describes the idealized air pathway, the scoring model, and the derivation of this model.

Contamination via the air pathway was significant in only 4% of the cases reported by the EPA in its survey (Table 2.1) (EPA, 1977). Although only a survey, it does suggest this pathway is frequently unimportant. From Table 2.1, landfills with little cover or haphazard waste sites were the most prevalent source when contamination via the air pathway was important.

Idealized Air Pathway

The air pathway begins at the waste site. Hazardous waste, deposited directly onto the ground or covered with less than 10 m of soil, escapes directly into the air either because it is volatile or because wind suspends soil particles that can be inhaled (less than 10 μm diam.) to which waste is adsorbed. These chemicals are transported by wind currents to a nearby borough where they are inhaled by permanent residents (Figure 7.1).

Method of Scoring

As with the other pathways, the air exposure [E_a] is evaluated as $E_a \propto W_o \cdot f_{eng} \cdot f_{site}$, where engineered-barrier reduction factor [f_{eng}] is

$$f_{eng} \simeq \frac{1 - \exp(-\lambda_s t_\ell)}{\lambda_s t_\ell} \cdot f_{put} \qquad [7.1]$$

where

f_{put} = subjective factor evaluating method of waste placement
t_ℓ = time frame of interest (day)
λ_s = decay rate while at site (day^{-1})

The subjective factors comprising f_{eng}, not being derived, are discussed in the instructions (Chapter 8). As with the other pathways, these factors adjust for sites with different exposure times and probabilities of contaminant release.

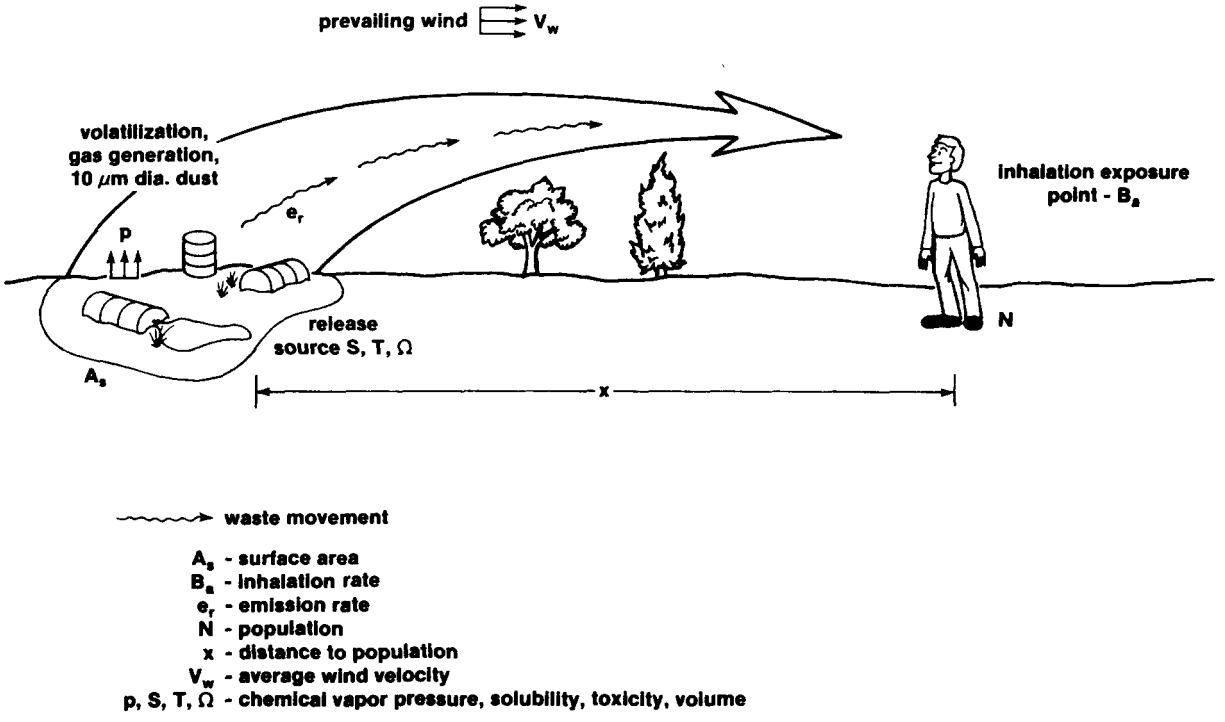


Figure 7.1 Conceptual model for air pathway

The site reduction factor [f_{site}] is evaluated by

$$f_{site} \simeq \left[\frac{1}{x^2} \cdot \Gamma_a \right] \cdot g_a \qquad [7.2]$$

where

x = pathway distance from waste to target (m)

$\Gamma_a = B_a/(0.0096\ V_w\ \pi)$ (m^3/day)

B_a = inhalation rate {20 m^3/day}

V_w = mean annual wind speed (m/day)

$g_a = 1\text{-}\exp\left[-(e_v + e_w)\ \frac{t_\ell}{W_i}\right]$ = mass-release adjustment

$e_v = 0.2 \cdot A_s \cdot f_{covr} \cdot f_{gen} \cdot p \cdot w_m^{1/2} \cdot \kappa$ (kg/day or Ci/day)

A_s = surface area contributing hazardous vapor (m^2)

f_{covr} = factor evaluating soil cover = $\phi^{4/3}/(350\ s)$

s = depth of soil cover over waste (m)

ϕ = soil porosity {0.3}

f_{gen} = increases emission if another gas sweeps waste

p = vapor pressure (mm Hg)

w_m = gram molecular weight (g/mol)

κ = $W_i/(\rho_b d_{cont} A_s)$ = mass concentration in soil (kg/kg)

d_{cont} = depth of contamination (m)

ρ_b = bulk soil density (kg/m^3)

$e_w = 0.2\ \frac{A_s}{PE^2} \cdot \kappa \cdot (1\text{-}\mu_{covr})$ (kg/day or Ci/day)

PE = Thornthwaite precipitation-effectiveness

μ_{covr} = portion of vegatative cover of soil (1 for covered to 0 for bare)

t_ℓ = average human life expectancy (2.56×10^4 day)

$W_i = W_o \cdot \frac{1 - \exp(-\lambda_s t_\ell)}{\lambda_s t_\ell}$ = release quantity (kg or Ci)

W_o = waste within 0.1 m of surface (kg or Ci)

λ_s = decay rate while at site (day^{-1})

Major assumptions used to arrive at equation [7.2] are as follows:

- thorough mixing occurs in the air
- Gaussian plume model adequately represents air transport
- no significant plume buoyancy
- vaporization rate represented by vapor pressure and molecular weight
- particulate emission rate represented by surface dryness which, in turn, is represented by Thornthwaite precipitation-effectiveness index

The scores for SRS are the logarithms of the factors of equations [7.1] and [7.2] rounded to the nearest integer. The instructions (Chapter 8) describe how to estimate and score these factors and the worksheets in Appendix A help organize these data.

Derivation of Scoring Model

Although uncovered landfills or haphazard waste sites were the most prevalent contaminant source for the air pathway, the following discussion assumes a lagoon or other surface impoundment. The emission rate is then modified for very near surface disposal.

The total rate of emission [e] of waste to the air pathway is the sum of the volatilization rate [e_v] and the wind erosion rate [e_w]: $e = \Sigma\, e_j$, where j is an emission process. There is no simple model capable of handling all air emission phenomena. Rather researchers have developed numerous empirical relations (Shen, 1981; Mackay, 1980; EPA, 1982). We present here two formulas for use in SRS that roughly approximate several of these empirical relationships.

Volatilization emission rate. To derive an approximate relation for the emission rate due to volatilization [e_v], we start with the diffusion equation assuming steady-state conditions (Mackay, 1980). Using the ideal gas law, we convert saturation concentration [C_v] to vapor pressure [p]:

$$n_v = D_c dC_v/d\chi = D_c \Delta C_v/\Delta\chi = D_c w_m\, \Delta p/(\Delta\chi R_c T_c) \qquad [7.3]$$

where

ΔC_v = difference between saturation vapor concentration and atmospheric concentration (kg/m^3)

D_c = diffusion constant

n_v = $e_v/(A_s\ \kappa)$ ($kg/m^2/day$)

A_s = surface area contributing hazardous vapor (m^2)

e_v = emission rate (kg/day)

κ = $W_i/(\rho d_{cont} A_s)$ = mass concentration in soil (kg/kg)

d_{cont} = depth of contamination (m)

W_i = quantity of soil available for release (kg or Ci)

ρ_b = bulk soil density (kg/m^3)

Δp = difference between saturation and atmospheric vapor pressure (for SRS, zero assumed for atmospheric vapor pressure) (mm Hg)

R_c = universal gas constant

T_c = mean annual absolute temperature (K)

w_m = gram molecular weight (g/mol)

$\Delta\chi$ = diffusion path distance (conceptual purpose only) (m)

If we simplify the complicated empirical expression for the diffusion constant reported by Perry and Chilton (1973), the diffusion constant in equation [7.1] is seen to be a function of turbulence in the diffusion layer, best approximated by the wind velocity [V_w]; the internal energy, approximated by the temperature squared [T_c^2]; and the molecular characteristics, approximated by the inverse of the square root of the molecular weight [$wm^{-1/2}$]:

$$D_c^* \simeq k\ V_w T_c^2\ w_m^{-1/2} \qquad [7.4]$$

Because mean annual temperature [T_c] varies only between 10 and 20°C and mean annual wind velocity [V_w] varies only between 2.5 and 6 m/s in the continental United States, these can be combined with the proportionality constant [k] for the ranking. Combining terms to form a mass-transfer coefficient [$\hat{k}$] and substituting equation [7.4] into equation [7.3] yields an

empirical expression for e_v (kg/day) [bracketed term reported by Mackay (1980)]:

$$e_v = \left[\hat{k}\ w_m^{1/2}\ \Delta p\ W_i\right] / (\rho d_{cont}) \qquad [7.5]$$

where

$$\hat{k} = D_c/R_c T_c \Delta z = k\ V_w T_c$$
$$\simeq 0.2 \text{ for p in mm Hg, } w_m \text{ in g/mol}$$

Equation [7.5] is for direct evaporation of liquids; evaporation of a solute from aqueous solutions theoretically requires a relationship that is dependent on Henry's law constant [H], but it is not considered for the ranking scheme. Instead, we assume the reservoir of volatile waste is in its pure chemical form.

Equation [7.5] expresses the vaporization rate of the chemical if exposed to the air. It therefore represents a potential upper limit of contamination. Several other empirical relations exist for vaporization from aqueous solutions, soils, and landfills covered by soil with and without internal generation of gases such as methane (EPA, 1986a). For this ranking scheme, however, we chose to adjust equation [7.5] to account for a few of these other conditions.

First, gas diffusivity [D_c^*] is modified by the solid matrix in porous media. Farmer et al. (1978) correlated observations with the relation:

$$D_c = D_c^* \phi^{4/3} \qquad [7.6]$$

Second, as shown by Thibodeaux (1981) and Thibodeaux et al. (1982), a soil cover can provide an effective vapor barrier when there is no gas generation within the landfill. The emission rate roughly decreases inversely with depth of soil cover [a/s], where s is the depth of soil cover and a is a proportionality constant (set equal to 1/350 m in SRS based on Thibodeaux, 1981); hence, for soil covers greater than 0.1 m thick, the emission rate [e_v] evaluated in equation [7.5] needs to be reduced by

$$f_{covr} = a\ \phi^{4/3}/s \quad \text{for } s \geq 0.1 \text{ m} \qquad [7.7]$$

where

a = 1/350 m (constant)

s = depth of soil cover

ϕ = porosity (0.3)

In contrast, generation of other gases, such as methane, in a landfill can sweep hazardous vapors along with them, greatly increasing the diffusion rate even with soil cover. Thus, when generation of gas occurs, the emission rate [e_v] needs to be increased. A cursory look at the results of Thibodeaux (1981) suggests an increase of about 10 times for soil cover of 1 m. Consequently, when substantial amounts of other gases are generated along with toxic vapor, the emission rate [e_v] is increased by a factor of 10 [f_{gen}= 10]. To account for the decreased influence of the soil cover, the maximum value of s is set at 1 m ($0.1 \leq s \leq 1$) in f_{covr}.

Should an assessor want more precise estimates of volatile emissions, numerous other empirical relations have been developed. Refer to Shen (1981) for empirical relations for waste piles and covered and uncovered landfills; Mackay (1980) for the Thibodeaux method for volatilization from surface impoundments; or EPA (1982) for Thibodeaux-Hwang method for volatilization from land treatment.

Particulate emission rate. Numerous toxic chemicals, especially organic chemicals, readily adsorb onto soil particles rather than percolate down to the ground water table or volatilize. If the soil is exposed or if the waste is a powdery solid, the toxic waste can be released into the air by wind erosion or vehicular traffic. Particles less than 10 μm in diameter are easily transported downwind and inhaled (EPA, 1986a) and, thus, form a component of the air route.

Although waste near the soil surface will likely pose a greater threat by water erosion via the surface-water pathway because of its ability to remove more soil and waste, circumstances such as drainage control or waste insolubility may make the air pathway more important.

We made an order-of-magnitude estimate of wind erosion and vehicular traffic emission [e_w] (kg/day) as follows. For surfaces with limited amounts

of erodible material, Cowherd et al. (1985) suggest using an empirical relation developed for surface mines:

$$e_w = 0.05\ f\ P(v^*)\ \frac{A_s}{PE^2} \cdot \frac{W_i}{\rho_b d_{cont} A_s} \cdot (1-\mu_{covr}) \quad \text{(kg/day)} \qquad [7.8]$$

where

A_s = contaminated surface area (m^2)

d_{cont} = depth of contamination (m)

f = number of disturbances per month

$P(v^*)$ = erosion potential (mass of erodible particles per surface area)

= $6.7 \times 10^{-3}(v^* - v_t)$ (kg/m^2)

v^* = fastest mile of wind for the period between disturbances

v_t = soil threshold velocity (m/s)

PE = Thornthwaite precipitation-effectiveness index (Strahler, 1964)

= $10\ \Sigma\ r_m/ET_m)$

ET_m = monthly evapotranspiration

r_m = monthly precipitation

W_i = mass available for release in near-surface ($s \leq 0.1$ m) (kg or Ci)

μ_{covr} = portion of vegatative cover (1 for 100% cover, 0 for bare soil)

ρ_b = soil bulk density (1500 kg/m^3)

Although evaluating the function $P(v^*)$ requires knowing the soil threshold velocity [v_t] and fastes mile [v^*] 7 m above the surface, for SRS we assume v^* is 27 m/s and v_t is 7 m/s (typical values). We further assume f is 30 times per month. Then equation 7.8 reduces to

$$e_w = 0.2\ \frac{A_s}{PE^2} \cdot \frac{W_i}{\rho d_{cont} A_s} (1-\mu_{covr}) \quad \text{(kg/day)} \qquad [7.9]$$

The expression correlates soil-surface dryness [PE] (PE indicative of antecedent moisture conditions) with emission (suspension) from wind or vehicular erosion. Setting ρ_b equal to 1500 kg/m^3, and d_{cont} to 0.03 m in equation [7.9] results in the relation $e_w = 4.4 \times 10^{-3}\ (1-\mu_{covr})\ W_i/PE^2$, an empirical relation that was found useful in the RCRA Risk Cost Analysis Model (EPA, 1984b) for waste piles.

Should an assessor want more precise emission (or transport) estimates, the complete calculations suggested by Cowherd et al. can be incorporated into SRS. For example, Cowherd et al. (1985) also discuss an empirical

relation for soil surfaces with unlimited amounts of erodible material. (It results in a same-order-of-magnitude estimate as equation [7.9] if PE in equation [7.9] is set equal to a mean value of 60.) As an alternative, one could use the SCS empirical equation (Skidmore and Woodruff, 1968) for wind erosion. Several empirical equations are also available for estimating dust from traffic on unpaved roads (EPA, 1986a).

Average mass release. As with the ground-water pathway, we assume the landfill behaves as a well-mixed reactor (equation [5.4]) (Weber, 1972). The average mass released per mass of waste [$\bar{M}_a/W_i$] over period t_ℓ is then

$$\bar{M}_a/W_i = (1/t_\ell)\ [1 - \exp(-\Sigma e_j t_\ell/\ W_i)] = g_a/t_\ell \qquad [7.10]$$

where

$\Sigma e_j = e_v + e_w$

g_a = mass release adjustment for air pathway

W_i = quantity available for release (kg or Ci)

As with the ground-water and surface-water pathways, the mass release adjustment [g_a] mathematically determines when the release over period t_ℓ is limited by the amount of waste [W_i], in which case $\bar{M}_a = W_i/t_\ell$, or limited by the emission rate, in which case $\bar{M}_a = e_v + e_w$. In the latter case, the emission rate is slightly overestimated because we did not initially partition the waste between e_v and e_w.

Air transport. We estimated the atmospheric transport of hazardous materials released from a waste site using the standard Gaussian plume expression for a continuous point source over a reflecting surface. For the small time for transport, we neglected the influence of waste degradation [λ] in the air. The concentration directly downwind (y=0) and at ground-level (z=0) [C_b] (kg/m^3) is as follows (Barr and Clements, 1984):

$$C_b = \bar{M}_a\ /(2\pi\sigma_y\sigma_z V_w)\ \exp[-1/\sigma_z^2) \qquad [7.11]$$

where

V_w = mean annual wind speed (m/day)

σ_y, σ_z = lateral and vertical dispersion coefficients (m)

To estimate the dispersion coefficients [σ_y and σ_z], we used Briggs curves (Barr and Clements, 1984), assuming an atmospheric stability rating of D [x is travel distance in meters irrespective of prevalent wind direction]:

$$\sigma_y = 0.08x\ (1+0.0001x)^{-1/2} \quad (m) \qquad [7.12]$$

$$\sigma_z = 0.06x\ (1+0.0015x)^{-1/2} \quad (m) \qquad [7.13]$$

The resulting atmospheric concentration per unit mass of waste [C_b/W_o] is multiplied by the average human inhalation rate [$B_a = 20\ m^3/day$] to arrive at the site reduction factor [f_{site}]:

$$f_{site} = (C_b/W_i)\ B_a\ t_\ell \qquad [7.14]$$

<u>Model equation.</u> Combining equations [7.10] through [7.14] yields the following expression for the site reduction factor [f_{site}] for the air pathway (terms previously defined):

$$f_{site} \simeq \frac{[1-\exp(-\Sigma e_i t_\ell/W_i)]\ \ \exp[-(1+0.0015x)/0.0036x^2]\ B_a}{2\pi\ (0.0048x^2)\ V_w} \qquad [7.15]$$

The most dramatic difference between the model equations for the air [7.14] and ground-water pathway [5.13] is the dispersion (and subsequent dilution) that occurs with distance [x]: dispersion varies inversely with x^2 for the air pathway and inversely with x for the ground-water pathway.

Because the third term of equation [7.12], $\exp[-(1+0.0015x)/0.0036x^2)]$, rapidly approaches unity for distances beyond 100 m, it was omitted from the ranking model. This left three major parameters to score in SRS, distance [x], quantity [W_o], and mass-release adjustment [$g = 1-\exp(-\Sigma e_i t_\ell/W_i)$] and one minor factor, wind velocity {$V_w = 4x10^5$ m/day; 4.5 m/s}, included with the model constants [Γ_a].

8. SITE RANKING SYSTEM (SRS) INSTRUCTIONS

Once you have collected the necessary data listed in Appendix D (much of it found in Appendix C), scoring the site with SRS is relatively easy; this is how (completed example in Appendix B).

Conventions Observed in the Instructions

1. Default scores for missing data are enclosed within braces, {}.
2. Mathematical symbols used throughout the text are enclosed in square brackets, [ ]. Appendix E lists definitions.
3. Units for variables are enclosed in parentheses, ( ).
4. Sections in the text where more detail on the scoring assumptions can be found are enclosed in angle brackets, <>.
5. In the discussion, the term "chemical" is frequently used to indicate both the toxic-chemical and radioactive components of the hazardous waste.
6. Data necessary to complete a step are listed at start of each step.

Overview of SRS

The following reviews major points discussed in preceding chapters.

Purpose of SRS. The purpose of SRS is to rank hazardous waste sites according to the relative human health risks they pose. Combining this technical ranking with other criteria, a manager can decide on the best order in which to begin detailed investigations and/or actions at each site.

Purpose of Instructions. These instructions describe how to use SRS to score and rank a hazardous waste site--both for administrative and public understanding. More importantly, they establish consistent methods of ranking a site--important because often more than one person (with varied expertise) ranks the sites. However, do not ignore scientific data relevant to a particular chemical because the instructions do not mention the information. Discuss the influence of the data, possibly proposing modifications to SRS, in the narrative accompanying the site score.

Method of Scoring. SRS ranks sites by scoring important and readily available factors influencing contaminant movement and ultimately human health risk. Although contaminant movement in the environment is complex, SRS simplifies this movement as shown in Figure 8.1 to

- three pathways (ground water, surface water, and air)
- minimal interaction between these pathways,
- direct ingestion or inhalation of the contaminant.

Intricate exposure pathways through food chains are not considered. Furthermore, recycling of contaminants between surface water, ground water, surface soil, and air is assumed a minor component of the ultimate risk.

SRS evaluates the relative risk of release [$\hat{R}_h$] along these three release pathways by measuring the potentially exposed population [N], the potential exposure [E] to each waste, and the toxicity [T] for each waste present <Scoring Concept of SRS, Chapter 3>:

$$R_h \propto \sum_k N_k \sum_\ell T_{\ell k} E_{\ell k} \qquad \ell = \text{chemical},\ k = \text{pathway} \qquad [8.1]$$

where $E_{\ell k}$ is divided further into components of initial waste [W_o], engineered-barrier-effectiveness factor [f_{eng}], and site-characteristic factor [f_{site}] <Chapters 5, 6, and 7 describe the parameters of f_{eng} and f_{site} on which scoring is based>

$$E_{\ell k} \propto W_{o\ell} \cdot f_{eng,k} \cdot f_{site,\ell k} \qquad \ell = \text{chemical},\ k = \text{pathway} \qquad [8.2]$$

To simplify the ranking, SRS tabulates scores [F] for the various factors in equations [8.1] and [8.2]. These scores are then combined according to equations [8.1] and [8.2] to obtain the final site score. In SRS, the score for a parameter is the logarithm of that parameter's value <Scoring Individual Factors, Chapter 3>. (Consequently the scores [F] are summed, rather than multiplied to arrive at a composite score.) Because the ranking is not precise, only the logarithm to the nearest integer is used in the tables. Tables ease the use of the ranking system but require specifying parameter units.

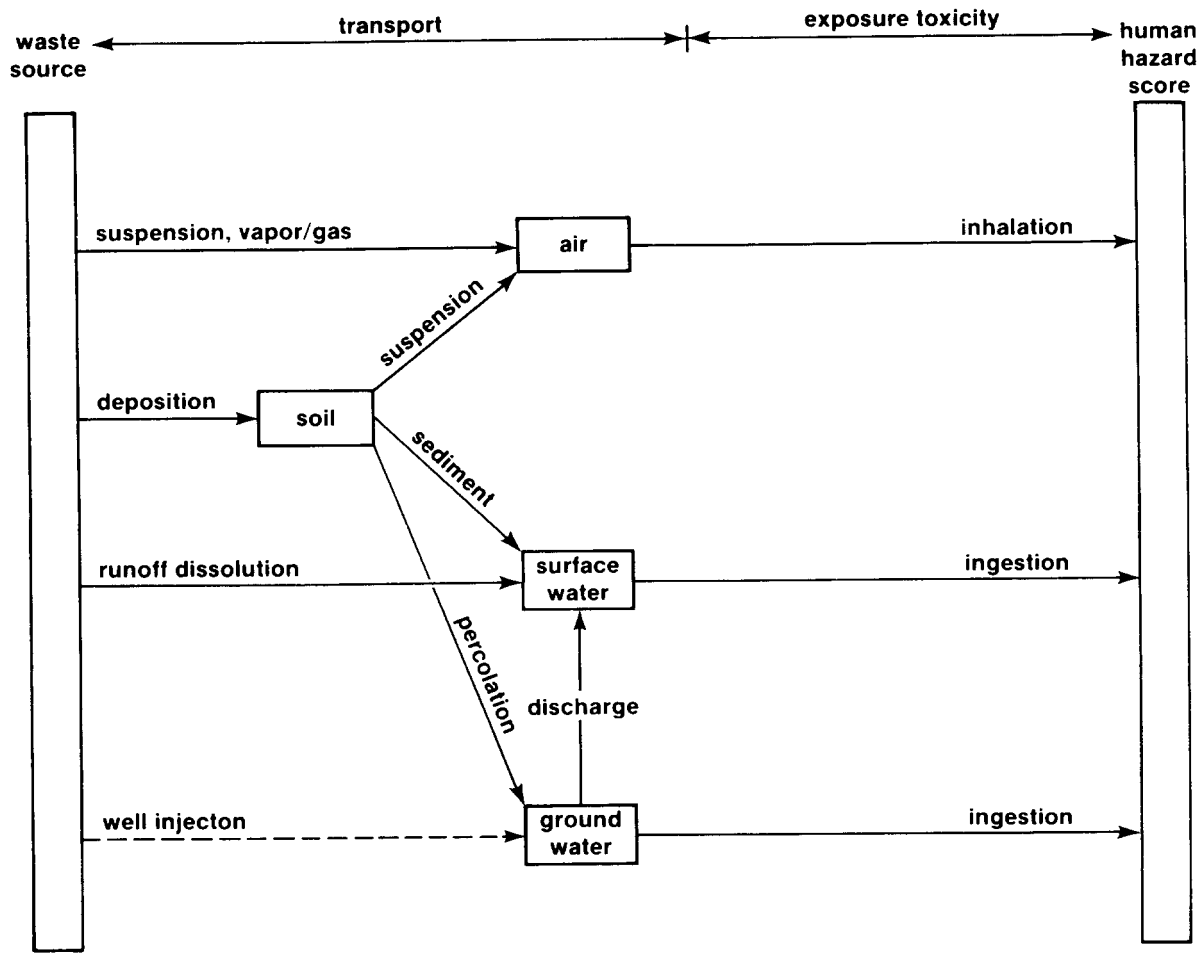


Figure 8.1 General pathways examined in SRS

General Scoring Guidelines

Observe the following rules when scoring a hazardous waste site:

1. Select the best estimate of each property (for example, chemical solubility), not conservative upper limits. Otherwise, the rankings could be distorted.

2. Handle uncertainty in property values by also supplying a variance $S(X_i)^2$ or pessimistic estimate (conservative).

3. The score is the logarithm (base 10) of the requested factor unless specifically noted (by a footnote on the worksheet).

4. Assign a default score when data for a factor are missing. A default score should be typical for the population of sites being ranked. (The instructions indicate default scores for the United States as a whole but may not be typical of the subset of sites you are ranking.) When using a default score, the pessimistic score should be at least one greater than the default score.

5. Use the scoring worksheets (Appendix A) to help organize and document the reasons for the assigned score for audits and reevaluations.

Site Ranking Procedure

Scoring a site with SRS consists of eight steps (Figure 8.2) (while working through the detailed instructions which follow also refer to the worksheets in Appendix A and the example in Appendix B):

1. Collect data on waste properties, site characteristics, and facility design.

2. Rank wastes found at the site by quantity and toxicity to screen out relatively minor waste components.

3. Describe the release pathways of concern for the site.

4. Evaluate engineered features at the facility.

5. Identify target populations along these pathways.

6. Score site features based on the manner waste is released from the site: ground-water (G), surface-water (S), and air (A) pathway.

6.G1, 6.S1, 6.A1	Score features applicable to all wastes.
6.G2, 6.S2 or 6.S3, 6.A2	Score features specific to each waste.

7. Part a) combine individual waste scores to arrive at a pathway score.
   Part b) combine pathway scores to obtain overall site score.

8. Rank the site in relation to other scored sites.

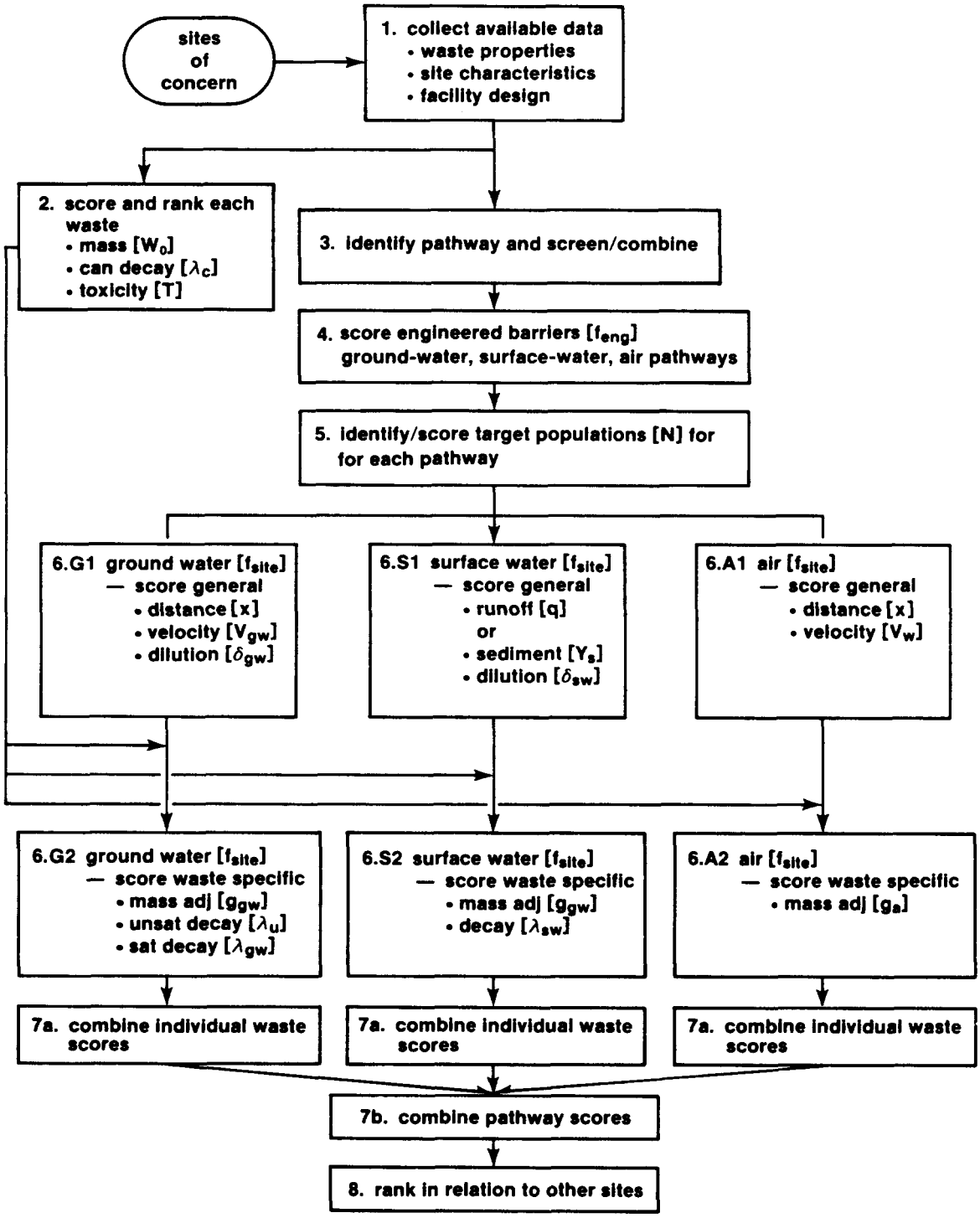


Figure 8.2 Diagram of SRS procedure

Step 1. **Collect data on waste properties, site features, and facility design**

The challenging and time-consuming portion of the SRS scheme (or any ranking scheme) is collecting the pertinent data. Each step lists data required (or that you need to estimate) for scoring. (Appendix D repeats this information plus additional unscored data that may help point out unusual features of a particular site.) To help you, Appendix C lists many of the required physical and chemical properties of hazardous waste.

Of all the data collected for SRS, the identity, quantity, and toxicity of waste placed (or to be placed) at a site are the most influential; they determine the maximum potential health risk per exposed individual. Unfortunately, for many abandoned and existing sites, this information is difficult to find. Your tendency may be to rely on site characteristics to mitigate any impact (for example, a slow seepage velocity to greatly reduce the potentially exposed population), but even fairly good sites can become menacing hazards if they contain vast quantities of nondegradable toxic waste and the time frame of interest is long enough; consequently, make a good effort to identify and estimate quantity of the chemical components of the waste. Conceivably, you can still use SRS when you know only the general types of wastes deposited at a site but estimating waste parameters is much more difficult.

Because SRS scores each chemical present along each pathway, the complexity and level of effort to score a site increases with the number of exposure pathways and number of chemicals and radionuclides present. To avoid collecting unncessary data, keep steps 2 and 3 in mind. These steps identify important chemicals and pathways and screen out the rest.

Step 2. **Score and rank chemicals found at site.**

Step 2.1: Waste description. First, generally describe the waste at the site (Appendix A), specifically, any major sources of the chemicals (for example, creosote from a tie treatment plant), whether chemicals were concentrated during recovery operations, etc. If less than 6 or 8 chemicals exist at the site, skip to Step 2.3, otherwise continue.

Step 2.2: Enter data on worksheet for screening chemicals (Appendix A). The specific data used in this step are

- quantity [W_o] of each chemical present (kg or Ci) (initial concentration [C_o] times volume times 70 yr),
- chronic ingestion toxicity [T_{oral}] (and inhalation toxicity [T_{air}] if air pathway thought important) (either ADI or UCR),
- possibly, solubility [S] {1 kg/m^3}.

Chemical quantity. Enter the quantity and score on the worksheet (Appendix A). Score the quantity of waste using Table 8.1. Although the quantity of waste available for release will vary between pathways, neglect these differences unless they are well known and differ significantly (a factor of 0.3 or less).

Chronic toxicity. Use chronic (long-term) toxicity data [T], either the allowable daily intake (ADI) or the unit cancer risk (UCR), and enter score (Table 8.3) on the worksheet. The allowable daily intake (ADI) is defined as the highest human intake of a chemical, expressed in mg/kg/day, that does not cause adverse effects when exposed for a lifetime. The unit cancer risk (UCR) is the upper lifetime risk per unit of dose, expressed as risk per mg/kg/day <Chronic Toxicity, Chapter 4>. Normally, use toxicity data for a standard cross-section of adults, children, etc. Because chemical toxicity [T] differs for inhalation and ingestion routes, two toxicity scores are needed when the air pathway is significant.

Although in principle the analyst should investigate every chemical present, chemicals with very low toxicity, chemicals with very low mobility, and chemicals that degrade very rapidly may not appreciably affect the overall site risk if in small quantities; consequently, they can be

disregarded. Therefore, when numerous chemicals are stored at a site, rank the chemicals according to their hazard as follows:

- list chemicals found or thought to be at site on preliminary worksheet
- If possible group chemicals together to form a class with similar properties.
- list quantity [W_o] (or if very difficult to estimate, solubility [S] (Table 8.6) for each chemical)
- record chronic toxicity [T] (UCR or 10^{-5}/ADI)
- add logartihms of W_o (Table 8.1) and T (Table 8.3) (or multiply)
- start step 2.3 using chemicals with the larger sums (and any other chemicals you feel especially concerned about)

Chemicals with scores more than 5 points (5 orders of magnitude) below the chemical with highest score may not influence the overall risk of the site. The actual score below which to ignore certain chemicals could, however, increase or decrease. Consequently, the cutoff value must be selected on the basis of the first few calculations with the top-ranked chemicals.

With this approach you will concentrate your efforts on hazardous materials more likely to lead to health risks once they escape from the site. Ideally, you will concentrate on no more than 8 chemicals. After screening the chemicals, begin scoring with the main chemical worksheet. [After completing the site scoring, examine the original list for chemicals that may behave similar to those dominating the site score (for example, metals).]

<u>Step 2.3: Score and rank dominant chemicals.</u> In addition to the data of Step 2.2, this step uses

- persistence of chemical while at site, expressed as an average half-life [$t_{1/2}$] (day)

Chemical half-life. For radioactive wastes, the half-life is a physical property. For toxic metals the half-life is infinite, unless innocuous compounds form. For toxic inorganic or organic compounds, the half-life describes the tendency to degrade into other chemical species, presumably less toxic. The degradation occurs because of hydrolysis,

oxidation, photolysis, and/or biodegradation and is usually specific to the medium <Chemical decay rate, Chapter 5>. Record here the half-life while contained at the site (Table 8.5). Estimates of the average persistence along the specific pathway in various media will be required later. If toxicity does not decrease with degradation or the half-life is greater than 10^5 days (Table 8.6), degradation may not be important.

On the main chemical worksheet add the scores for the quantity [W_o] and toxicity [T] for each chemical. If the chemical can degrade while at the site, add the score (Table 8.5) for the product of half-life [$t_{1/2}$] x $6x10^{-5}$:

chemical score [F_{chem}] = F_{mass} + F_{decay} + F_{tox}

where

F_{mass} = score for chemical quantity
F_{decay} = score for chemical decay
F_{tox} = score for inhalation or ingestion toxicity

After the dominant chemicals have been evaluated, again rank the chemicals according to the chemical risk calculated with T_{oral} (or T_{air} when evaluating an air pathway).

Begin scoring the most likely scenario for release (chosen in Step 3) using the chemicals with the highest rank (highest potential chemical risk). Completely evaluate the scenario, before starting another. Knowing the dominant chemicals for one scenario will help you evaluate other scenarios.

Table 8.1 Scores for waste quantity

Quantity [W_o] (kg or Ci)	Score[a]
...	
0.03-0.3[b]	-1
0.3-3	0
3-30	1
30-300	2
300-3,000	3
3,000-30,000	4
...	

[a]Score = log(quantity)
[b]Log(0.03) through log(0.3)= -1

Table 8.2 Volumes of common waste containers

Container	Volume (m^3)
55-gallon drum	0.21
Large wooden box	3.5
Small wooden box	0.45
Large low-level waste liner	4.8
Small low-level waste liner	1.4

Table 8.3 Chemical/radionuclide chronic toxicity[a]

Chronic toxicity [T]		Score[c]
(mg or μCi/kg/day)$^{-1}$ UCR	(mg or μCi/kg/day) ADI[b]	
$3x10^{-6} < 10^{-5} \leq 3x10^{-4}$	$3x10^{0} < 1 \leq 3x10^{-1}$	-5
10^{-4}	10^{-1}	-4
10^{-3}	10^{-2}	-3
10^{-2}	10^{-3}	-2
10^{-1}	10^{-4}	-1
10^{0}	10^{-5}	{0}[d]
10^{1}	10^{-6}	1
10^{2}	10^{-7}	2
10^{3}	10^{-8}	3

[a]Toxicity to average population
[b]UCR and ADI scales aligned assuming similar severity of effects; divide 10^{-5} by ADI for UCR
[c]Score = log(UCR toxicity)
[d]Score chosen by default

Table 8.4 Scores for source decay

Half-life [$t_{1/2}$] (days)	Score
>5600	0
5600 - 560	-1
559 - 56	-2
<56	-3

Table 8.5 Qualitative descriptions of half-lives

Description [$t_{1/2}$]	Range (days)
Unreactive	{ $> 10^4$ }
Slightly reactive	10^4 - 10^3
Moderately reactive	10^3 - 10^2
Reactive	$< 10^2$

Table 8.6 Scores for solubility

Solubility [S] (kg/m^3)[a]	Qualitative description	Score[b,c]
<0.003	almost insoluble	-3
0.003-0.03[d]	slightly soluble	-2
0.03-0.3	partially soluble	-1
0.3-3.0	soluble	{0}
3.0-30	very soluble	1
30-300	extremely soluble	2
>300	unlimited	3

[a] $10^3 mg/\ell = 1\ kg/m^3$
[b] Score = log(solubility)
[c] If chelating agents available, increase by 1
[d] Log(3) through log(30) ≃ 1

Step 3. **Describe release pathways**

Step 3.1: Generally describe site. First, generally describe the site on the title page of the worksheets (Appendix A).

Step 3.2: Develop and describe potential release scenarios. A release scenario is a series of events that could lead to the release of chemicals from the waste site, transport to the environment, and finally damage to the environment or man. Develop and describe these events (Pathways Worksheet, Appendix A) by following the instructions below:

- List events or processes that could cause chemical release from the waste source.
- List processes that could affect transport of the chemical to the environment and the target biologic system.
- Combine the events and processes to form scenarios and document them on the pathway worksheet (Appendix A). In general, develop all the reasonable scenarios to ensure both yourself and any auditor of the breadth considered. This step identifies for the decision maker the potentially affected targets.
- Screen out all but the most probable scenarios and/or combine closely related scenarios into one. (Probabilities based on your own judgment are sufficient for this ranking.) In general, we presume you will easily identify the human population targets of most concern, but unique conditions may require you to reexamine your preliminary decisions after scoring the site. In addition, note but set aside scenarios that may damage sensitive environments (defined as areas greater than $2x10^4$ m^2) because SRS only ranks human risks. However, have a trained biologist examine the environmental data.
- Group scenarios according to the way in which the released chemical leaves the waste site (air, surface-water, and ground-water pathways) for subsequent scoring.

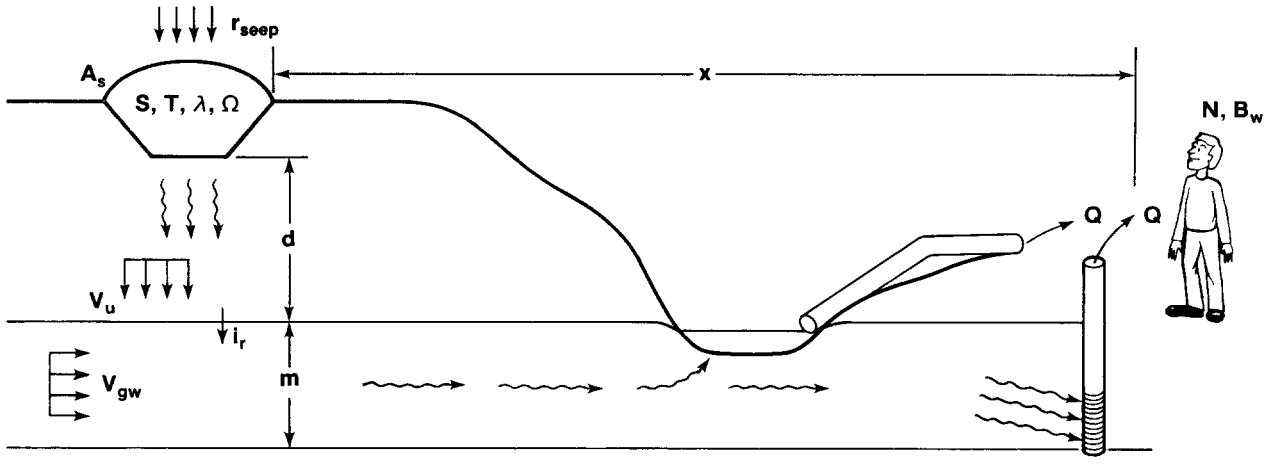
To clarify the above steps consider the following example. After examining an abandoned waste dump site, you find that several nearby farms withdraw water from an aquifer potentially contaminated by the dump. Only one of these farms uses the aquifer for drinking water; the others use it for livestock. In addition, a distant town withdraws water from this aquifer. One scenario involves release from the site into the aquifer, transport to several farmers' wells, and then direct consumption. A second scenario

involves consumption only by cattle. A third scenario involves release, transport over a great distance to the town water wells, and then direct consumption. Only the first and third scenarios of the ground-water pathway group are scored by SRS, but the second should be documented.

In selecting the target population for a scenario involving the ground-water pathway, the contaminant must be accessible at the withdrawal point to be considered, a fact easily determined if a regional flow net of the area exists. Unfortunately, you may need to resort to an estimation. If the withdrawal point is within the same aquifer and within 100 m of the site, assume potential contamination. For greater distances, where the withdrawal well is upgradient of a waste site, assume contamination only if the distance separating the water well and waste site is less than $100+(i_r+Q_w)/(2mV_{gw})$, where i_r is leachate flow rate, Q_w is well withdrawal rate, m is aquifer thickness, and V_{gw} is aquifer velocity--all evaluated in Step 6 (Bear, 1979). For greater distance where the withdrawal well is downgradient, assume contamination only if the lateral distance [y] (distance perpendicular to uniform ground-water flow) is less than $100 + (i_r+Q_w)/(2mV_{gw})$. (Because heterogeneity or fractured media can greatly effect the influence zone of the waste site, the analyst should search for as much information on the aquifer as possible.)

Other factors influence the likelihood of health risks via the surface-water and air pathways, as well. For example, the waste must be either volatile, capable of being swept along with other volatiles, or absorbed to soil particles on a surface without appreciable grass cover to escape via the air pathway. Similarly, a pathway along the surface must exit to transport contaminants via the surface-water pathway.

Steps 4, 5, and 6 described below score each scenario of a pathway using worksheets specific to the air, surface-water, or ground-water paths. Figures 8.3, 8.4, and 8.5 depict the factors scored for each generic pathway.



A_s - surface area
B_w - ingestion rate
i_r - leachate rate
m - aquifer thickness
r_{seep} - precipitation seeping into landfill
N - population
Q - pumping rate
V_u - percolation velocity
V_{gw} - ground water velocity
x - distance to population
S, T, λ, Ω - chemical solubility, toxicity, decay, and volume

Figure 8.3 Conceptual model and definition of terms for ground-water pathway

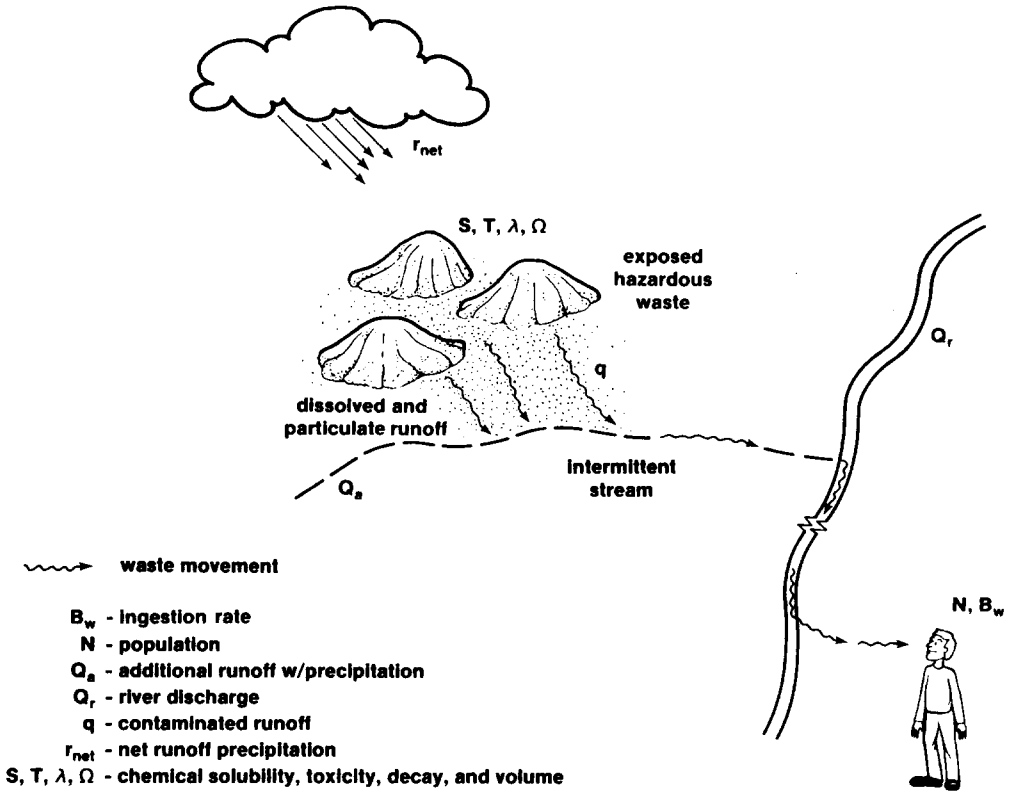


Figure 8.4 Conceptual model and definition of terms for surface-water pathway

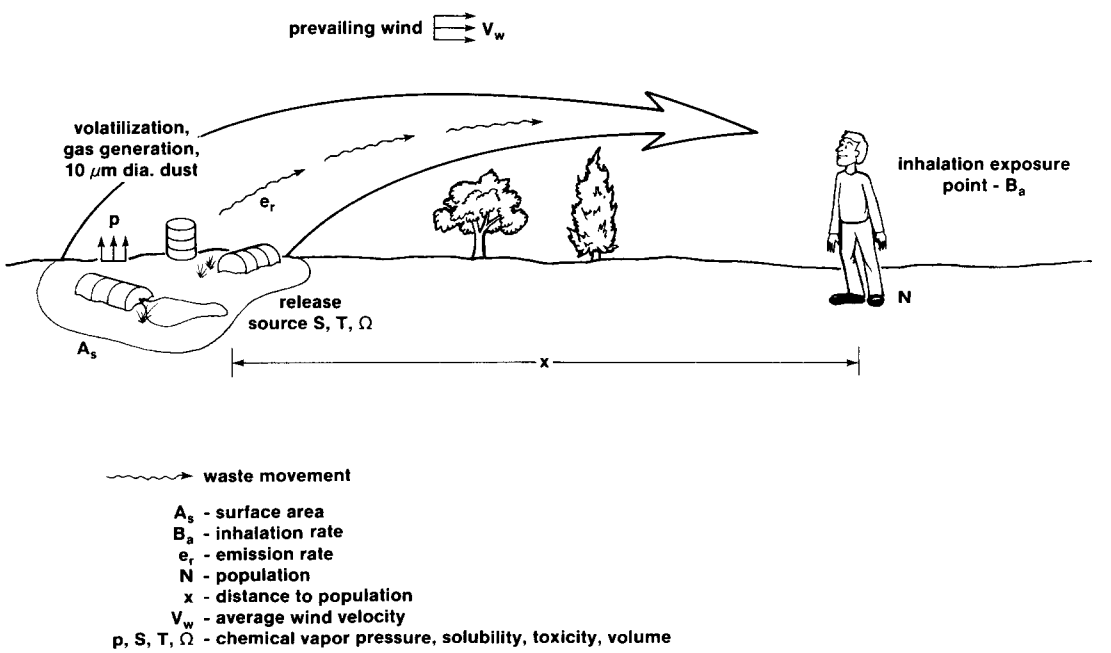


Figure 8.5 Conceptual model and definition of terms for air pathway

Step 4. **Evaluate engineered barriers at site**

Engineered barriers serve to

1. extend containment of the chemical (beneficial if decay occurs),
2. lower the release rate, and
3. minimize access to the chemical.

They do not, however, always provide indefinite isolation, especially for nondegradable waste contaminating ground-water. Under topic 1, "extend containment of the chemical," individual container life was evaluated with the chemical hazard, Step 1. Under topic 3, "minimize access to the chemical," waste covers and liners are evaluated along with leachate and gas generation, Step 6. The topics evaluated here are primarily concerned with barriers that lower the release rate of the chemical.

Usually, scores for the engineered barriers will apply to all pathways in a group (for example, the ground-water route) and, thus, reduce the evaluation effort. This grouping was assumed in the design of the worksheets (Appendix A). This grouping is not universal, however, and barriers could be very specific to a particular chemical waste. Furthermore, a waste facility could involve several disposal methods. In this latter case, consider scoring each disposal method individually and combining scores to determine an overall facility score using the combination scheme described in Step 7.

Step 4.1: Type of storage. The probability of failure based on the type of storage is partially accounted for in this step. For example, haphazard disposal on vacant property would most likely lead to contamination by any pathway; storage of liquid wastes in lagoons would rate next, landfills of questionable design next; and well-designed or specially constructed landfills would presumably provide the lowest risk. In other words, although engineered containment intact today may fail later, current risks are greater when the containment is poor. Furthermore, good containment today provides more time for a permanent solution. Consequently, a small weighting is used to penalize sites with poor waste placement. The

scores for storage type are closely related to the reliability of the storage type (probability of failure). Table 8.7 provides some guidance.

Because environmental laws (SARA, 1986) emphasize finding permanent disposal solutions, omit the scores in Table 8.7 to deemphasize the role of delayed risks when using SRS to quickly screen remedial alternatives. Provided all sites are scored consistently, you may ignore the scores if you wish to deemphasize delayed risks in other situations, also.

Table 8.7 Waste placement scores for all routes

Condition	Score
Engineered landfill: compacted, surface drainage liners (synthetic or clay); cover and moisture barrier; no monitored release at site	-1
Engineered lagoons and unspecified landfills, w/potential settlement (no compaction, no surface drainage); little or no field monitoring to indicate release	{0}
Lagoons, unspecified surface disposal; some monitored release	1
Haphazard disposal on vacant property, on farmland, etc.; significant monitored release (health hazard at measured point)	2

Step 4.2: Evaluate engineered barriers for ground-water route. For the ground-water route, reduction of leachate release rate and collection of leachate are scored.

Leachate reduction. Usually, with abandoned and currently active waste sites, no special technology (encasement in glass, concrete, or polymers) has been incorporated to reduce the leach rate, but an analyst may want to examine possible remedial solutions. Table 8.8 is a preliminary table that you may have to modify for specific applications. Because each point implies a decrease in risk by tenfold, you may subtract up to two points.

Table 8.8 Leachate reduction for ground-water route

Condition	Score
No special treatment	{0}
Concrete encasement	-1
Synthetic organic polymers	-2

Leachate collection system. A leachate collection system can reduce the risk of release (Table 8.9). Even though a leachate collection system will not last 70 yr (average life expectancy), a leachate system operated for many years can remove a substantial percentage of the waste since concentration of the leachate decreases exponentially if no additional material is added. Consequently, a good site might include synthetic liners and a leachate collection system for reducing the chemical hazard for the first few years plus a clay cover to reduce infiltration over the long term.

Table 8.9 Leachate collection system for ground water route

Condition	Score
None	{0}
Collection with treatment	-1

Step 4.3: Evaluate engineered barriers for surface-water route. Evaluate the hydraulic drainage structures around the site and the depth of soil cover using Table 8.10. If no structures exist or surface-water pathway is unimportant, skip to Step 4.4.

The use of drainage facilities and 1 or 2 m of soil cover [s] can significantly reduce the possibility of release of toxic chemicals via the surface-water pathway; however, flooding may greatly increase the possibility

of release. Table 8.10 qualitatively considers both soil cover [s] and the potential for flood inundation [U]. The probability of at least one event equaling or exceeding the hydraulic design of the drainage structures [U] is calculated by

$$U = [1 - (1-u)^{t_\ell}]$$

where

t_ℓ = average life expectancy (70 yr)

u = the storm probability used to design hydraulic drainage structures For example, u=1/100 if structures are designed to handle storm with 100-yr return period. (A return period of 100 yr means that, on average, a storm of this magnitude, or greater, is not expected to occur more often than once in 100 yr.)

Table 8.10 Protection of waste from surface runoff

Probability of failure [U]	Soil cover [s] (m)	Score
$U \leq 0.03$	$s \geq 1$	-4
$0.03 \leq U \leq 0.3$ $U \leq 0.03$	$s \geq 1$ or $1 \leq s \leq 0.5$	-3
$0.03 \leq U \leq 0.3$	$1 \leq s \leq 0.5$	-2
$0.3 \leq U$; $0.03 \leq U \leq 0.3$	$1 \leq s \leq 0.5$ or $s \leq 0.5$	-1
$0.3 \leq U$;	$s \leq 0.5$	(0)

[a] $U = [1 - (1-u)^{t_\ell}]$

Step 5. **Identify target populations for selected pathways**

Step 5.1: Identify target populations. The target population is the number of persons that would regularly drink or breathe the contaminated water or air <Population Score, Chapter 4>. Use U.S. Bureau of Census data whenever possible. If only the number of residences is known, assume the national average of 3.8 persons per residence. The target population is assumed to have a normal distribution of adults, children, elderly, ill, etc. In rare instances when this is not true, select the appropriate ADI or UCR (Step 2) for the population of concern.

Step 5.2: Score population and distances. After identifying the target population for each pathway, enter the score for the number (Table 8.11) on ground-water, surface-water, and air pathway worksheets.

Score distance with Table 8.12 or Table 8.13 on ground-water and air pathway worksheets (Appendix A). (Because simple dilution is assumed for the surface-water pathway (Chapter 6), distance is usually irrelevant.) For the ground-water pathway do not include river miles if scenario includes surface-water transport. When the ground-water and air pathway scenarios involve several or continuously larger target populations, construct mileage rings around the site at intervals shown in Table 8.12 or Table 8.13. Use the largest combined population-distance score for subsequent scoring.

Table 8.11 Target-population scores

Population [N]	Score[a]
<3	0
3-30	1
30-300	2
300-3,000	3
3,000-30,000	4
30,000-300,000	5
...	

[a]Score = log(population)

Table 8.12 Score for distance to population for <u>ground-water</u> route

Distance [x] (m)	Score[a] <Eq. 5.1>
<10	0
10-1,000	-1
1,000-100,000	-2
...	

[a]Score = -log(distance) / 2

Table 8.13 Score for distance to population for <u>air</u> route

Distance [x] (m)	Score[a] <Eq. 7.2>
<20	-2
20-60	-3
60-200	-4
200-600	-5
600-2000	-6
...	

[a]Score = -log(distance) • 2

Step 6. **Score site features based on way in which waste is released**

The following instructions for scoring site features are specific to the way in which the waste leaves the site (via air, surface water, or ground water). The steps applicable to the ground-water route are designated 6.Gx; those for the surface-water route, 6.Sx; and those for the air route, 6.Ax.

6.G1, 6.S1, 6.A1	Score features applicable to all wastes.
6.G2, 6.S2 or 6.S3, 6.A2	Score features specific to each waste.

For Step 6, completely score one scenario, and then all scenarios in a pathway before moving on to a scenario in another pathway.

Step 6.G1 **Score ground-water dilution and aquifer velocity and thickness**

Necessary data for Step 6.G1. This step requires

- aquifer interstitial velocity [V_{gw}] or, if not directly known
  - hydraulic gradient between site and withdrawal point [η] or if unavailable, topographic slope [θ] {0.03 m/m; 3%}
  - hydraulic conductivity of aquifer [K_{gw}] {1 m/day} or description of aquifer material (Table 8.15) {clean, unconsolidated sand}
  - aquifer porosity [ϕ] (Table 8.16) {0.3}
- flow rate of leachate from site to aquifer [i_r], or if not directly known
  - waste site area capturing precipitation [A_s]
  - average daily precipitation [r_a] (Figure 8.6) {1.6×10^{-3} m/day}
  - hydraulic conductivity from site to aquifer [K_u] {10^{-2} m/day}
  - hydraulic conductivity of cover (if any) [K_{covr}] {10^{-3} m/day}
- average aquifer thickness [m] {10 m},
- withdrawal rate from aquifer [Q_w] {250 m^3/day or if only source $B_u \cdot N$}

or if intervening river
- river discharge [Q_r] {0 m^3/day},

  if short river travel distance
  - river transport distance [x_{riv}]
  - river depth [d_{riv}]
  - river width [w_{riv}] {$w_{riv} \leq x_{riv}/40$}
- additional uncontaminated water sources [Q_a] {0 m^3/day}

Step 6.G1.1: Calculate flow rate from site to aquifer. Although the amount of liquid percolating into the waste is important in determining the leakage (mass-loading rate) to the aquifer, precise lysimeter data is often lacking. Thus, roughly estimate the leakage from precipitation data. (If liquid waste has been stored at the site, the difference in volume remaining and volume stored may help determine the leach rate.)

Estimate potential seepage. Estimate potential seepage precipitation [r_{seep}] by using a fraction [μ_r] of mean daily precipitation [r_a] (Table 8.14); obtain r_a from rain gages in vicinity of site (use Figure 8.6 for rough estimates). (Alternate methods include (1) summing precipitation when aquifer recharge occurs, frequently in early spring when soil moisture has returned to field capacity but before significant evapotranspiration occurs, or (2) using a standard monthly water budget. However, these latter methods may not be feasible at all sites.)

The actual percolation rate [r_{perc}] must be less than the maximum possible seepage rate into the landfill [K_{covr}] and into the unsaturated zone above the target aquifer [K_u]; hence for landfills

$$r_{perc} = \text{minimum of } r_{seep}, K_{covr}, \text{ and } K_u$$

where

K_{covr} = hydraulic conductivity of the cover (obtain data or evaluate from qualitative discriptions using Table 8.15)

K_u = hydraulic conductivity of strata between site and aquifer

$$= \frac{\Sigma_i L_i}{\Sigma_i \frac{L_i}{K_i}} \quad \text{(assuming horizontal layering)}$$

K_i = hydraulic conductivity of each geologic stratum or liner above the target aquifer (Table 8.15)

L_i = thickness of each geologic stratum

For a lagoon or pond, r_{perc} will lie somewhere between r_{seep} and K_u. For a small range, use an average. Unfortunately, the range can be several orders of magnitude. In this latter case when water-budget data (waste volumes placed in the pond and water evaporation estimates) are lacking, select a value for r_{perc} midway in magnitude between r_{seep} and K_u.

When calculating K_u or K_{covr},

- Consider that deep surface cracks from excessive drying are possible when determining the permeability of clay or soil covers.
- Reduce the hydraulic conductivity of the liner by 1 order of magnitude when calculating the average permeability (EPA, 1983) if significant chemical reaction of the leachate with a clay liner is expected.

- Note that except for liners, we have assumed in our expression for the average permeability that the permeability of each geologic stratum precludes formation of perched water tables (~3 order of magnitude difference).

- Do not including synthetic liners in the calculations for K_u because synthetic membrane liners will likely fail within 35 yr. We believe they will provide little protection thereafter, however, accounting for any residual protection is up to your judgment. Recall that credit is already given for the fact that the site is "engineered" under step 4, "Evaluate engineered barriers."

Check that $K_{covr} \leq K_u$. If this is true, continue the calculations; if not, consider the pathway in which the landfill becomes a bathtub and overflows the liner. Also be sure to note the proper placement type under Step 4.

Estimate flow rate. The flow rate from the site to the aquifer [i_r] site equals the surface area of the waste site capturing precipitation [A_s] times the portion of precipitation that percolates into the landfill [r_{perc}]: $i_r = r_{perc} \cdot A_s$. If hydraulic drainage structures are absent, so that more area can contribute water, then also include this additional area in A_s for a landfill.

Table 8.14 Fraction of precipitation percolating into waste

Description	Fraction [μ_r]
Below average e.g., mounded	0.10
Normal e.g., level, little clay	{0.25}
High e.g., depressed surface	0.40

Table 8.15 Hydraulic conductivity for various rock types (Freeze and Cherry, 1979; Reprinted with permission)

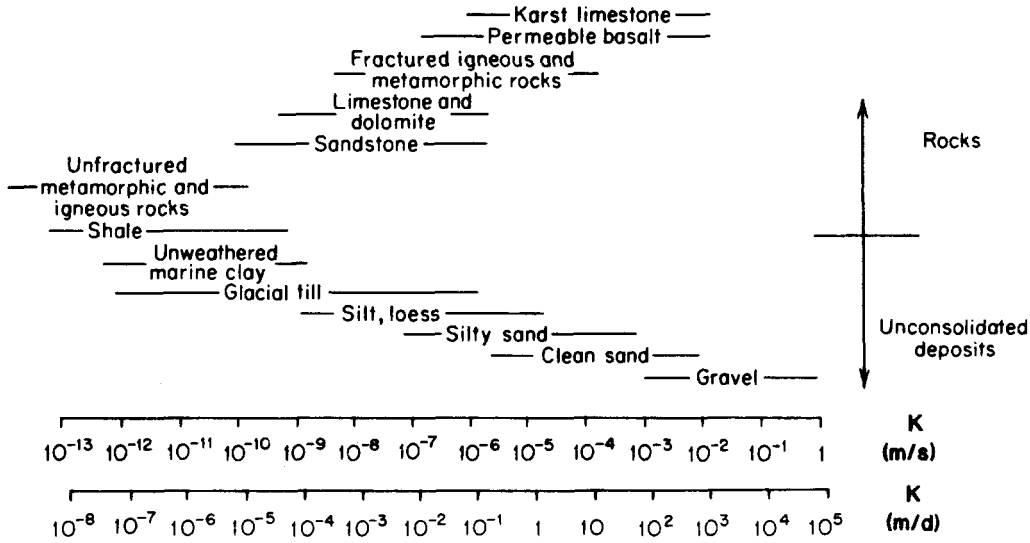


Table 8.16 Range of porosity for various rock types (Freeze and Cherry, 1979; Reprinted with permission)

Type of material	Range %
Unconsolidated deposits	
gravel	25-40
sand	25-50
silt	35-50
clay	40-70
Rocks	
fractured basalt	5-50
karst limestone	5-50
sandstone	5-30
limestone, dolomite	0-20
shale	0-10
fractured crystalline rock	0-10
dense crystalline rock	0- 5

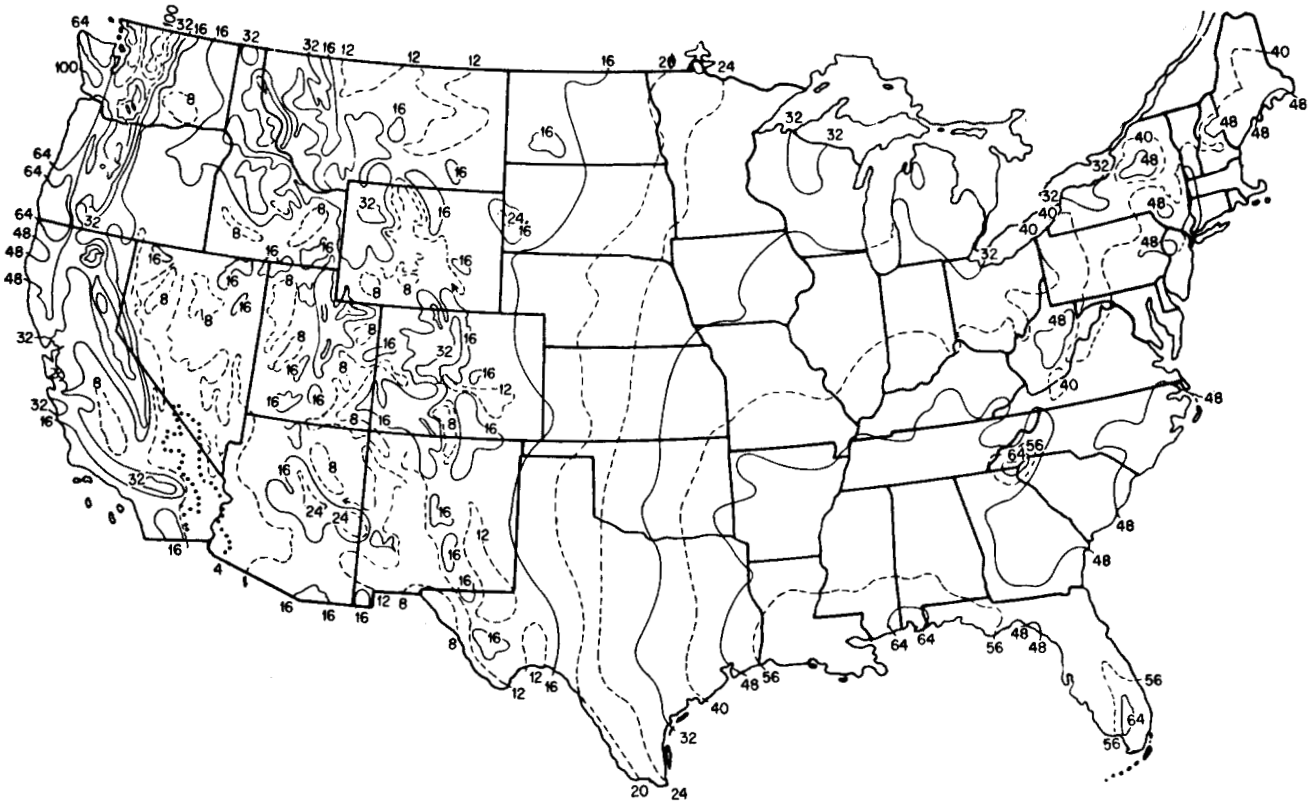


Figure 8.6 Mean annual rainfall (in./yr) in United States (1 in./yr = 7×10^{-5} m/day) (NCC, 1979)

Step 6.G1.2: Score aquifer fluid velocity and aquifer thickness. Scoring the ground-water velocity of aquifer pore fluid [V_{gw}] (Table 8.17) and thickness of aquifer [m] (Table 8.18) are self-explanatory, but obtaining estimates of these parameters can be easy at some sites and difficult at others.

When no hydrologic data exist for approximating V_{gw}, use Darcy's law, $V_{gw} = K_{gw}\eta/\phi$. Assume the hydraulic gradient [η] is the same as the slope of the surface topography [θ], and select, using qualitative descriptions of the aquifer, average hydraulic conductivity [K_{gw}] and porosity [ϕ] from Table 8.15 and Table 8.16, respectively. Enter score on ground-water worksheet. After determining V_{gw}, check the ground-water travel time (x_{gw}/V_{gw}). If the travel time is greater than 1000 yr, stop. (Ignore this scenario.)

SRS assumes the waste is completely miscible in the ground-water. If this is not true or the density of the waste causes it to float or sink within the aquifer, ignore the aquifer thickness. (Set score to 0.)

Table 8.17 Scores for aquifer fluid velocity in pores

Pore velocity [V_{gw}] (m/day)	Score[a] <Eq. 5.1>
...	
$3x10^{-5} < 10^{-4} \leq 3x10^{-4}$	4
10^{-3}	3
10^{-2}	2
10^{-1}	1
10^{0}	0
10^{1}	-1
10^{2}	-2
...	

[a]Score = -log(velocity)

Table 8.18 Scores for aquifer thickness

Thickness [m] (m)	Score[a]
<3	0
3-30	(-1)
30-300	-2

[a]Score = -log(thickness)

Step 6.G1.3: Evaluate and score pathway dilution. Calculate the pathway dilution [δ]:

$$\delta = i_r/(i_r+Q_a+Q_w+Q_r)$$

where

i_r = flow rate from site to aquifer (m^3/day)

Q_a = additional water from uncontaminated source

Q_w = pumping discharge through well or recharge into river (m^3/day) If unknown and well is only water source assume $B_u \cdot N$ where

B_u = average per capita water use {0.76 m^3/day/person}

N = community population

Q_r = mean daily river discharge (m^3/day) if $x_{riv} \geq \ell_m$ (default case); otherwise

$$Q_r = \text{river discharge} \cdot \left[\frac{x_{riv}}{\ell_m} \right]^{1/2} ; \ \ell_m = 15 \cdot w_{riv}^2 / d_{riv}$$

The river discharge [Q_r] will be zero for pathways that do not include a surface-water segment. Likewise, Q_w will be zero for pathways including a river route. See Step 6.S1.5 for methods on estimating Q_r, w_{riv}, and d_{riv}.

Score the pathway dilution [δ] using Table 8.19 and enter on ground-water pathway worksheet (Appendix A).

Table 8.19 Ground-water route dilution scores

Pathway dilution [δ][a]	Score[b] <Eq. 5.1>
...	
0.0003-0.003	-3
0.003-0.03	-2
0.03-0.3	-1
0.3-1	0

[a]Dilution = $i_r/(i_r+Q_w+Q_r+Q_a)$
[b]Score = log (dilution)

6.G2. Score ground-water mass, decay, and retardation adjustments

Necessary data

- flow rate from site to aquifer [i_r] (Step 6.G1)
- chemical or radionuclide solubility [S] {1 kg/m^3 or 1 Ci/m^3}
- quantity available for release [W_i] (kg or Ci) (Step 1); usually equivalent to mass originally placed [W_o]
- decay rate while transported in unsaturated zone [λ_u] {0 day^{-1}} if λ_u nonzero
  - depth to aquifer (from lowest waste to seasonal top of aquifer) [d]
  - percolation velocity [V_u]; equivalent to r_{perc}/ϕ (Step 6.G1) unless leachate collection system present
- decay rate while transported in aquifer [λ_{gw}] {0 day^{-1}} if λ_{gw} nonzero
  - ground-water distance traveled from site to target [x_{gw}]
  - aquifer velocity [V_{gw}] (Step 6.G1)
- possibly, chemical retardation at site [R] {1} or
  - K_d or K_{oc} {0}
  - soil density {1500 kg/m^3}
  - soil porosity {0.3}

Step 6.G2.1: Evaluate mass-release adjustment. The mass-release adjustment [g_{gw}] for ground-water pathway for each chemical is calculated by

$$g_{gw} = 1-\exp(-i_r\ t_\ell S/W_i)$$

where

i_r = aquifer recharge (step 6.G1) (m^3/day)
S = chemical solubility (kg/m^3 or Ci/m^3)
t_ℓ = average human life expectancy {2.56x10^4 days}
W_i = quantity of waste available for release (kg or Ci)

The mean annual release of waste over period t_ℓ is limited either by the quantity or solubility of waste present. The mathematical expression for mass-release adjustment [g_{gw}] smooths the transition between these two

extremes. As an alternative, you may calculate the products W_i/t_ℓ and $S \cdot i_r$ and then assign g as follows:

If $W_i/ t_\ell \leq S \cdot i_r$, then $g_{gw} = 1$; $F_{adj} = \{0\}$
If $W_i/ t_\ell > S \cdot i_r$, then $g_{gw} = S\ i_r t_\ell / W_i$

Score g using Table 8.20 and enter in ground-water worksheet (Appendix A).

Table 8.20 Mass-release adjustment scores for ground-water route

Release adjustment [g][a]	Score[b]
...	
0.003-0.03	-2
0.03-0.3	-1
0.3-1	{0}

[a]Adjustment = $1-\exp(-i_r t_\ell S/W_i)$
[b]Score = log(adjustment)

Step 6.G2.2: Evaluate transport decay. Degradation of the waste while in transport in either the unsaturated zone or aquifer can have a profound effect on the ultimate hazard posed. Evaluate the decay in the unsaturated zone as follows <Unsaturated-zone transport, Chapter 6> and enter on the ground-water pathway worksheet (Appendix A). If $\alpha_u \lambda_u / V_u < 0.25$, then

$$\text{Score } [F_{unsat}] = \text{nearest integer of } \left[\frac{-d}{2.3} \left(\frac{\lambda_u}{\alpha_u V_u} \right)^{1/2} \right]$$

where

α_{gw} = dispersivity {0.1x for x < 200 m; 20 m for x ≥ 200 m} (Pickens and Grisak, 1981; Figure 5.2)

$V_u \simeq r_{perc} / \phi$

otherwise,

$$\text{Score } [F_{unsat}] = \text{nearest integer of } \left[\frac{-d}{2.3} \frac{\lambda_u}{V_u} \right]$$

Likewise, the score for the decay while transported in the aquifer is <Aquifer transport, Chapter 6> as follows. If $\alpha_{gw}\lambda_{gw}/V_{gw} < 0.25$, then

$$\text{Score } [F_{sat}] = \text{nearest integer of } \left[-\frac{x_{gw}}{2.3} \left(\frac{\lambda_{gw}}{\alpha_{gw} V_{gw}}\right)^{1/2} \right]$$

where

α_{gw} = dispersivity {0.1x for x < 200 m; 20 m for x ≥ 200 m}

otherwise,

$$\text{Score } [F_{unsat}] = \text{nearest integer of } \left[-\frac{x_{gw}}{2.3} \frac{\lambda_{gw}}{V_{gw}} \right]$$

If only soil or surface-water decay rate is known, assume decay is 100 times smaller (half-life [$t_{1/2}$] x 100) {default} in ground-water.

Step 6.G2.3: Evaluate chemical retardation. Because steady-state transport forms the basis of an SRS score, waste retardation [R] is not used explicitly; R affects only the rate at which the system reaches steady state. However, if waste transport is significantly retarded, exposure of a receptor is delayed. Even though the ultimate risk is the same over the long term, the delayed exposure can influence priorities for remedial action. In some cases, you have more time to clean up the site, in other cases, less time (for example, flushing out the waste from contaminated soil is less feasible as retardation increases). Recognizing both facets of retardation, we recommend neglecting retardation [F_{rtrd}= 0], except when it is large (R ≥ 100 or $K_d \geq 0.02\ m^3/kg$) or very large (R ≥ 1000 or $K_d \geq 0.2\ m^3/kg$) where you may decrease the score [F_{rtrd}] by 1 or 2 (Table 8.21). (Neglect retardation if using SRS to examine alternatives for permanent means of disposal.)

If the partition coefficient [K_d] is known, estimate retardation by

$$R \simeq 1 + \frac{\rho_b K_d}{\phi}$$

where

K_d = partition coefficient (0 m^3/kg)

$$= \frac{\text{solute mass adsorbed on solid phase (kg)/ mass of solid phase (kg)}}{\text{concentration of solute in solution (kg/m}^3\text{)}}$$

ρ_b = material bulk density (1700 kg/m^3)

ϕ = material porosity (0.3)

Because K_d (and R) is specific to soil type, quantitative data are difficult to find. However, for organic waste, a closely related term, organic carbon partition coefficient [K_{oc}] measures the tendency for organics to adsorb on soil but is largely independent of soil properties:

$$K_{oc} = \frac{\text{mass of solute on solid phase/ mass of organic carbon}}{\text{concentration of solute in solution}}$$

To obtain K_d from K_{oc}, multiply K_{oc} by fraction of organic carbon in soil (Table 8.22). Use 0.03 (3%) if unknown.

Table 8.21 Scores for retardation in ground-water

Description	Score F_{rtrd}
Low retardation ($R < 100$ or $K_d < 0.02$ m^3/kg) or permanent disposal	{0}
Significant retardation ($100 \leq R < 1000$)	-1
Very large retardation ($R \geq 1000$; $K_d \geq 0.2$ m^3/kg) and limited impact on clean up	-2

Table 8.22 Fraction of organic matter of soil in several areas of United States (Lyon et al., 1957)

Area	No. of soils measured	Organic fraction Range	Av
West Virginia	240	0.0074 - 0.15	0.029
Pennsylvania	15	0.017 - 0.099	0.036
Kansas	117	0.0011 - 0.036	0.034
Nebraska	30	0.024 - 0.053	0.038
Minnesota prairie	9	0.034 - 0.074	0.052
Southern Great Plains	21	0.012 - 0.022	0.017
Utah	21	0.015 - 0.049	0.027

Step 6.S1. **Calculate dilution for surface-water pathway**

Necessary data. (All scoring tables except Table 8.24 based on dimensionless quantities; thus, you may easily use other units)

- mean daily precipitation [r_a] (Figure 8.6) {1.6×10^{-3} m/day; 0.6 m/yr}
- surface area contaminated or contributing runoff [A_s]
- SCS runoff curve number [CN] or description of soil {CN = 80}
- flow rate of river receiving contaminated runoff [Q_r]

  if river travel distance short
  - x_{riv} = watercourse distance
  - d_{riv} = mean river depth
  - w_{riv} = river width {$w_{riv} \leq x_{riv}/40$}
- flow rate of additional uncontaminanted water sources (e.g., storm water or wells) [Q_a] {0 m^3/day}
- estimate of retardation [R] {1} or partition coefficient [K_d]{0 m^3/kg}

Step 6.S1.1: First, check if drainage from site possible (not closed basin). If open basin, then estimate the hydrologic soil group for the site from a description of the surface soil (Table 8.23).

Step 6.S1.2: Second, estimate the SCS runoff curve number from a description of the land use and the hydrologic soil group (Table 8.26).

Step 6.S1.3: Next, calculate the excess precipitation [r_{net}] (m/day):

$$r_{net} = \frac{(r_a - 0.2S_w)^2}{r_a + 0.8S_w}$$

where

$$S_w = 7 \times 10^{-5} \left(\frac{1000}{CN} - 10 \right)$$

Step 6.S1.4: Next, calculate runoff [q] as follows and score with Table 8.24:

$$q = r_{net} \cdot A_s$$

Step 6.S1.5: Finally, calculate the pathway dilution [δ] as follows and score with Table 8.25:

$$\delta = \frac{q}{q + Q_r + Q_a}$$

where

Q_r = mean daily river discharge (m^3/day) if $x_{riv} \geq \ell_m$ (default case) otherwise,

$$Q_r = \text{river discharge} \cdot \left[\frac{x_{riv}}{\ell_m} \right]^{1/2}; \quad \ell_m = 15 \cdot w_{riv}^2 / d_{riv}$$

If either river discharge, width, or depth is unknown, assume

Q_r (m^3/day) $= 0.25\ A_{drain}^{0.8}$ (Leopold and Miller, 1956)

w_{riv} (m) $= 1400\ Q_r^{0.5}$ (Lacey, 1930; Rechard and Hasfurther, 1980)

d_{riv} (m) $= 0.3\ w_{riv}^{0.6}$ (Lindley, 1919)

where

A_{drain} is basin drainage area (m^2)

Although the intercept coefficients vary in these empirical relationships, the exponent values only change slightly between regions (Richards, 1982).

Step 6.S1.6: Select surface-runoff model. From the estimate of the retardation [R] or the partition coefficient [K_d], select whether to continue with Step 6.S2 and use the dissolution model for contaminant release or skip to Step 6.S3 and use the sediment model for contaminant release <Method of Scoring, Chapter 6>.

If $K_d < 0.02\ m^3/kg$ or $R < 100$, then go on to Step 6.S2.

If $K_d \geq 0.02\ m^3/kg$ or $R \geq 100$, then skip to Step 6.S3.

Table 8.23 Definition of SCS hydrologic soil groups (Barfield et al., 1981)

Group	Runoff	Soil Type
A	Very low	Chiefly deep, well-drained sands and gravels
B	Low	Moderately deep, well-drained soils with moderately fine to moderately coarse texture
{C}	Moderate	Soils with a layer that impedes downward movement or soils with moderately fine to fine texture
D	High	Clay soils with a high swelling potential, soils with a permanently high water table, soils with clay pan at or near surface, and shallow soils over impervious materials

Table 8.24 Scores for runoff

Runoff (1/q)	Score[a] <Eq. 6.2>
...	
$3x10^0 > 10^0 \geq 3x10^{1}$	0
10^{-1}	-1
10^{-2}	-2
10^{-3}	-3
...	

[a]Score = - log (runoff)

Table 8.25 Surface-water route dilution scores

Pathway dilution $[\delta_{sw}]$[a]	Score[b] <Eq 6.2>
...	
0.00003-0.0003	-4
0.0003-0.003	-3
0.003-0.03	-2
0.03-0.3	-1
0.3-1	0

[a]Dilution = $q/(q + Q_r + Q_a)$
[b]Score $\cong$ log(dilution)

Table 8.26 Runoff curve numbers for selected agricultural, suburban, and urban land use (antecedent moisture condition II) (USBR, 1977 and Barfield et al, 1981)

Land use	Potential for runoff	Hydrologic soil group A	B	{C}	D
Cultivated (newly reclaimed land)					
Row crops	High	72	81	88	91
	Low	65	75	82	86
Small grain	High	65	76	84	88
	Low	61	73	81	84
Legumes or rotation meadow	High	66	77	85	89
	Low	55	69	78	83
Pasture	High	68	79	86	89
	Low	39	61	74	80
Woods or farm woodlots	High	45	66	77	83
	Low	25	55	70	77
Meadow (permanent)		30	58	71	78
Western range land					
Grass-weed-mixture w/brush	High		78	85	92
	Low		59	71	84
Sagebrush w/grass understory	High		64	78	
	Low		35	46	
Juniper or pinon w/grass	High		73	84	
	Low		40	59	
Aspen, oak, or maple w/other mountain brush mixtures	High		63	71	
	Low		30	40	
Forest land	High	56	75	86	91
	Medium	36	60	70	76
	Low	15	44	54	61
Developed land					
Open spaces (parks, golf, etc.)	Medium	49	69	79	84
	Low	39	61	74	80
Business area (85% impervious)		89	92	94	95
Industrial area (75% impervious)		81	88	91	93
Residential: <1/8 acre, 65% impervious		77	85	90	92
1/4 acre, 38% impervious		61	75	83	87
1/2 acre, 25% impervious		54	70	80	85
1 acre, 20% impervious		51	68	79	84
Streets, roads, and parking lots					
Paved with curbs -normal climate		98	98	98	98
-very warm climate		95	95	95	95
Gravel		76	85	89	91
Dirt		72	82	87	89

Step 6.S2 **Score surface-water mass and decay adjustments for dissolved waste**

Step 6.S2 assumes the waste escapes from the site dissolved in the runoff ($K_d < 0.02\ m^3/kg$ or $R < 100$).

Necessary data.

- runoff [q] (Step 6.S1)
- chemical or radionuclide solubility [S] {1 kg/m^3 or 1 Ci/m^3}
- quantity available for release [W_i] (kg or Ci) (Step 1); usually equivalent to mass originally placed [W_o]
- decay rate while transported in surface water [λ_{sw}] {0 day^{-1}} if λ_{sw} nonzero:
  - watercourse distance from site to target population [x]
  - mean surface-water velocity [V_{sw}]

Step 6.S2.1: Evaluate mass-release adjustment. The mass-release adjustment [g_{sw}] for surface-water pathway for each chemical is calculated by

$$g_{sw} = 1-\exp(-qt_\ell S/W_i)$$

where

q = runoff (Step 6.S1) (m^3/day)
S = chemical solubility (kg/m^3 or Ci/m^3)
t_ℓ = average life expectancy (2.56×10^4 days)
W_i = mass of waste available for release (Step 2) (kg or Ci)

Score g_{sw} using Table 8.27 and enter in ground-water worksheet (Appendix A).

The mean daily release of waste over period t_ℓ is limited either by the quantity of waste present or the solubility of waste. The mass release adjustment [g_{sw}] mathematically smooths the transition between these two extremes. As an alternative, you may calculate the products W_i/t_ℓ and $S \cdot q$ and then assign g as follows:

if $W_i/t_\ell \leq S \cdot q$, then $g_{sw} = 1$; $F_{adj} = \{0\}$; otherwise,
if $W_i/t_\ell > S \cdot q$, then $g_{sw} = (S \cdot q) \cdot (t_\ell/W_i)$

Step 6.S2.2: Find fraction of waste dissolved. Estimate the fraction of waste dissolved and removed [μ_{dis}] as follows and score with Table 8.28.

$$\mu_{dis} = \frac{r_{net}}{r_a}$$

Step 6.S2.3: Evaluate decay. Although usually insignificant, score decay while transported in surface water as follows (where α_{sw} = surface-water dispersivity = 0.6 $d_{riv}^{5/6}$ {1 m}) <Derivation of Scoring Model, Chapter 6>. If $\alpha_{sw}\lambda_{sw}/V_{sw} < 0.25$, then

$$\text{Score } [F_{decay}] = \text{nearest integer of } \left[-\frac{x_{riv}}{2.3} \left(\frac{\lambda_{sw}}{\alpha_{sw} V_{sw}}\right)^{1/2} \right]$$

otherwise,

$$\text{Score } [F_{decay}] = \text{nearest integer of } \left[-\frac{x_{riv}}{2.3} \frac{\lambda_{sw}}{V_{sw}} \right]$$

Table 8.27 Mass-release adjustment scores for surface-water route

Release adjustment [g][a]	Score[b]
...	
0.003-0.03	-2
0.03-0.3	-1
0.3-1	{0}

[a]Adjustment = $1-\exp(-q\ t_{\ell} S/W_i)$
[b]Score = log(adjustment)

Table 8.28 Scores for runoff dissolution

Runoff ratio[a] [μ_{dis}]	Score[b] <Eq. 6.2>
> .3	0
0.3-0.03	-1
0.03-0.003	-2
...	

[a] $\mu_{dis} = r_{net}/r_a$
[b] Score = log (μ_{dis})

Step 6.S3. **Score surface-water sediment yield and decay for adsorbed waste**

Rather than assume that the waste is dissolved in the runoff, this step assumes that the waste is adsorbed onto sediment particles ($R > 100$; $K_d > 0.02\ m^3/kg$).

Necessary data

- sediment yield [Y_s] {0.5 $kg/m^2/yr$} or if unavailable,
  - SCS rainfall erosivity factor [R_E] {150} (available from local U.S. Soil Conservation Service (SCS) office or Figure 8.7)
  - SCS control-practice factor [CP] {0.35} (local SCS office or Table 8.29)
  - SCS length-slope topographic factor [LS] {0.4} (local SCS office or Figure 8.8)

Step 6.S3.1: Estimate sediment yield if necessary. If sediment yield data are lacking, estimate the annual sediment yield [Y_s] ($kg/m^2/yr$) as follows <Derivation of Scoring Model, Chapter 6>

$$Y_s \simeq 5.6\text{x}10^{-2}\ CP\ LS\ R_E$$

Check value with Table 8.29. Reduce the sediment yield [Y_s] to a maximum of 100 times average basin yield (Table 8.30) if it exceeds this value. Increase the sediment yield [Y_s] to a minimum low basin yield (Table 8.30) if it is smaller. Score Y_s with Table 8.31.

$$100 \cdot basin_{av} \leq Y_s \leq basin_{low}$$

Step 6.S3.2: Find fraction of waste carried away with sediment. The fraction of waste removed is the ratio of annual sediment yield [Y_s] to original mass of erodible soil per unit area [$\rho_b h$], where ρ_b is bulk density of the soil {1500 kg/m^3} and h is soil depth subject to erosion annually {0.01 m}:

$$\mu_{soil} = \frac{Y_s}{\rho_b h} = \frac{Y_s}{15}$$

Step 6.S3.3: Score sediment-yield fraction. Use Table 8.30 to score the sediment yield fraction [μ_{soil}] and enter on surface-water worksheet.

Step 6.S3.4: Evaluate decay. Although usually insignificant, score decay while transported in the surface water as follows, where α_{sw} = surface-water dispersivity = 0.6 $d_{riv}^{5/6}$ {1 m}, V_{sd} = sediment velocity {V_{sw}}. If $\alpha_{sw}\lambda_{sw}/V_{sd} < 0.25$, then

$$\text{Score } [F_{decay}] = \text{nearest integer of } \left[-\frac{x_{riv}}{2.3} \frac{\lambda_{sw}}{V_{sd}} \right]$$

otherwise,

$$\text{Score } [F_{decay}] = \text{nearest integer of } \left[-\frac{x_{riv}}{2.3} \left(\frac{\lambda_{sw}}{\alpha_{sw} V_{sd}} \right)^{1/2} \right]$$

Table 8.29 Control-practice factor [CP] for pasture, rangeland, and woodlands (Barfield et al., 1981)

Soil condition	Vegetal canopy Type	Vegetal canopy % Cover	Ground cover (contacts surface) Ground Type	Percent ground cover 0	20	40	60	80	100
Permenant (undisturbed for >5-8 yr)	Little canopy		Grass[a]	0.45	0.20	0.11	0.04	0.013	0.003
			Leafy[b]	0.45	0.24	0.15	0.09	0.043	0.011
	Brush or trees w/little brush	25	Grass	0.40	0.18	0.09	0.04	0.013	0.003
			Leafy	0.40	0.22	0.14	0.09	0.043	0.011
		50	Grass	{0.35}	0.16	0.08	0.04	0.012	0.003
			Leafy	{0.35}	0.17	0.12	0.08	0.041	0.011
		75	Grass	0.28	0.14	0.09	0.04	0.012	0.003
			Leafy	0.28	0.15	0.10	0.08	0.041	0.011
	Forest/woodland	>75	Grass					0.001	0.0001
Bare soil (> 5 yr)	Bulldozer scraped			1.20					
	Freshly disked			1.00					

[a]Cover is grass, grasslike plants, or decaying compacted litter > 5 cm deep
[b]Broadleaf plants and weeds w/little lateral root network and/or litter

Table 8.30 Sediment yield from drainage areas of 100 mi^2 (2.6×10^8 m^2) or less of the United States (Todd, 1970)

Area	Sediment Yield ($kg/m^2/yr$)		
	$basin_{av}$	$basin_{low}$	$basin_{high}$
North Atlantic	0.088	0.011	0.42
South Atlantic	0.28	0.035	0.65
Great Lakes	0.035	0.003	0.28
Ohio	0.30	0.056	0.74
Tennessee	0.25	0.16	0.55
Upper Mississippi	0.28	0.003	1.4
Lower Mississippi	1.8	0.55	2.9
Souris-Red-Rainy	0.018	0.003	0.16
Missouri	0.52	0.003	2.3
Arkansas-White-Red	0.77	0.09	2.9
Texas Gulf	0.63	0.032	1.1
Rio Grande	0.46	0.053	1.2
Upper Colorado	0.63	0.053	1.2
Lower Colorado	0.21	0.053	0.56
Great Basin	0.14	0.035	0.62
Columbia, N. Pacific, California	0.14	0.011	0.39

Table 8.31 Scores for <u>surface-water</u> sediment yield

Sediment yield fraction[a] [μ_{soil}]	Score[b] <Eq. 6.3>
> .3	0
0.3-0.03	(-1)
0.03-0.003	-2
...	

[a] $\mu_{soil} = Y_s/(\rho_b h) \simeq Y_s/15$
[b] Score = log (μ_{soil})

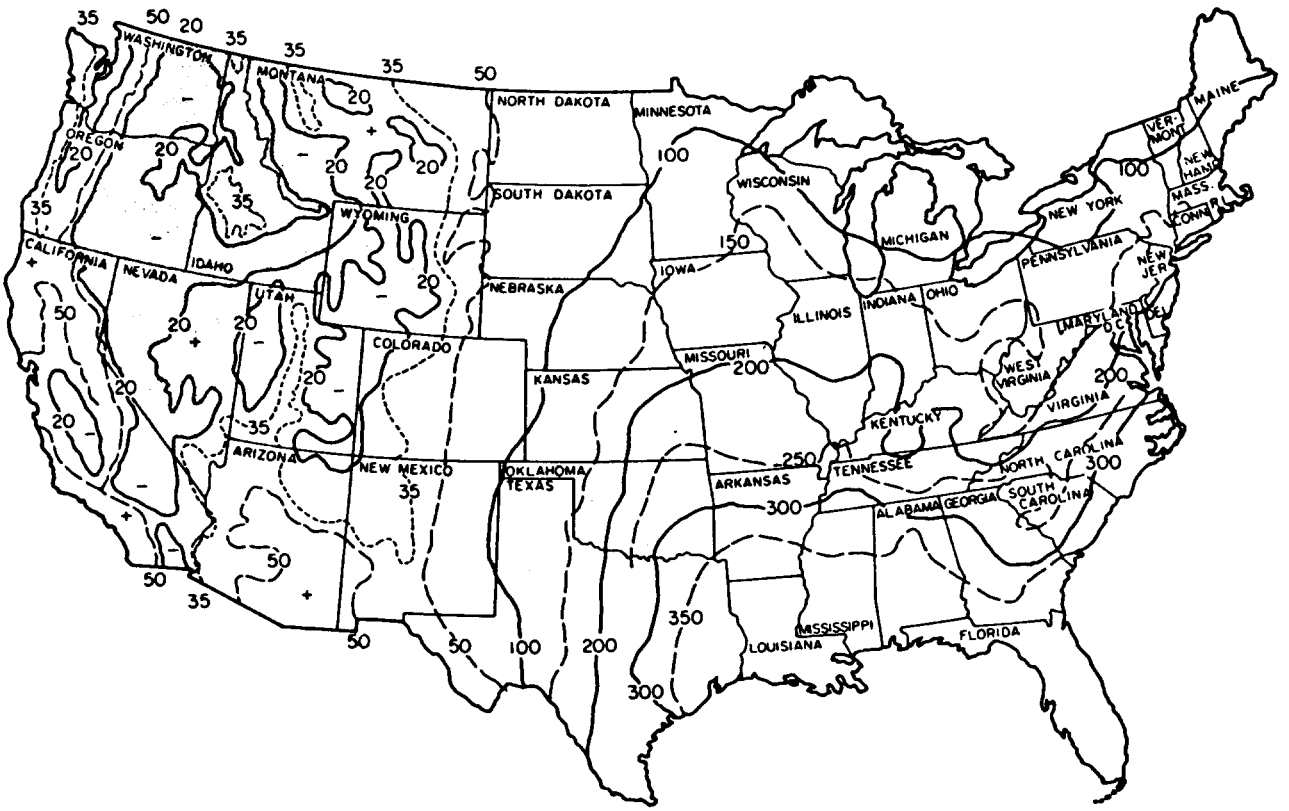
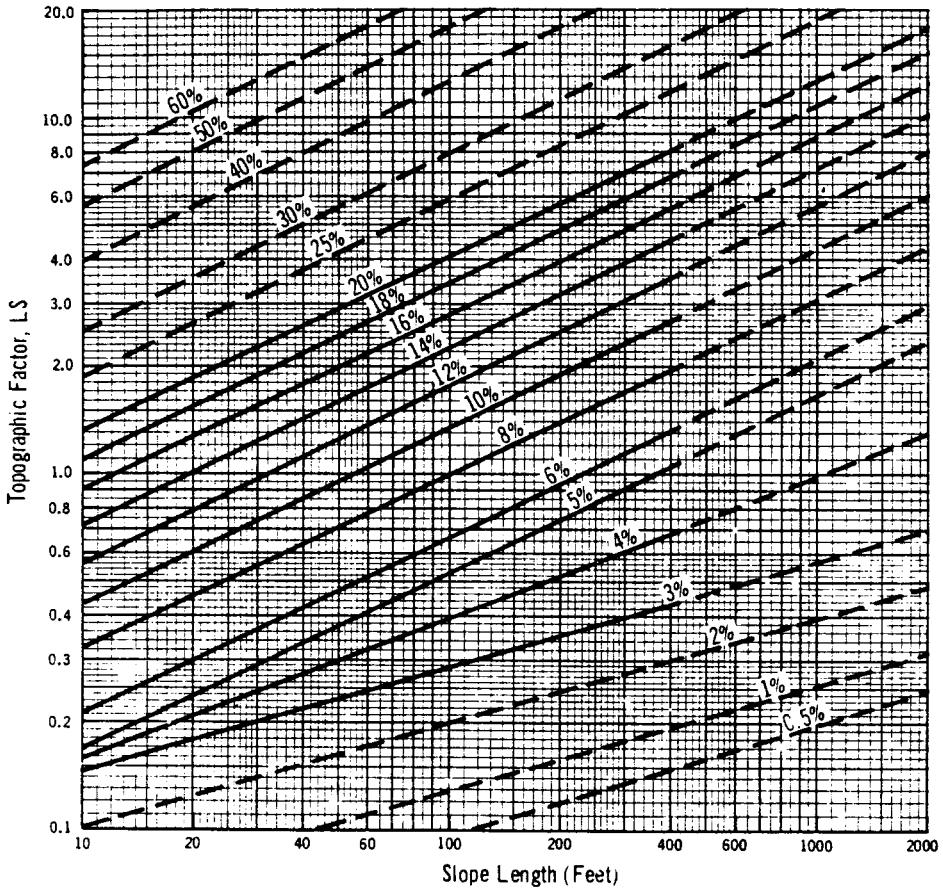


Figure 8.7 Mean annual rainfall-erosivity factor in United States (Barfield et al., 1981)



*The dashed lines represent estimates for slope dimensions beyond the range of lengths and steepnesses for which data are available. The curves were derived by the formula:

$$LS = \left(\frac{\lambda}{72.6}\right)^m \left(\frac{430x^2 + 30x + 0.43}{6.613}\right)$$

where λ=field slope length in feet and m=0.5 if s= 5% or greater, 0.4 if s=4%, and 0.3 if s=3% or less; and $x=\sin\theta$. θ is the angle of slope in degrees.

Figure 8.8 Length-slope (LS) topographic factor (Barfield et al., 1981)

Step 6.A1. **Assume mass-release adjustment**

Only the waste-specific, mass-release adjustment factor [g_a] must be evaluated in Step 6 for the air pathway. Because the air pathway is seldom of major importance, first assume the score [F_{adj}] for the mass-release adjustment [g_a] is zero and skip Step 6.A2. The air pathway score is readily completed. Should the air pathway determine the site score (highest pathway score), return to Step 6, estimate [g_a] as described in Step 6.A2, and adjust the air pathway.

Step 6.A2. **Calculate mass-release adjustment**

Necessary data

- quantity of waste available for release [W_i] (kg or Ci)
- vaporization emission rate [e_v], or if unavailable:
  - vapor pressure of volatile chemical [p]
  - mass concentration $\left[\kappa = \frac{W_i}{\rho d_{cont} A_s}\right]$
  - area of surface containing hazardous vapor [A_s]
  - gram molecular weight of chemical [w_m]
  - cover reduction factor [f_{covr}] estimated in Step 6.A2.1
  - gas generation factor [f_{gen}] estimated in Step 6.A2.5
- fugitive dust emission rate [e_w], or if unavailable
  - Thornthwaite precipitation-effectiveness index (PE) (Figure 8.9) {60}
  - fraction of covered soil [μ_{covr}] {bare, $\mu_{covr} = 0$} (unbroken grass prevents particle resuspension, $\mu_{covr} = 1$)

The mass-release adjustment factor [g_a] depends upon the emission rate of waste into the atmosphere. The emission rate [e] of chemical waste to the air pathway is the sum of the volatilization rate [e_v], wind erosion rate [e_w], and any contribution from dust generated by vehicular traffic. As with all the pathways, the rate of waste release is important information but measured data are often scarce and/or precise calculation techniques are time-consuming and data intensive. For the air pathway, estimate the emission rates from

- measured data;
- empirical equations provided;
- other empirical equations for which data are available [for example, USDA wind erosion equation (Skidmore and Woodruff, 1968)], particulate emission rate equations (Cowherd et al., 1985), vapor emission rate equations (Mackay, 1980; Shen, 1981; EPA, 1982).

Step 6.A2.1: Volatilization emission rate. Estimate the volatilization emission rate [e_v] (kg/day) by <Derivation of Scoring Model, Chapter 7>

$$e_v = 0.2 \; w_m^{1/2} \cdot p \cdot f_{covr} \cdot f_{gen} \cdot \kappa \cdot A_s$$

The two factors, f_{covr} and f_{gen}, are calculated as follows.

Soil cover. A simple engineering feature, 1 to 2 m of compacted soil above the waste, can significantly reduce the release rate of toxic chemicals via the air pathway to a small and possibly safe rate. If a soil cover exists that is greater than 0.2-m thick, the soil cover reduction factor [f_{covr}] is <Volatilization emission rate, Chapter 7>

$$f_{covr} = a \; \phi^{4/3}/s$$

where

$a = 1/350$ m (constant for SRS)

s = depth of soil cover (m)

ϕ = soil porosity (0.3)

Gas generation. If the hazardous waste is disposed along with other organic wastes that readily degrade into gas products such as methane, this supplemental gas can sweep hazardous vapors along with it. The gas generation factor [f_{gen}] accounting for this increased release is

$f_{gen} = 10$ for gas generation and
$s \leq 1$ m in calculation of f_{covr}

Step 6.A2.2: Particulate emission rate. Use the following equation for estimating the particulate emissions [e_w] (kg/day) from wind erosion or vehicular traffic at a waste site:

$$e_w = 0.2 \cdot \frac{A_s}{PE^2} \cdot \kappa \cdot (1 - \mu_{covr})$$

Step 6.A2.3: Sum emission rates to find total emission rate. Estimate total emission rate [Σe_j] by summing e_v and e_w .

Step 6.A2.4 Calculate mass-release adjustment. Calculate the mass-release adjustment [g_a] for the air pathway as follows. Score using Table 8.32:

$$g_a = 1-\exp(-t_\ell \, \Sigma e_j/W_i)$$

where

t_ℓ = average life expectancy {2.56×10^4 day}

As an alternative,

If $W_i/t_\ell \leq \Sigma e_j$, then $g_a = 1$; $F_{adj} = \{0\}$; otherwise,
If $W_i/t_\ell > \Sigma e_j$, then $g_a = \Sigma e_j \, t_\ell/W_i$

Table 8.32 Mass-release adjustment for air route

Release adjustment [g][a]	Score[b]
...	
0.003-0.03	-2
0.03-0.3	-1
0.3-1	{0}

[a]Adjustment = $1-\exp(-t_\ell \Sigma e_j/W_i)$
[b]Score = log(adjustment)

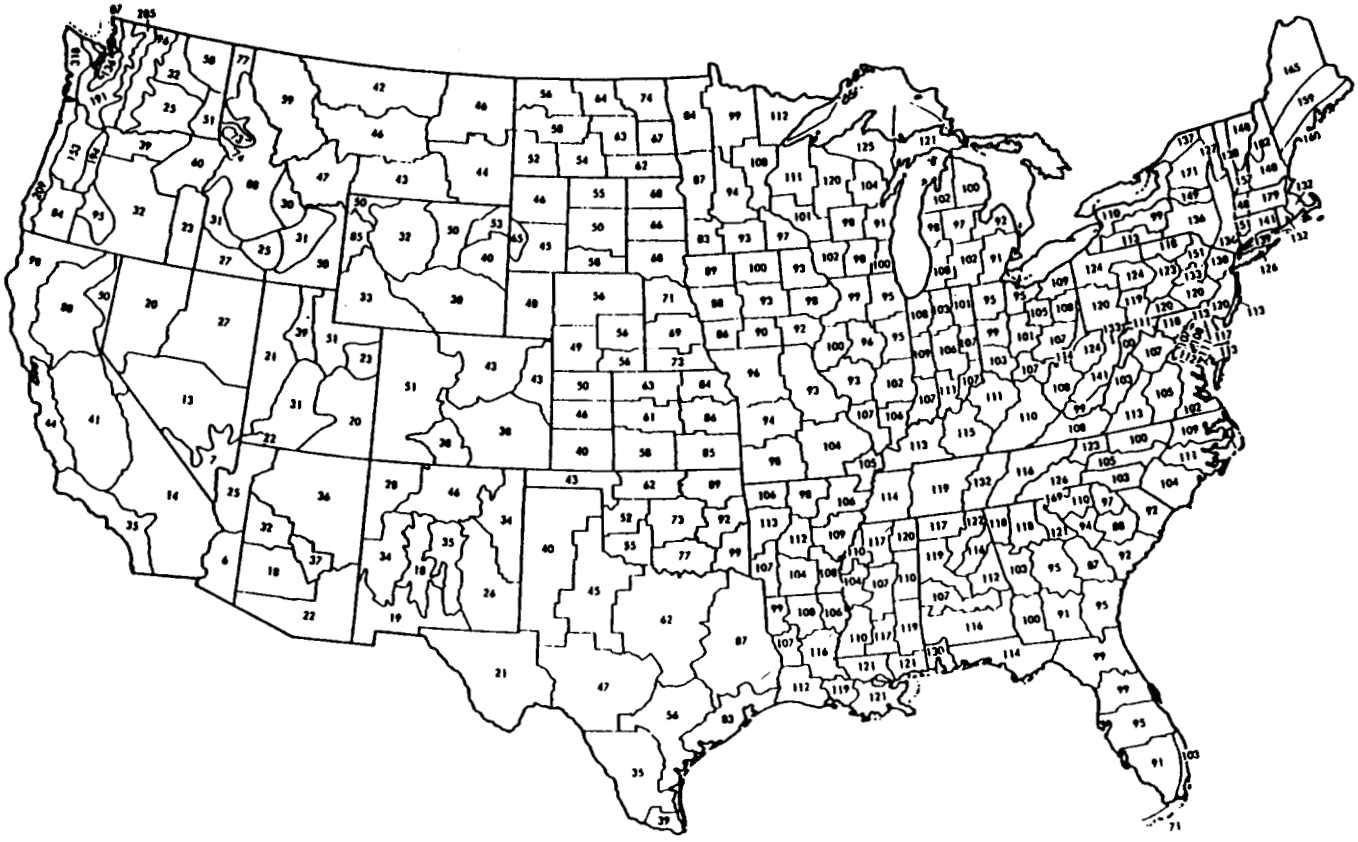


Figure 8.9 Map of PE index for United States (Cowherd et al., 1985)

Step 7. **Combine chemical scores then pathway scores to obtain site score**

Part a: Combine individual chemical scores to obtain pathway score. To evaluate a scenario score (for example, one of several in the ground-water pathway group), start with the highest individual chemical score for that scenario. Then account for the number of chemicals with this score or one lower as follows:

$$F_{seq} \simeq F_a + 0.1\ n_a + 0.01\ n_b + \ldots \qquad [8.3]$$

where

F_{seq} = scenario score
F_a = highest individual score (for example, chemical a)
n_a = number of other chemicals with same score F_a
n_b = number of chemicals with next highest score $F_b = F_a - 1$

Next evaluate the pathway score as

$$F_{path} \simeq F_1 + 0.1\ n_1 + 0.01\ n_2 + \ldots \qquad [8.4]$$

where

F_{path} = pathway score (for example, ground-water pathway)
F_a = highest individual score (for example, scenario 1)
n_a = number of other scenarios with same score F_1
n_b = number of scenarios with next highest score $F_b = F_a - 1$

Equation [8.4] has omitted the score for the contants [F_Γ] because they were roughly equivalent, that is,

$$F_\Gamma = \begin{cases} -3 \text{ for ground-water pathway <constants of model eq. [5.1]>} \\ -3 \text{ for surface-water pathway <eq. [6.2]>} \\ -3 \text{ for air pathway <eq. [7.2]>} \end{cases}$$

Part b: Evaluate site score. The site score is the highest score among the three pathways unless two or more are identical, in which case raise the score by one unit.

Step 8. **Construct ranked list of waste sites**

Ordering the sites based on their rank is straightforward. The only difficulty comes in ordering sites with almost the same score. Several additional factors can help rank these sites:

1. The uncertainty in the scores as represented by the variance (or pessimistic scores) will likely differ. Rank the site with the greater uncertainty higher because it potentially involves more risk.

2. Check whether SRS adequately scores unique features at each site; for example, check whether sensitive habitats are threatened. Rank the site with the unscored features higher.

3. As a tie-breaker, use the difference in the chemical scores and/or the site scores ignoring population.

4. Rank according to existence and/or magnitude of monitored releases.

5. SRS provides only technical input on human risk. The final ranking must also account for feasibility, costs, and public desires (Figure 8.6). These managerial inputs will also differentiate between sites.

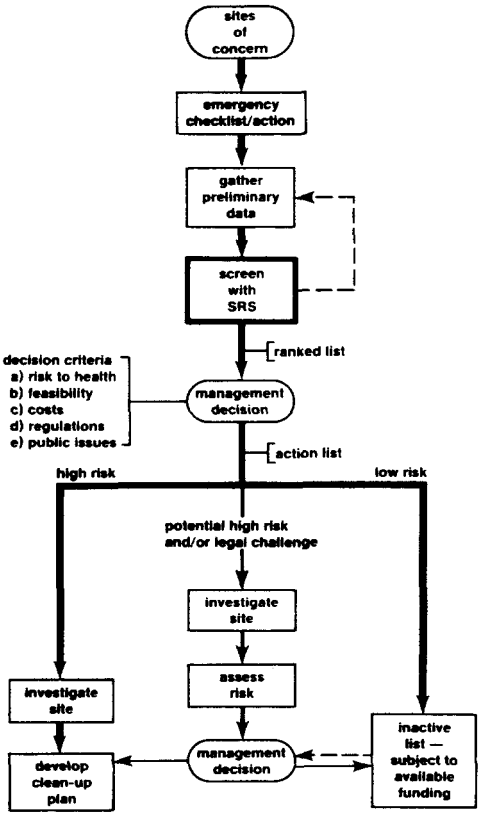


Figure 8.10 Juxtaposition of SRS ranking with other waste site decisions

9. COMPARISON OF SRS WITH OTHER ASSESSMENT SCHEMES

Following are three hypothetical examples where we apply SRS. Although the examples illustrate the use of SRS, when learning SRS, refer to Appendix B, which shows completed worksheets for an actual Superfund site. Here we compare SRS results with results from other ranking and rapid assessment techniques. The comparisons serve to verify SRS to a limited extent. However, because the SRS scores must be converted to concentrations, the calculations are not straightforward unless familiar with the equations in Chapters 5, 6, and 7.

Three Hypothetical Sites Contaminating Ground Water

Whelan et al. (1985, 1986) present three simplified cases of contaminant migration through the ground water to demonstrate differences between HRS, mHRS, and the more detailed RAPS ranking system. Applying SRS to these same three sites, we demonstrate its ability to rank sites similar to RAPS.

Site description. The following text briefly summarizes detailed discussion found in Whelan et al. (1985, 1986) for each of the three sites. In general, the simplified sites formulated by Whelan et al. (1985, 1986) primarily looked at differences in migration once the contaminant left the site; numerous other features were identical between sites. For example, all sites involved two wastes, arsenic and strontium-90, each at quantities such that the chemical health risk of each waste, $W_o \cdot T_{oral}$, was the same. Furthermore, the exposed population, climatic conditions, and aquifer properties were identical.

At sites 1 and 2, the mixture of chemical and radioactive sludge containing arsenic and strontium-90 is stored in unlined landfills. The bottom of the landfills coincide with the top of an unconsolidated, unconfined sand aquifer. At site 1, 500 people obtains all its water from wells located 1 km directly downgradient of the waste site [N = 500, x_{gw}= 1000 m]; at site 2, 500 people obtain water from wells 6 km downgradient from the site, rather than 1 km [N = 500, x_{gw}= 6000 m].

At site 3, the same mixture of arsenic and strontium-90 is stored in an unlined landfill, but the landfill lies 6 m above, rather than directly in

contact with, a similar unconfined, unconsolidated sand aquifer [d = 6 m]. The unsaturated soil zone consists of a 1-m thick clay layer and a 5-m thick alluvial sand similar to the aquifer sand. The permeability of each layer does not hinder the movement of leachate, but the adsoption of arsenic on the clay layer is important. The aquifer supplies water to a nearby river, 500 m from the waste site [x_{gw} = 500 m]. This large river is the only source of water for a town of 500 people located 1 km downstream [x_{riv}= 1000 m].

Data general to all three sites are tabulated in Table 9.1; data unique to site 3, in Table 9.2.

Table 9.1 Data general to three hypothetical sites (Whelan et al., 1985; 1986)

Parameter	Value
Potentially exposed population [N]	500
Area of disposal site [A_s]	2916 m^2
Infiltration rate [r_{seep}]	6.91×10^{-4} m/day
Aquifer characteristics	
Thickness [m]	53 m
Porosity [ϕ]	0.35
Bulk density [ρ_b]	1920 kg/m^3
Pore-water velocity [V_{gw}]	0.432 m/day
Dispersivity	
x-direction [α_x]	21.3 m
y-direction [α_y]	4.27 m
z-direction [α_z]	4.27 m
Waste characteristics	
Arsenic (As)	
Toxicity [T_{oral}]	15 $(mg/kg/day)^{-1}$
Half-life [$t_{1/2}$]	∞ day
Partition coefficient [K_d]	0.050 m^3/kg
Strontium-90 (^{90}Sr)	
Toxicity [T_{oral}]	400. $(\mu Ci/kg/day)^{-1}$
Half-life [$t_{1/2}$]	10,400 day
Partition coefficient [K_d]	0.003 m^3/kg

Table 9.2 Data specific to site 3 (Whelan et al., 1986)

Parameter	Value
Ground water distance [x_{gw}]	500 m
Unsaturated zone characteristics	
Clay layer	
Depth [d_{clay}]	1 m
Porosity [ϕ_{clay}]	0.495
Bulk density [ρ_{clay}]	1320 kg/m^3
Conductivity [K_{clay}]	1.04×10^{-2} m/day
Arsenic partition [K_d]	0.500 m^3/kg
Strontium partition [K_d]	0.034 m^3/kg
Sand layer	
Depth [d_{sand}]	5 m
Porosity [ϕ_{sand}]	0.35
Bulk density [ρ_{sand}]	1920 kg/m^3
Conductivity [K_{sand}]	13.0 m/day
Arsenic partition [K_d]	0.050 m^3/kg
Strontium partition [K_d]	0.003 m^3/kg
River characteristics	
River distance [x_{riv}]	1000 m
Width [w_{riv}]	91.4 m
Depth [d_{riv}]	1.5 m
Velocity [V_{sw}]	2.59×10^4 m/day
Water treatment	
Arsenic water purification factor	0.7
Strontium-90 purification factor	0.2

SRS Scoring. Because all pertinent data are given, Step 1 can be skipped, making scoring with SRS relatively easy. Data that are often difficult to obtain, such as dispersivity [α] were also given and were used in the SRS scoring rather than the SRS default values. Step 2 evaluates chemical scores. Because, for these three sites, the product, $W_o \cdot T_{oral}$, was identical for both arsenic and strontium-90, the quantity of arsenic, being

unimportant to relative ranking, was arbitrarily set at 1 kg. Because arsenic has an UCR of 15 $(mg/kg/day)^{-1}$ and strontium-90, 400 $(\mu Ci/kg/day)^{-1}$ (Appendix C), 1 kg of arsenic implied 0.04 Ci of strontium-90 was deposited at the site. The scores are shown on a modified version of the chemical worksheet (Appendix A) (Table 9.3).

Table 9.3 SRS chemical score at sites 1, 2, and 3

Property	Table		As score	^{90}Sr score
Quantity $[W_o]$	8.1		0	-1
Source decay	8.4			
$[6x10^{-5} \cdot t_{1/2}]$	8.5		0	0
		Subtotal $[W_i]$	0	-1
Chronic toxicity	8.3			
Ingestion $[T_{oral}]$			1	2
	Chemical score $[F_{chem}]$		1	1

Because the ground-water pathway was specifically chosen and because no engineered barriers existed, Steps 3 and 4, identifying pathways and scoring engineered barriers, were passed over. Step 5, identifying and scoring target populations, involved simply scoring with Table 8.11. Similarly, ground-water distance to target populations were scored with Table 8.12. Note that for site 3, the distance was 500 m, the distance while transported in the ground water, not the total distance. Scoring for these two site factors are shown in Table 9.4 (modified ground-water worksheet, Appendix A).

Scores for features of the ground-water pathway applicable to all wastes, Step 6.G1, are also shown in Table 9.4. Only the score for pathway dilution $[\delta = i_r/(i_r + Q_w + Q_r + Q_a)]$, Step 6.G1.3, needs explanation.

For all three sites, the leachate flow rate [i_r] is $A_s \cdot r_{seep}$, waste site surface area times rainfall seepage rate. (No layer at site 3 had a permeability low enough to impede rainfall infiltration.) For sites 1 and 2, the well-withdrawal rate [Q_w] was estimated as $B_u \cdot N$, the national mean usage rate per capita times town population. There was no additional dilution; thus, Q_a is zero. For site 3, Q_r, the river dilution was estimated from the $V_{riv} \cdot d_{riv} \cdot w_{riv}$, the given mean river velocity, depth, and width. However, the mean distance for complete mixing was 9×10^5 m, greater than the 1000-m river distance traversed by the waste; hence, thorough mixing and dilution had not occurred. Therefore,

$$Q_r = \left[\frac{1000\ d_{riv}}{w_{riv}^2 \cdot 15}\right]^{1/2} \cdot V_{sw} \cdot d_{riv} \cdot w_{riv} = 4.5\ m^3/day$$

Using these values, one obtains the dilution scores reported in Table 9.4.

Table 9.4 Scores unaffected by chemical type at the three sites

Site parameter	Table	Site 1	Site 2	Site 3
Population [N]	8.11	3	3	3
Distance [$1/x_{gw}^{1/2}$]	8.12	-1	-2	-1
Pore vel [$1/V_{gw}$]	8.17	0	0	0
Thickness [1/m]	8.18	-2	-2	-2
Pathwa dilution	8.19			
[$i_r/(i_r+Q_w+Q_r+Q_a)$]		-2	-2	-4
	Site subtotal	-2	-3	-4

Table 9.5 shows the calculations for Step 6.G2. When calculating the decay factor, the given dispersivity [α] (Table 9.2) was used rather than the typical SRS default value. For the saturated zone, decay incorporating dispersivity [$-(\lambda_{gw}/\alpha_x V_{gw})^{1/2} x_{gw}/2.3$] applied at all sites. For the unsaturated zone, the factor $\alpha\lambda/V$ was less than 0.25 at site 3; hence, simple exponential decay applied [$-(\lambda/V_u)\ d/2.3$].

In this example, Whelan et al. (1986) also provided data on the capability of the water treatment plant for the town effected by site 3 (Table 9.2). For strontium-90, there was almost an order of magnitude purification that is important enough to include in the SRS score; however, the overall ranking of the sites does not change (Table 9.5). The final steps for SRS, Steps 7 and 8, could be omitted for this example.

Table 9.5 Ground-water scores at sites 1, 2, and 3

Site parameter	Table	Site 1		Site 2		Site 3	
		As	^{90}Sr	As	^{90}Sr	As	^{90}Sr
Site subtotal		-2	-2	-3	-3	-4	-4
Chemical score		1	1	1	1	1	1
Engineered barrier		0	0	0	0	0	0
Mass adjustment	8.20						
$[1-\exp(-i_r t_\ell S/W_i]$		(0)	(0)	(0)	(0)	(0)	(0)
Retardation [R]	8.21	-1	0	-1	0	-2	0
Unsaturated decay $\left[-\frac{d}{2.3}\frac{\lambda_u}{V_{gw}}\right]$		0	0	0	0	0	~0
Saturated decay $\left[-\frac{x_{gw}}{2.3}\left(\frac{\lambda_{gw}}{\alpha_{gw}V_{gw}}\right)^{1/2}\right]$		0	-1	0	-7	0	-1
		-2	-2	-3	-9	-5	-4
Water treatment		0	0	0	0	0	-1
Individual chemical score		-2	-2	-3	-9	-5	-5
Ground-water site score		-5		-6		-8	

From Table 9.5, one can easily discern the influence of delayed risks on the ranking of the sites. Of the two factors accounting for delayed risks, only retardation influenced the risk because no engineered barriers existed.

If retardation was neglected, the relative ranking of these three sites would not change (albeit, the ranking of these sites with other sites could).

Comparison of SRS with RAPS. The SRS relative scores for the sites match very well with the RAPS scores. (SRS only ranks relative risks so absolute values have no meaning; further, arbitrary amounts of arsenic and strontium-90 were used.) Both methods would have scored site 1 as having the highest risk to human health, site 2 as being about 1 order of magnitude lower in risk, and site 3, 3 orders of magnitude lower in risk than site 1 when including water purification and retardation factors (although, the relative ranking is the same even without these factors) (Table 9.6). The only discrepancy between SRS and RAPS occurs at site 2 where SRS estimates an order-of-magnitude difference of 6 and RAPS an order-of-magnitude difference of 8 in risk between arsenic and strontium-90.

Table 9.6 also shows HRS and mHRS scores for the three sites. [HRS and mHRS scores vary between 0-100; a score greater than 28.5 qualifies a site for inclusion on the Superfund national priorities list (NPL).] Although applying HRS and mHRS is straightforward, for site 3 we had to assume river transport was included in the "distance-to-nearest-well" score (40CFR300) to use HRS and mHRS. This example demonstrated the inability of HRS and mHRS to distinguish between order-of-magnitude differences in health risks when contaminant migration and radioactive decay heavily influenced health risk.

Table 9.6 Relative health risks as scored by SRS, RAPS, HRS, and mHRS

Ranking scheme	Site 1		Site 2		Site 3	
	As	^{90}Sr	As	^{90}Sr	As	^{90}Sr
SRS	-5	-5	-6	-12	-8	-7(-8)[a]
RAPS	$2x10^{-4}$	$2x10^{-4}$	$2x10^{-5}$	$1x10^{-13}$	$4x10^{-7}$	$5x10^{-7}$
HRS	29.5	29.5	29.5	29.5	29.5[b]	29.5[b]
mHRS	29.5	12.5	29.5	12.5	29.5[b]	12.5[b]

[a]Water treatment

[b]Includes river travel distance in "distant-to-nearest-well" score

Table 9.7 SRS chemical score at PCB site

Property	Table	Quantity	PCB Score
Quantity [W_o]	8.1	65 kg	2
Source decay			
[1 if $6x10^{-5} \cdot t_{1/2} > 1$]	8.4	1[a]	(0)
Subtotal [W_i]		65 kg	2
Chronic toxicity	8.3		
Ingestion [T_{oral}]		4.3 $(mg/kg/day)^{-1}$	1
Inhalation [T_{air}]			N/A
Chemical score [F_{chem}]		1) oral	---
		2) air	3

[a]Assumed very long in soil
($t_{1/2}$ in air >58 days, $t_{1/2}$ in surface water 2-13 days)

Table 9.8 Air score at PCB site

Site parameter	Table	Targets			
		Farm		Mobile homes	
		Quantity	Score	Quantity	Score
Chemical score [F_{chem}]			3		3
Waste placement	8.7		2		2
Population [N]	8.11	3.8 people	1	144 people	2
Distance [$1/x^2_{air}$]	8.13	2.1 km	-7	2.6 km	-7
Mass adjustment	8.29				
[$1-\exp(-t_\ell e_v/W_i)$]		0.01	-2	0.01	-2
	Senario score		-3		-2
	Air pathway score		-2		

Hypothetical Site Affecting Air Quality

Cowherd et al. (1985) present an example to illustrate their emergency response methodology which we repeat. Here, their unnamed contaminant is assumed to be polychlorinated biphenols (PCBs).

A hypothetical site, storing abandoned transformers leaking PCB, near North Platte, Nebraska, is among several sites the state wishes to clean up. A site survey reveals about 6.4 ppm contamination to 0.15 m below the surface spread over an area of 150 by 300 m. The soil is essentially unvegetated, and consists of easily eroded finely divided material without surface crusting. No tire track or ruts were found in the area. The nearest residences are the Loner farm, 2.1 km NW of the site, and 38 mobile homes, 2.6 km NE of the site. Winds usually come out of the south.

Inhalation of soil particles impregnated with PCB is the assumed exposure scenario for this example. Table 9.7 presents the SRS chemical scores (Step 2). The 65 kg of PCB was estimated from the measured contamination (6.4 ppm) by assuming a default soil bulk density [ρ_b] of 1500 kg/m^3 (default) and a bulk soil volume of 6750 m^3 (150•300•0.15). Because only ingestion toxicity data were available for PCB, they were used for inhalation toxicity of PCB, also.

Table 9.8 shows steps 4, 5, and 6 of the SRS scoring for this Nebraska site. Although Step 3, selecting important pathways and sequences, is the next step, it was irrelevant to this example. Step 4 for the air route considers the type of waste placement of the waste. Although the site is an unspecified surface disposal, the release of 1.5×10^{-4} kg/day calculated below (Step 6.A2.2) is equivalent to ~0.32 mg/kg/day (PCB concentration in half sphere above contaminated surface times daily inhalation rate [B_a], a hundred thousand times greater than the allowable daily intake (ADI) of 2.3×10^{-6} mg/kg/day [10^{-5}/UCR], assuming a cancer risk of 10^{-5}. Consequently, the monitored soil concentration (6.4 ppm) suggests a significant health hazard at the site and results in a score of 2 (Table 8.7, Chapter 8).

From the site description, only the number of residences was known and so the national average of 3.8 persons per residence was used to estimate the persons potentially affected (Step 5).

The SRS-estimated emission rate [e_v] (Step 6.A2.2) (needed for the mass-loading adjustment factor [g_a]) was 2.4×10^{-5} kg/day calculated from

$$e_v = 0.2 \frac{A_s}{PE^2} \kappa (1-\mu_{covr}) \qquad [7.9]$$

where

A_s = 150 m x 300 m
PE = 49 (Figure 8.9)
κ = 6.4×10^{-6} kg/kg
μ_{covr} = 0 (bare soil)

For this example, the emission rate roughly approximated the 5.8×10^{-5} kg/day emission estimated using more rigorous methods of Cowherd et al. (1985). The resulting mass-loading adjustment factor was 0.01 [$g_a = 1 - \exp(-t_\ell e_w/W_i) \simeq t_\ell e_w/W_i$ if $W_i/t_\ell > e_w$] which, in turn, results in a score of -2 (Table 8.29).

In the example, Cowherd et al. (1985) only predicted the contaminant concentration at the Loner farm and mobile home park; therefore, we compare concentrations (Table 9.9). Although the transport calculations of Cowherd et al. accounted for more realistic atmospheric conditions, SRS was able to estimate the concentration within an order of magnitude (Table 9.9). For example, SRS estimated a air concentration of 10^{-15} kg/m^3 (4.5×10^{-16} using actual values instead of rounded-off logarithms) at the Loner farm while Cowherd et al. estimated 1.25×10^{-16} kg/m^3. Although the SRS concentration (10^{-15}) can be found by neglecting toxicity, waste placement, and population scores; adding in the score accounting for the constants [F_Γ]; and subtracting out the logarithms of the inhalation rate [B_a] and the time frame [t_ℓ], one understands the calculation better by using equation 7.11 in Chapter 7.

Table 9.9 Comparision of SRS with rapid assessment technique for air pathway

Calculation method	Concentration (kg/m^3) Loner farm	Mobile homes
SRS	10^{-15}	10^{-15}
Cowherd et al.	1.2×10^{-16}	5.0×10^{-17}

Comparison of SRS with EPA rapid assessment technique

Donigian et al. (1983) present an example to illustrate their methodology for incidents threatening ground-water that we repeat here. The example points out differences that can occur because of approximations in SRS.

The example was a recently discovered continuous leak in a surface tank storing industrial solvent that was 100 m [x_{gw}] upgradient of a local stream feeding a water-supply reservoir. No further description of the hypothetical site was given, rather, site charactersitics were merely listed (Table 9.10). To perform a SRS scoring we assumed, in addition to the given data, that 25,000 people [N] were at risk and that the industrial solvent was similar in toxicity [T] to carbon tetrachloride (CCl_4).

Table 9.10 Data for CCl_4 site (Donigian et al., 1983)

Parameter	Value
Waste concentration [C_o]	1.5 kg/m^3
Potentially exposed population [N]	25,000
Diameter of storage tank	20 m
Unsaturated zone characteristics	
Infiltration rate [r_{seep}]	8.22×10^{-4} m/day
Depth [d]	2.5 m
Effective porosity [ϕ]	0.15
Dispersivity [$\alpha = 0.1d$]	0.25 m
Aquifer characteristics	
Ground-water distance [x_{gw}]	100 m
Effective thickness [m]	6 m
Effective porosity [ϕ]	0.26
Bulk density [ρ_b]	1500 kg/m^3
Hydraulic conductivity [K_{gw}]	0.864 m/day
Hydraulic gradient [η]	0.001 m/m
Longitudinal dispersivity [α]	2.6 m
Waste characteristics	
Toxicity [T_{oral}]	~0.13 $(mg/kg/day)^{-1}$
Soil decay rate [λ_u]	0.004 day^{-1}
Ground-water decay [$\lambda_{gw} = 0.1\lambda_u$]	0.0004 day^{-1}
Partition coefficient [K_d]	7×10^{-4} m^3/kg

Step 2 of SRS consists of scoring the waste (data were collected in Step 1). The given concentration of waste must be converted to an equivalent mass over 70 yr for the SRS scoring (specifically, concentration x yearly leak rate x 70 yr). Because the leak rate was not given it was assumed equal to the infiltration rate of the soil x area occupied by the storage tank. Consequently, approximately 9900 kg of solvent would be released over 70 yr. The scores for the quantity and assumed toxicity are given in Table 9.11. For this example, both the logarithmic scores and multiple factors are recorded to show round-off errors.

Table 9.11 SRS chemical score at CCl_4 site

Property	Table	Factor		Score
Quantity [W_o]	8.1	9900	kg	4
Source decay	8.4			
[$6x10^{-5} \cdot t_{1/2}$]	8.5	1		0
subtotal [W_i]		9900	kg	4
Chronic toxicity	8.3			
Ingestion [T_{oral}]		0.13	$(mg/kg/day)^{-1}$	-1
Chemical score [F_{chem}]		1290	cancer risk	3

Because the release pathway is given and because no engineered barriers existed, Steps 3 and 4 in SRS were irrelevant. Table 9.12 records logarithmic scores and multiple factors for site characteristics scored in Steps 5 and 6.G1. All scores are straightforward except possibly those for dilution [δ]. For δ, the leachate rate [i_r] is infiltration rate x area of storage tank from table 9.10. The river flow rate was assumed sufficient to supply the water needs of 25,000 people, in other words, population [N] x average consumption rate [B_u = 0.76 m^3/day/person]. Both Q_a and Q_w were zero. The resulting dilution was $1.4x10^{-5}$ (Table 9.12).

Table 9.12 Scores unaffected by chemical type at CCl_4 site

Site parameter	Table	Quantity		Factor	Score
Population [N]	8.11	25,000	people	25,000	4
Distance [$1/x_{gw}^{1/2}$]	8.12	100	m	0.1	-1
Pore vel [$1/V_{gw}$]	8.17	0.0332	m/day	30.1	2
Thickness [1/m]	8.18	6	m	0.167	-1
Pathway dilution	8.19				
[$i_r/(i_r+Q_w+Q_r+Q_a)$]		1.4×10^{-5}		1.4×10^{-5}	-5
		Site subtotal		0.176	-1

Step 6.G2 scores parameters specific to the waste. Again, with the given waste parameters, the scoring is straightforward (Table 9.13). In both the unsaturated and saturated zones, the factor $\alpha\lambda/V$ was less than 0.25, where α is dispersivity, λ is decay rate, and V is pore-water velocity, indicating that slug flow with simple decay approximated the waste transport. Because of round-off, the individual chemical score obtained by summing the logarithmic tabular values differs by an order of magnitude from the score obtained by multipling factors together in Table 9.13.

We compared the results with those reported by Donigian et al. (1983), using their rapid assessment technique. Their results are reported as concentration at the unsaturated-zone-aquifer interface and at the aquifer-river interface; hence, SRS results must be expressed as concentration. In the expression for exposure [$E = W_o\ f_{site}\ f_{eng}$], both reduction factors, f_{site} and f_{eng}, are dimensionless; thus, if W_o is replaced with initial concentration [C_o], the result is in units of concentration.

For direct comparison, the toxicity score and factors accounting for delayed risks must also be neglected (retardation and engineered barrier). The concentration at the unsaturated-zone-aquifer interface [C_a] <equation [5.8], Chapter 6, Derivation of Scoring Model> is then 0.24 kg/m^3 ($C_o \cdot d\lambda_u/V_u$ = 1.5 $kg/m^3 \cdot$ 0.16) (Table 9.14).

Table 9.13 Ground-water scores at CC_4 site

Site parameter	Table	Quantity	Factor	Score
Site subtotal			0.176	-1
Chemical score			1290	3
Engineered barrier		{none}	{1}	{0}
Mass adjustment	8.20			
$[1-\exp(-i_r t_\ell S/W_i]$		soluble	{1}	{0}
Retardation [R]	8.21	R_u=1.7; R_{gw}=1.06	1	0
Unsaturated decay $\left[-\frac{d}{2.3}\frac{\lambda_u}{V_u}\right]$		$\exp\left(\frac{-2.5 \cdot 0.004}{0.0055}\right)$	0.16	-1
Saturated decay $\left[-\frac{x_{gw}\ \lambda_{gw}}{2.3\ V_{gw}}\right]$		$\exp\left(\frac{-100 \cdot 0.0004}{0.0332}\right)$	0.30	-1
Individual chemical score $[F_S]$			10.9	0
Equation constants $\left[\Gamma_{gw} = \frac{B_w}{\phi\ \sqrt{\pi\alpha_{gw}}}\right]$			0.0027	-3
Ground-water site score $[F_{gw}]$			0.029 (0.011)[a]	-3

[a]Assuming one-dimensional ground-water transport <Chapter 6>

A minor complication results for the aquifer-river interface. For this calculation, constants $[\Gamma_{gw}]$ of the aquifer transport equation [5.9] must be included. Further, because Γ_{gw} also includes the daily consumption rate $[B_w]$ (see Table 9.13), it must be divided out. Making this adjustment, the concentration at the aquifer-river interface $[C_p]$ is 0.054 kg/m^3 (Table 9.14):

$$C_p = C_o \cdot \frac{\Gamma_{gw}}{B_w} \cdot \frac{1}{x^{1/2}} \cdot \frac{1}{V_{gw}} \cdot \frac{1}{m} \cdot \exp\left(\frac{d^\lambda u}{V_u}\right) \cdot \exp\left(\frac{d^\lambda gw}{V_{gw}}\right)$$

The discrepancy between 0.054 and 0.029 kg/m^3 (Table 9.14) is mostly explained by noting that SRS uses a two-dimensional model and Donigian et al. (1983) a one-dimensional model for transport. Because the factor, $\alpha\lambda/V$, was

less than 0.25, the one-dimensional model was more appropriate for this example. (In the example by Whelan et al. (1986), a two-dimensional model was more appropriate.)

The one-dimensional model was obtained by setting the equation constant $[\Gamma_{gw,1-D}]$ to $r_{perc} \cdot w_{plume} / \phi_{gw}$ where r_{perc} is the percolation rate, w_{plume} is the width of the plume, and ϕ_{gw} is the effective aquifer porosity (r_{seep}, 20 m, and 0.26, respectively, for this example) and omitting the ground-water distance factor $[1/x_{gw}^{1/2}]$ <Chapter 6, Derivation of Scoring Model>. This modification results in a value of 0.023 kg/m^3, in close agreement with the Donigian et al. (1983) approximation of 0.029 kg/m^3. The SRS approximation for the exponential term accounts for the remaining error. Note that the coarse logarithmic score with intermediate roundoff came reasonably close to matching these values.

We recommend using the logarithmic scores even with the intermediate roundoff because it automatically restricts the sensitivity of the ranking system to order-of-magnitude effects. Uncertainty in data collected for screening the site can easily overwhelm the decrepancy between the logarithmic score and multiple factors (or even the factor-of-two decrepancy between the one-dimensional and two-dimensional models above). For example, Donigian et al. (1983) assumed that the contaminant decay rate in the soil was ten times greater than in the ground water. If the decay rates were instead the same, the results would change by an order of magnitude. However, as demonstrated, the analyst is by no means restricted to using logaritmic scores. He can easily use the numerical values of each factor.

Table 9.14 Comparison of SRS with rapid assessment technique for ground-water pathway

Calculation method	Concentration (kg/m^3) Aquifer	River
SRS score	10^{-1}	10^{-2}
SRS calculation	0.24	0.054 (0.023)[a]
Donigian et al.	0.30	0.029

[a]Concentration using one-dimensional model

10. **APPENDIX A**

SRS Worksheets

Appendix A presents sample worksheets useful for organizing and recording data for the site ranking system (SRS). They can help both in performing the scoring and in documenting the reasons for the assigned score should an audit or reevaluation be necessary.

SITE RANKING SYSTEM

Site Name _____

Site Location _____

Company and _____

Person in Charge _____

_____

Analyst _____ Date _____

Page 1 of _____

S C O R E _____ **S I T E R A N K** _____

General description of wastes _____

_____

_____

_____

General description of site _____

_____

_____

_____

Comments on score and site rank _____

_____

_____

_____

SITE RANKING SYSTEM

Worksheet for Screening Chemicals

Site Name_____ Analyst_____ Date_____

Page_____

Chemical	Quantity[a] kg or Ci	Toxicity[b] (mg or μCi/kg/d)$^{-1}$	Product[c]	Rank[d]	Ref

Comments and Assumptions _____

[a] $W_o \simeq C_o \cdot$ Volume + $\kappa_o \cdot \rho_b \cdot$ Volume; if C_o unknown, then let C_o = S

[b] UCR(mg/kg/d)$^{-1}$ or 10^{-5}/ADI(mg/kg/d)

[c] Product of quantity [W_o] and toxicity [T]

[d] Order according to largest product

SITE RANKING SYSTEM

Worksheet for Scoring Waste Chemicals

Site Name_____ Analyst_____ Date_____

Page_____

Chemical_____ C H E M I C A L R A N K[a] _____

Property	Table	Quantity (best est)	Factor[b]	Best score	Variance[c] or worst score	Ref
Quantity (kg or Ci) [W_o]	8.1					
Source decay						
[1 if $6x10^{-5} \cdot t_{1/2} > 1$]	8.4					
Half-life (day) [$t_{1/2}$]			_____			
$\left[W_i = W_o \cdot 6x10^{-5} t_{1/2}\right]$						
Chronic toxicity (mg or μCi/kg/d)						
Ingestion [T_{oral}]	8.3					
Inhalation [T_{air}]	8.3			_____	_____	
Chemical score [F_{chem}][d]		1) oral 2) air				

Comments _____

and _____

Assumptions _____

[a]Ranking based on chemical score

[b]Bracketed expression shown with parameter

[c]Variance = $S(X_i)^2$; $S(X_i)$ = standard deviation

[d]Chemical score [F_{chem}] = $F_{mass} + F_{decay} + F_{tox}$

SITE RANKING SYSTEM

Supplemental Worksheet for Recording Waste Quantity Data

Site Name_____ Analyst_____ Date_____

Page_____

Contaminant	Concentration					Conversion	Volume	Quantity	Ref
	Hi	Mean	Low	Back-ground	No. samples				

SITE RANKING SYSTEM

Worksheet for Describing Pathways

Site Name_____ Analyst_____ Date_____

Page_____

Scenario identifier_____

Release from site by: ground water surface water air (circle one)

General description
of scenario
(diagram or words)

Target: sensitive-environment humans (circle one)

Probability of release: observed very high high medium low (circle one)

Source/release mechanism[a]

Exposure point and method[b]

Comments _____
and _____
Assumptions _____

---

[a]e.g., leaching from contaminated soil

[b]e.g., ingestion of drinking water; wells 2 miles--serving rural neighborhood

SITE RANKING SYSTEM

Worksheet for Scoring Waste Placement and Engineered Barriers

Site Name_____ Analyst_____ Date_____

Page_____

Property	Table	Description	Best score	Variance or worst score	Ref
Ground-water route containment					
Waste placement	8.7				
Leachate reduction	8.8				
Leachate collection	8.9				
		Total [F_{bar}]	_____	_____	
Surface-water route containment					
Waste placement	8.7				
Leachate collection	8.9				
Surface drainage	8.10				
		Total [F_{bar}]	_____	_____	
Air route containment					
Waste placement [F_{bar}]	8.7				

SITE RANKING SYSTEM

Worksheet for Scoring General Parameters of Ground-Water Pathway

Site Name_____ Analyst_____ Date_____

Scenario_____ Page_____

Site parameter	Table	Quantity (best est)	Factor[a]	Best score	Variance or worst score	Ref
Population [N]	8.11					
Distance (m) [$1/x_{gw}^{1/2}$]	8.12					
Engineered barrier [F_{bar}]						
Pore vel (m/d) [$1/V_{gw}$]	8.17					
Thickness (m) [1/m]	8.18					
Pathway dilution	8.19					
[$i_r/(i_r+Q_w+Q_r+Q_a)$] where:						
i_r= leachate rate (m^3/d)						
Q_w= well withdrawal (m^3/d)						
Q_r= river discharge[b] (m^3/d)						
Q_a= added dilution (m^3/d)						
				_____	_____	

Site subtotal[c]

Check travel time (x_{gw}/V_{gw})_____

Comments _____

and _____

Assumptions _____

[a]Bracketed expression shown with parameter

[b]If $x_{riv} < \ell_m$, then Q_r= discharge • $\left(\frac{x_{riv}}{\ell_m}\right)^{1/2}$ = ; otherwise Q_r = discharge;

where $\ell_m = 15 \frac{w_{riv}^2}{d_{riv}}$ = w_{riv}= river width = d_{riv}= river depth =

[c]Subtotal [F_{sub}] = $F_{pop} + F_{dist} + F_{vel} + F_{thick} + F_{dilution}$

SITE RANKING SYSTEM

Supplemental Worksheet for Scoring Population for Ground-Water Pathway

Site Name_____ Analyst_____ Date_____

Scenario_____ Page_____

Distance (m) [x]	Population [N]	Population score	Distance score [$1/x^{1/2}$]	Sum	Ref
< 10			0		
10- 999			-1		
1,000-100,000			-2		

Population and distance sum (largest sum[a]) _____

Comments and Assumptions _____

[a]If 3 or more sums are the same, increase the sum by one unit

SITE RANKING SYSTEM

Supplemental Worksheet for Estimating Flow Rates in Ground-Water

Site Name_____ Analyst_____ Date_____

Scenario_____ Page_____

Strata description and/or name	Thickness [L] (m)	Hydraulic conductivity [K][a] (m/d)	Porosity [ϕ]	Hydraulic head [η] (m)	Pore-water velocity[b] [V] (m/d)	Ref

Potential rainfall infiltration (m/d) [$\mu_r r_a$]:

Percolation rate (m/d) [landfill: r_{perc} = minimum {$\mu_r r_a$, K_{cover}, K_{unsat}}]:
[lagoon: r_{perc} = average {$\mu_r r_a$, K_{unsat}}]:

Unsaturated velocity (m/d) [$V_{unsat} = r_{perc} / \phi_{unsat}$]:

Waste site surface area (m^2) [A_s]:

Leachate flow rate (m^3/d) [$i_r = r_{perc} \cdot A_s$]:

[a] $K_{ave} = (\Sigma L_i K_i)/\Sigma L_i$
[b] $V = \eta K/\phi$

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Ground-Water Pathway

Site Name_____ Analyst_____ Date_____

Scenario_____ Chemical_____ Page_____

Site parameter (chemical dependence)	Table	Quantity	Factor	Best score	Variance or Ref worst score
Site subtotal [F_{sub}]					
Chemical score [F_{chem}]					
Mass adjustment	8.20				
[1-exp($-i_r t_\ell S/W_i$] where:					
i_r= leachate rate (m^3/d)					
t_ℓ= time frame [2.6×10^4 d]					
S = solubility (kg or Ci/m^3)					
W_i= quantity (kg or Ci)					
Retardation [R] (or K_d)	8.21				
Unsaturated decay[a]					
$t_{1/2}$= half-life (d)					
V_{unsat}= unsat velocity (m/d)					
d = aquifer depth (m)					
α = dispersivity (m) {20 m if < 0.1d}					
Saturated decay[a]					
$t_{1/2}$= half-life (d)					
V_{gw} = gw velocity (m/d)					
x_{gw} = gw distance (m)					
α = dispersivity (m) {20m if < $0.1x_{gw}$}					
Individual chemical score[b]				_____	_____

Comments _____

and _____

Assumptions _____

[a]Decay score is the following value rounded to nearest integer:

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3\ x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

Score = $F_{sub} + F_{chem} + F_{adj} + F_{rtrd} - F_{unsat\ decay} - F_{sat\ decay}$

SITE RANKING SYSTEM

Worksheet for Scoring General Parameters of Surface-Water Pathway

Site Name_____ Analyst_____ Date_____

Scenario_____ Page_____

Site parameter	Table	Quantity	Factor	Best score	Variance or Ref worst score
Engineered barrier					
Population [N]					
Runoff [1/q]	8.24				
q = runoff (m^3/d) [$A_s \cdot r_{net}$]					
A_s = area (m^2)					
r_a = annual rainfall (m/d)					
CN = curve number					
r_{net} = runoff rainfall (m/d)					
Dilution [$q/(q + Q_a + Q_r)$]	8.25				
Q_a = added dilution (m^3/d)					
Q_r = river discharge[b] (m^3/d)					
				_____	_____
Site subtotal[c]					

Comments _____

and _____

Assumptions _____

[a] $r_{net} = \left(\frac{r_a - 0.2S_w}{r_a + 0.8S_w}\right)^2 =$ $S_w = 7\times10^{-5}\left(\frac{1000}{CN} - 10\right) =$

[b] If $x_{riv} < \ell_m$, then Q_r = discharge $\cdot \left(\frac{x_{riv}}{\ell_m}\right)^{1/2} =$; otherwise Q_r = discharge;

where $\ell_m = 15\,\frac{w_{riv}^2}{d_{riv}} =$ w_{riv} = river width = d_{riv} = river depth =

[c] Subtotal [F_{sub}] = $F_{pop} + F_{barrier} + F_{runoff} + F_{dilution}$

SITE RANKING SYSTEM

Worksheet of Waste-Specific Parameters of Surface-Water Pathway

Site Name_____ Analyst_____ Date_____

Scenario_____ **Nonadsorbed**[a] Chemical_____ Page_____

Site Parameter (chemical dependent)	Table	Quantity	Factor	Best score	Variance or Ref worst score
Site subtotal [F_{sub}]					
Chemical score [F_{chem}]					
Runoff dissolution [r_{net}/r_a]	8.28				
Mass adjustment [$1-\exp(-qt_\ell S/W_i)$] where:	8.27				
q = runoff (m^3/d)					
t_ℓ = time frame (2.6×10^4 d)					
S = solubility (kg or Ci/m^3)					
W_i = quantity (kg or Ci)					
Decay factor[b]					
$t_{1/2}$ = half-life (d)					
V_{riv} = river velocity (m^3/d)					
x_{riv} = river distance (m)					
α = dispersivity (1 m)					
Individual chemical score[c]				_____	_____

Comments and Assumptions _____

[a]Retardation [R] small ($R < 100$, or $K_d < 0.02\ m^3/kg$)

[b]Decay score is the following value rounded to nearest integer:

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

[c]Score = $F_{sub} + F_{chem} + F_{dissolution} + F_{adj} + F_{decay}$

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Surface-Water Pathway

Site Name_____ Analyst_____ Date_____

Scenario_____ **Adsorbed**[a] Chemical_____ Page_____

Site parameter (chemical dependent)	Table	Quantity	Factor	Best score	Variance or worst score	Ref
Site subtotal [F_{sub}]						
Chemical score [F_{chem}]						
Sediment yield [$3.5 \times 10^{-3} \cdot CP \cdot LS \cdot R_E$] where:	8.31					
CP = control practice						
LS = length-slope factor						
R_E = rainfall-erosivity						
Decay factor[b]						
$t_{1/2}$ = half-life (d)						
V_{riv} = river velocity (m^3/d)						
x_{riv} = river distance (m)						
α = dispersivity (1 m)						
				_____	_____	
Individual chemical score[c]						

Comments _____

and _____

Assumptions _____

[a]Retardation [R] large (R > 100, or $K_d > 0.02\ m^3/kg$)

[b]Decay score is the following value rounded to nearest integer

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3\ x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

[c]Score = $F_{sub} + F_{chem} + F_{sed\ yield} + F_{decay}$

SITE RANKING SYSTEM

Worksheet for Scoring Population and Distance for Air Pathway

Site Name_____ Analyst_____ Date_____

Scenario_____ Page_____

Distance (m) [x]	Population [N]	Population score	Distance score [$1/x^2$]	Sum	Ref
0- 17			0		
17- 55			-2		
56- 175			-4		
176- 550			-5		
551- 1750			-6		
1751- 5500			-7		
5501-17500			-8		
			Largest sum[a]	_____	
		Waste placement score		_____	
			Site subtotal[b]		

Comments and Assumptions _____

_____

_____

[a]If 3 or more sums are the same, increase the sum by one unit

[b]Add largest sum and waste placement score

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Air Pathway

Site Name_____ Analyst_____ Date_____

Scenario_____ Chemical_____ Page_____

Site parameter	Quantity	Factor	Best score	Variance or Ref worst score
Site subtotal [F_{sub}]				
Chemical score [F_{chem}]				
Mass adjustment				
$[1-\exp(-(e_v+e_w)t_\ell/W_i)]$ where:				
t_ℓ = time frame (2.6×10^4 d)				
W_i = quantity (kg or Ci)				
$e_v = 0.2\ A_s \kappa\ w_m^{1/2} p\ f_{covr} f_{gen}$				
A_s = surface area (m^2)				
$\kappa = \frac{W_i}{\rho_b d_{cont} A_s}$ (conc., kg/kg)				
w_m = gram weight (g/mole)				
p = partial pressure (mm Hg)				
$f_{covr} = \phi^{4/3}/(350\ s)$ where $s>0.1m$				
f_{gen} = 10 if gas generation				
$e_w = 0.2\ \frac{A_s}{PE^2}\ \kappa\ (1-\mu_{covr})$				
PE = Thornthwaite index				
μ_{covr} = vegetative cover				
Individual chemical score[a]			_____	_____

Comments _____

and _____

Assumptions _____

[a]Score = $F_{sub} + F_{chem} + F_{adj}$

SITE RANKING SYSTEM

Worksheet for Scoring Air Pathway

Site Name_____ Analyst_____ Date_____

Scenario_____ Page_____

Site parameter	Table	Quantity	Factor[a]	Best score	Variance or worst score	Ref
Population [N]	8.11					
Waste placement	8.7					
Distance [$1/x^2_{air}$]	8.13			_____	_____	
Site subtotal[b]						

Chemical_____

Site parameter	Table	Quantity	Factor	Best score	Variance or worst score	Ref
Site subtotal [F_{sub}]						
Chemical score [F_{chem}]						
Mass adjustment						
[$1-\exp(-t_\ell \Sigma e_j/W_i)$] where:						
t_ℓ = time frame {2.6×10^4 d}						
Σe_j = volatile [e_v] + dust[c] [e_w]						
W_i = quantity (kg or Ci)				_____	_____	
Individual chemical score[d]						

Comments _____

and _____

Assumptions _____

[a]Bracketed expression shown with parameter

[b]Subtotal [F_{sub}] = $F_{pop} + F_{place} + F_{dist}$

[c]Adsorbed chemicals, stack emissions, or resuspension of stack emissions

[d]Score = $F_{sub} + F_{chem} + F_{adj}$

SITE RANKING SYSTEM

Summary Worksheet

Site Name_____ Analyst_____ Date_____

Page_____

Pathway	Scenario	Chemical	Scenario score <eq 8.3>	Variance or worst score	Pathway[a] score <eq 8.4>
Ground water	1.	a.			
		b.			
		c.			
		d.			
		e.			
	2.	a.			
		b.			
		c.			
	3.	a.			
		b.			
		c.			
Surface	1.	a.			
		b.			
		c.			
		d.			
		e.			
	2.	a.			
		b.			
		c.			
Air route	1.	a.			
		b.			
		c.			
		d.			

S I T E S C O R E[b]

[a]Pathway score = $F_a + 0.1(n_a) + 0.01(n_b)$ <equation 8.4>

where F_a = highest scenario score

n_a = no. of scenarios with score A

n_b = no. of scenarios with score $F_b = F_a - 1$

[b]Largest pathway score unless 2 same, then increase 1 unit

SITE RANKING SYSTEM

References

Site Name_____ Analyst_____ Date_____

Page_____

Reference ID	Reference

11. Appendix B

SRS Applied to a Superfund Site

The purpose of Appendix B is to show the process necessary to score the site, specifically,

- how to complete the worksheets,
- how they document the ranking for quality assurance (QA),
- ways to estimate waste quantities,
- how to select chemicals for final scoring, and
- how information from the worksheets helps direct further investigations at a site.

Appendix B accomplishes these goals by applying SRS to an actual Superfund site as it existed in June 1982. However, to reinforce the fact that this is primarily a demonstration, names of places and physical features have been omitted.

Step 1. Collect Data on Waste Properties, Site Features, and Facility Design

The publicly available sources for data at this site are listed on the reference worksheet. Although the chemical data are more extensive than for many sites, the example demonstrates the chemical screening process.

Step 2. Score and Rank Chemicals Found at Site

Samples from monitoring wells indicated 32 chemicals present--enough chemicals to require screening. Thus, we first preliminarily ranked the chemicals based on quantity and toxicity, Step 2.2.

Although many chemicals did not have toxicity values evaluated by EPA some estimates were available (Appendix C, Table C.7). These were entered on the worksheet for screening chemicals. The estimates for waste quantity came from estimates of contaminated soil volume and concentration and contaminated aquifer volume and concentration. The calculations are shown on the supplemental sheet for recording waste quantity data. These results were entered on the worksheet for screening chemicals. At this point, we preliminarily ranked the chemicals. About 14 chemicals appeared important.

The next step, Step 2.3, was to make a final ranking folding in potential decay of the waste at the source. Precise ground-water decay rates available were not available. We used 100 x surface-water decay rates as an estimate of ground-water decay rates. The primary reason for not including decay in the initial chemical ranking is to flag the influence of decay--a highly important variable when decays rates for the wastes are poorly known.

After estimating decay, the chemicals were again ranked. About 8 or 9 chemicals appeared important at this point. Only chemical data sheets for 5 chemicals (which later proved important) are shown, but their chemical ranking among the initial 8 or 9 chemicals is indicated.

Because the calculations are easier and adequately flag highly uncertain variables, a worse-case or pessimistic value is used as a measure of uncertainty rather than summing variances $[\Sigma_i\{S(X_i)^2\}]$ for this example. However, the pessimistic value is not used as another site score; the probability of obtaining this extreme value is too low.

Step 3. Describe Release Pathways

Three ground-water scenarios appeared possible. The most likely scenario, identified as G-A-R, involved seepage from lagoons and solid waste dumps on the site, tranport through the alluvial aquifer, release into the river, and consumption by a few residences downstream. The second and third scenarios (G-A-W and G-M-W) involved seepage of waste into the alluvial and Morrison geologic units, respectively, and transport to drinking water wells used by numerous residences on both sides of the river. These later two scenarios are less likely but the consequences much more severe; hence, the risk requires evaluating.

The surface-water pathway had one scenario--transport of waste by runoff into the river and subsequent consumption by people downstream. The air pathway also had one scenario--vaporization of organic volatiles, transport to nearby residences, and inhalation by the occupants.

Step 4. Evaluate Engineered Barriers at Site

Wastes were disposed of in local depressions on site until 1958 when four unlined ponds were dug in the center of the site. No engineered features existed at the site prior to 1983. For the site score, we treated the area as a lagoon disposal site. For the pessimistic score, we treated the area as a haphazard disposal site.

Step 5. Identify Target Populations for Selected Pathways

The population consuming surface water is about 4 people. However, the population drinking or inhaling potentially contaminated ground-water or air, respectively, varies with the distance from the site. The supplemental worksheets for scoring population and distance for the ground-water and air pathways select the highest combined population and distance score possible at the site.

Step 6. Score Site Features

Step 6 scores site features based on the manner waste is released from the site. For this step, the best approach is to completely score one scenario, and then all scenarios in a pathway before moving on to a scenario in another pathway. With this approach you identify chemicals that predominately control the site score from those ranked high in Step 2.

We first scored the most likely scenario in the ground-water pathway, seepage into the river (G-A-R). The first substep, Step 6.G1, scores site features applicable to all wastes. The second substep, Step 6.G2, scores site features that vary with each waste. We began this step using the highest ranked chemical and proceding down the list. Of the 8 or 9 highly ranked chemicals, only 5 remained important, and of these 5 only 3, arsenic, napthalene, and pentachlorophenol (PCP), determined the site score as seen on the summary worksheet. Only the worksheets for the five highly ranked chemicals (anthracene, arsenic, PCP, phenanthrene, and napthalene) are presented here.

Next, we scored the scenario involving well-water consumption from the alluvial aquifer. Only the worksheet for PCP is shown, but the results for

the 5 dominant chemicals are shown on the summary worksheet. As seen on the summary worksheet, this scenario determines the site score.

Next, we scored the scenario involving well-water consumption from the Morrison aquifer. Only the worksheet for PCP is shown. This completed the ground-water pathway.

The surface-water and air pathways only have one scenario each. Completed work sheets for several of the waste chemicals are shown and summarized on the summary worksheet.

Step 7. Combine Chemical Scores and Pathway Scores to Obtain Site Score

The first part of this step is to combine the chemicals scores of each scenario. For this site, the well-water comsumption scenario (G-A-W) has three chemicals each with a score of 3. This situation results in a scenario score of 4 according to equation [8.3] as shown on the summary worksheet. This score of 4 is larger than any other scenario score in the ground-water pathway and, thus, becomes the ground-water pathway score.

The second part of the this step is to combine pathway scores. No other pathway has a score equal to or larger than 4; thus, the site score is 4.

Step 8. Rank the Site in Relation to Other Scored Sites

Ranking the sites based on their score is straightforward. Because only one site was scored, this example stops here. However, we discuss anticipated distribution of scores and how the scores can be used in future investigations.

Distribution of scores. The SRS scoring would divide the hazardous sites into numerous major groups, but each group would not necessarily have equal numbers of sites as the NPL (40CFR300); rather, they would have a distribution. This type of grouping still allows a risk manager to allocate cleanup resources and yet more realistically represents the distribution of health risks that waste sites pose. If a risk manager needed to more finely divide the major groupings (scores), additional criteria such as listed in Step 8 of the instructions can be used.

The distribution of scores depends heavily on the type of sites being scored. SRS has not been extensively tested and so we cannot state the range or distribution of scores. However, based on a preliminary ranking of five EPA Superfund sites, we surmise CERCLA-type sites would typically score between -10 and +10, with +15 and -20 encompassing almost all sites. The most probable value would probably lie between +2 and +5.

Further investigations. The results from SRS can be used in two ways:

1. During the site screening, early use of SRS with readily available data can identity important pathways and/or variables. A risk manager can use this information to direct data collection efforts that are still within the scope of site screening yet more costly and/or difficult to obtain (for example, drilling monitoring wells, throughly searching government records on well completions, or requesting information from potentially liable parties).

2. Final results can be used in designing RI/FS studies. Although more detailed data will be collected on all variables and pathways, less resources can be directed toward low risk pathways or unimportant variables at the site.

We can demonstrate these concepts with the example site. First, a minor data refinement might occur during screening: Because well use near the site was only sketchy, a portion of any remaining resources could be used to identify well use. Second, a more detailed risk assessment may wish to collect data on transport under the river to the numerous wells and collect data on air quality to more carefully assess the hazards from these less likely but more severe consequence scenarios. Third, although air stripping, a common cleanup technique, could successfully remove several organic volatiles at the site, the large air-pathway hazard identified by SRS could help direct RI/FS studies toward alternate cleanup techniques.

SITE RANKING SYSTEM

Site Name Example

Site Location

Company and

Person in Charge

Analyst R. P. Rechard Date 5-4-87

Page 1 of 62

S C O R E 4 S I T E R A N K

General description of wastes

Wastes from railroad tie treatment - primarily
a) zinc chloride (1886-1931)
b) creosote and asphalt-based petroleum/residuum oil mixture (1928-1983)
c) pentachlorophenol (PCP) (1956-1983)

General description of site

~700 acre site bordered on east by railroad, north by interstate, and west by river. Plant ½ mile from residences and 1½ miles from downtown of city. Relatively flat surface drains to river. In 1983 raised river levee to remove site from 100 yr flood plain

Comments on score and site rank

Site scored based on PCP, arsenic, napthalene contaminating wells completed in alluvial aquifer. Use of the Morrison aquifer would lower score to 3. On the other hand, anthracene exists under the site in extremely high concentration (higher than its water solubility). Site score jumps to 8 if anthracene mobile (score disregarding solubility of anthracene)

SITE RANKING SYSTEM

Worksheet for Screening Chemicals

Site Name Example Analyst R PR Date 5-4-87

Page 2

Chemical	Quantity[a] kg or Ci	Toxicity[b] (mg or μCi/kg/d)$^{-1}$	Product[c]	Rank[d]	Ref
Creosote	-	?			A-1
Zinc chloride	-	?			A-1
Pentachlorophenal (PCP) (teratogenic)	4.5×10^5	1.3* 300 mg/kg/d	5.8×10^5 1.2×10^2	5	A-1,F
Copper Arsenate	-	?			A-1
Acenaphthene	6.5×10^5	15*	9.9×10^6	2	A-1,F
Acenaphthylene	-	?			A-1
Anthracene	8.0×10^5	11.5*	9.2×10^5	3	A-1,F
Benzo(a)anthracene	3.9×10^4	11.5*	4.5×10^5	6	A-1,F

Comments and Assumptions: * Table C.7

[a] $W_o = C_o \cdot$ Volume + $\kappa_o \cdot \rho_b \cdot$ Volume; if C_o unknown, then let $C_o = S$

[b] UCR(mg/kg/d)$^{-1}$ or 10^{-5}/ADI(mg/kg/d)

[c] Product of quantity [W_o] and toxicity [T]

[d] Order according to largest product

SITE RANKING SYSTEM

Worksheet for Screening Chemicals

Site Name Example Analyst RPR Date 5-4-87

Page 3

Chemical	Quantity[a] kg or Ci	Toxicity[b] (mg or μCi/kg/d)$^{-1}$	Product[c]	Rank[d]	Ref
Benzo(a)pyrene	2.7×10^4	11.5	3.1×10^5	7	A-1, App C
Chrysene	7.2×10^4	2.5*	1.0×10^5	9	A-1, F
Fluoranthene	8.4×10^5	0.7*	5.9×10^5	4	A-1, F
Fluorene	-	?			A-1
Naphthalene	2.5×10^6	0.07*	1.7×10^5	8	A-1, F
Phenanthrene	2.5×10^6	6.3*	1.6×10^7	1	A-1, F
Pyrene	6.9×10^5	0.11*	7.6×10^4	10	A-1, F
Phenol	1.5×10^4	w 0.1 mg/kg/d a 0.02 mg/kg/d	1.5	14	A-1, App C

Comments and Assumptions: * Table C.7

[a] $W_o \simeq C_o \cdot$ Volume + $\kappa_o \cdot \rho_b \cdot$ Volume; if C_o unknown, then let C_o = S

[b] UCR(mg/kg/d)$^{-1}$ or 10^{-5}/ADI(mg/kg/d)

[c] Product of quantity [W_o] and toxicity [T]

[d] Order according to largest product

SITE RANKING SYSTEM

Worksheet for Screening Chemicals

Site Name Example Analyst RPR Date 5-4-87

Page 4

Chemical	Quantity[a] kg or Ci		Toxicity[b] (mg or μCi/kg/d)$^{-1}$	Product[c]	Rank[d]	Ref
Benzene	2.7×10^{2}		0.052	1.4×10^{1}		A-1, App C
			0.057*			F
Ethylbenzene	7.4×10^{3}		0.42*	3.1×10^{3}	11	A-1,F
Toluene	5.2×10^{3}		0.047	2.4×10^{2}	12	A-1
			0.3mg/kg/d	1.7×10^{-1}		App C
Arsenic	4.7	w	15	6.9×10^{1}	13	A-1
		a	50			App C
Barium	1.3×10^{1}	w	0.05mg/kg/d	2.5×10^{3}		A-1
		a	0.0001 "			App-C
Chromium**	4.9		0.005 "	9.8×10^{-3}		A-1
Lead	1.2×10^{1}	w	0.001 "	8.7×10^{-2}		A-1
		a	0.0004 "			App C
2,4 dimethylphenol	-		?			A-1

Comments and Assumptions

* Table C.7

** assumed +4 valence

[a] $W_o \approx C_o \cdot$ Volume + $\kappa_o \cdot \rho_b \cdot$ Volume; if C_o unknown, then let C_o = S

[b] UCR(mg/kg/d)$^{-1}$ or 10^{-5}/ADI(mg/kg/d)

[c] Product of quantity [W_o] and toxicity [T]

[d] Order according to largest product

SITE RANKING SYSTEM

Supplemental Worksheet for Recording Waste Quantity Data

Site Name Example Analyst RPR Date 5-4-87

Page 6

Contaminant	Concentration Hi	Mean	Low	Back-ground	No. samples	Conversion	Volume	Quantity	Ref

Arsenic

alluvial aquifer $K_o \cdot \rho_w \cdot \text{Volume} = W_o$

$$0.018\times10^{-6}\ \frac{kg}{kg\ H_2O} \cdot 10^3\ \frac{kg}{m^3} \cdot \frac{m^3}{1.3\ yd^3} \cdot 300{,}000\ yd^3{*} \qquad = 4.2\ kg$$

alternately

$$0.018\times10^{-6}\ \frac{kg}{kg\ H_2O} \cdot 10^3\ \frac{kg}{m^3} \cdot 260{,}000\ m^3\ {**} \qquad = 4.7\ kg$$

Pentachlorophenol

alluvial aquifer

$$1.2\times10^{-3}\ \frac{kg}{kg\ H_2O} \qquad = 3.1\times10^5\ kg$$

soil $K_o \cdot \rho_b \cdot \text{Volume} = W_o$

$$320\times10^{-6}\ \frac{kg}{kg\ soil} \cdot 1300\ \frac{kg}{m^3} \cdot \frac{2.8\times10^{-2} m^3}{ft^3} \cdot 1.2\times10^7 ft^3{***} \qquad = \frac{1.4\times10^5}{4.5\times10^5}\ kg$$

Napthalene

alluvial aquifer

$$6.3\times10^{-3}\ \frac{kg}{kg\ H_2O} \qquad = 1.6\times10^6\ kg$$

soil

$$1.97\times10^{-3}\ \frac{kg}{kg\ soil} \qquad = \frac{0.9\times10^6}{2.5\times10^6 kg}$$

* alluvium nearly saturated, volume = area · depth

** ~9.4 x 10^4gal/day recharge to river; ~2 yr travel time

*** contaminated area · depth - $6.1\times10^6 ft^2 \cdot 2ft = 1.2\times10^7 ft^3$

SITE RANKING SYSTEM

Supplemental Worksheet for Recording Waste Quantity Data

Site Name Example Analyst RPR Date 5-4-87

Page 7

Contaminant	Concentration					Conversion	Volume	Quantity	Ref
	Hi	Mean	Low	Back-ground	No. samples				

Anthracene

alluvial aquifer

$2.1\times10^{-3}\ \frac{kg}{kg\ H_2O}$ $= 5.5\times10^{5}kg$

Morrison aquifer

$2.3\times10^{-6}\ \frac{kg}{kg\ H_2O}$ $= 5.3\times10^{2}kg$

soil

$570\times10^{-6}\ \frac{kg}{kg\ soil}$ $= 2.5\times10^{5}kg$

river sediment

$224\times10^{-6}\ \frac{kg}{kg\ soil} \cdot 1300kg \cdot 613m^3$ $= \frac{1.79\times10^{2}kg}{8.0\times10^{5}kg}$

estimate from river concentration $K_o \cdot \rho_w \cdot Q_r \cdot t_\ell$

$1.8\times10^{-12}\ \frac{kg}{kg\ H^2O} \cdot 10^3\ \frac{kg}{m^3} \cdot 2.57\times10^{5}\frac{m^3}{d} \cdot 2.6\times10^{4}d = 12\ kg$

Phenanthrene

alluvial aquifer

$7.85\times10^{-3}\ \frac{kg}{kg\ H_2O}$ $= 2.0\times10^{6}kg$

soil

$1.2\times10^{-3}\ \frac{kg}{kg\ soil}$ $= \frac{.52\times10^{6}kg}{2.5\times10^{6}kg}$

SITE RANKING SYSTEM

Worksheet for Scoring Waste Chemicals

Site Name Example Analyst RPR Date 5-4-87

Page 12

Chemical Phenanthrene CHEMICAL RANK[a] 4*

Property	Table	Quantity (best est)	Factor[b]	Best score	Pessimistic score	Ref
Quantity (kg or Ci) [W_o]	8.1	$2.5x10^6$	$2.5x10^6$	6	7	p7
Source decay						
[1 if $6x10^{-5} \cdot t_{1/2} > 1$]	8.4					
Half-life (day) [$t_{1/2}$]		100d **	$\frac{6x10^{-3}}{1.5x10^4}$	-2	-2	App C
$\left[W_i = W_o \cdot 6x10^{-5} t_{1/2}\right]$						
Chronic toxicity (mg or μCi/kg/d)						
Ingestion [T_{oral}]	8.3	6.3				
Inhalation [T_{air}]	8.3			1	1	F
				7-2=5	6	
Chemical score [F_{chem}][c]		1) oral 2) air				

Comments and Assumptions

* in preliminary ranking, ranked 1st

** 100 times surface water decay

[a]Ranking based on chemical score

[b]Bracketed expression shown with parameter

[c]Chemical score [F_{chem}] = $F_{mass} + F_{decay} + F_{tox}$

SITE RANKING SYSTEM

Worksheet for Scoring Waste Chemicals

Site Name Example Analyst RPR Date 5-4-87

Page 14

Chemical Anthracene CHEMICAL RANK[a] 1*

Property	Table	Quantity (best est)	Factor[b]	Best score	Pessimistic score	Ref
Quantity (kg or Ci) [W_o]	8.1	8.0×10^5		6	6	p7
Source decay						
[1 if $6 \times 10^{-5} \cdot t_{1/2} > 1$]	8.4					
Half-life (day) [$t_{1/2}$]		unknown		0	0	App C
$\left[W_i = W_o \cdot 6 \times 10^{-5} t_{1/2}\right]$			8.0×10^5			
Chronic toxicity (mg or μCi/kg/d)						
Ingestion [T_{oral}]	8.3	11.5				
Inhalation [T_{air}]	8.3			1	1	F
Chemical score [F_{chem}][c]		1) oral 2) air		7	8	

Comments and Assumptions: * neglecting decay, anthracene ranks 3rd

[a]Ranking based on chemical score

[b]Bracketed expression shown with parameter

[c]Chemical score [F_{chem}] = $F_{mass} + F_{decay} + F_{tox}$

SITE RANKING SYSTEM

Worksheet for Scoring Waste Chemicals

Site Name Example Analyst RPR Date 5-4-87

Page 16

Chemical PCP CHEMICAL RANK[a] 5

Property	Table	Quantity (best est)	Factor[b]	Best score	Pessimistic score	Ref
Quantity (kg or Ci) [W_o]	8.1	$4.5x10^5$	$4.5x10^5$	6	6	p6
Source decay						
[1 if $6x10^{-5} \cdot t_{1/2} > 1$]	8.4		3.10^{-2}	-2	-2	
Half-life (day) [$t_{1/2}$]		500d				App C
$\left[W_i = W_o \cdot 6x10^{-5} t_{1/2}\right]$			$1.4x10^4$kg			
Chronic toxicity (mg or μCi/kg/d)						
Ingestion [T_{oral}]	8.3	1.3		0	0	F
Inhalation [T_{air}]	8.3					
Chemical score [F_{chem}][c]		1) oral 2) air		4	4	

Comments and Assumptions

[a]Ranking based on chemical score

[b]Bracketed expression shown with parameter

[c]Chemical score [F_{chem}] = $F_{mass} + F_{decay} + F_{tox}$

SITE RANKING SYSTEM

Worksheet for Scoring Waste Chemicals

Site Name Example Analyst RPR Date 5-4-87

Page 19

Chemical Naphthalene CHEMICAL RANK[a] 3

Property	Table	Quantity (best est)	Factor[b]	Best score	Pessimistic score	Ref
Quantity (kg or Ci) [W_o]	8.1	2.5×10^6		6	7	p6
Source decay						
[1 if $6 \times 10^{-5} \cdot t_{1/2} > 1$]	8.4					
Half-life (day) [$t_{1/2}$]		unknown		0	0	App C
$\left[W_i = W_o \cdot 6 \times 10^{-5} t_{1/2}\right]$			2.5×10^6			
Chronic toxicity (mg or μCi/kg/d)						
Ingestion [T_{oral}]	8.3	0.07				
Inhalation [T_{air}]	8.3			-1	-1	F
Chemical score [F_{chem}][c]		1) oral 2) air		5	6	

Comments and Assumptions

[a]Ranking based on chemical score

[b]Bracketed expression shown with parameter

[c]Chemical score [F_{chem}] = $F_{mass} + F_{decay} + F_{tox}$

SITE RANKING SYSTEM

Worksheet for Scoring Waste Chemicals

Site Name Example Analyst RPR Date 5-4-87

Page 23

Chemical Arsenic CHEMICAL RANK[a] 11*

Property	Table	Quantity (best est)	Factor[b]	Best score	Pessimistic score	Ref
Quantity (kg or Ci) [W_o]	8.1	4.7		1	1	p6
Source decay						
[1 if $6x10^{-5} \cdot t_{1/2} > 1$]	8.4					
Half-life (day) [$t_{1/2}$]		metal		0	0	App C
$\left[W_i = W_o \cdot 6x10^{-5} t_{1/2}\right]$			4.7 kg			
Chronic toxicity (mg or μCi/kg/d)						
Ingestion [T_{oral}]	8.3	15				
Inhalation [T_{air}]	8.3			1	1	App C
Chemical score [F_{chem}][c]		1) oral 2) air		2	2	

Comments and Assumptions: * ranked 13th in preliminary ranking (no decay)

[a]Ranking based on chemical score

[b]Bracketed expression shown with parameter

[c]Chemical score [F_{chem}] = $F_{mass} + F_{decay} + F_{tox}$

SITE RANKING SYSTEM

Worksheet for Describing Pathways

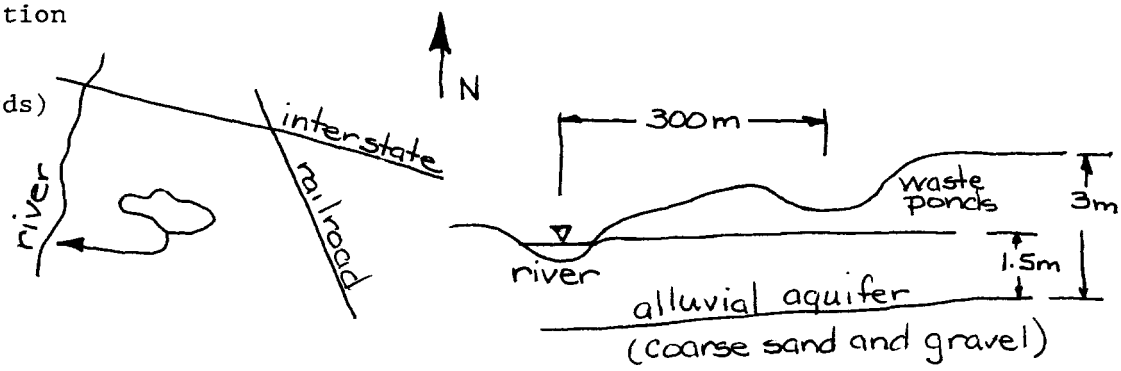
Site Name Example Analyst RPR Date 5-4-87

Page 24

Scenario identifier 1.G-A-R

Release from site by: ground water surface water air (circle one)

General description of scenario (diagram or words)



Target: sensitive-environment humans (circle one)

4 people use river water 4800m downstream

Probability of release: observed very high high medium low (circle one)

river is contaminated

Source/release mechanism[a]

leaching from unlined waste ponds

Exposure point and method[b]

Comments and Assumptions references A-1, B, D

[a] e.g., leaching from contaminated soil

[b] e.g., ingestion of drinking water; wells 2 miles--serving rural neighborhood

SITE RANKING SYSTEM

Worksheet for Describing Pathways

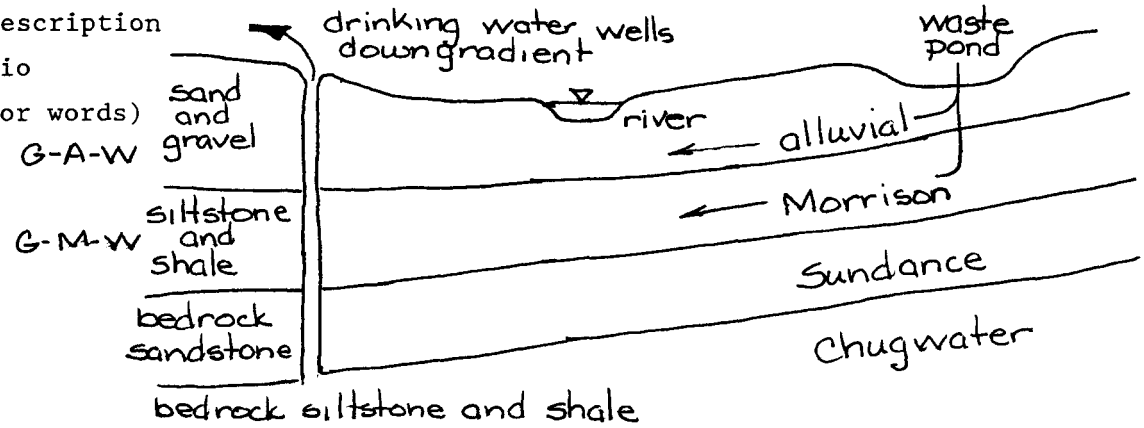
Site Name Example Analyst RPR Date 5-4-87

Page 25

Scenario identifier 2.G-A-W; 3.G-M-W

Release from site by: ground-water surface-water air (circle one)

General description of scenario (diagram or words)



Target: sensitive-environment humans (circle one)

Probability of release: observed very high high medium low (circle one)

monitoring wells at site have observed contamination in all aquifers, but no chemicals were detected at drinking wells

Source/release mechanism[a]

Exposure point and method[b]

Comments and Assumptions references A-1, B, D

[a]e.g., leaching from contaminated soil

[b]e.g., ingestion of drinking water; wells 2 miles--serving rural neighborhood

SITE RANKING SYSTEM

Worksheet for Describing Pathways

Site Name Example Analyst RPR Date 5-4-87

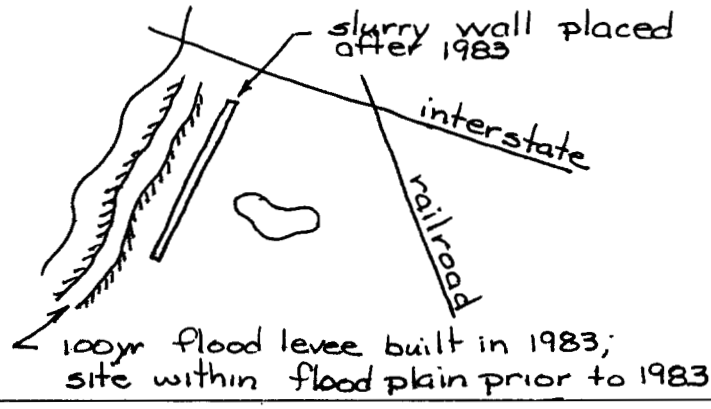
Page 26

Scenario identifier 1. S-R

Release from site by: ground-water surface-water air (circle one)

General description of scenario (diagram or words)

runoff from contaminated soil to river



Target: sensitive-environment humans (circle one)

4 surface water users downstream

Probability of release: observed very high high medium low (circle one)

runoff prior to remedial action in 1983

Source/release mechanism[a]

Exposure point and method[b]

Comments and Assumptions references A-1, B, B

[a]e.g., leaching from contaminated soil

[b]e.g., ingestion of drinking water; wells 2 miles--serving rural neighborhood

SITE RANKING SYSTEM

Worksheet for Describing Pathways

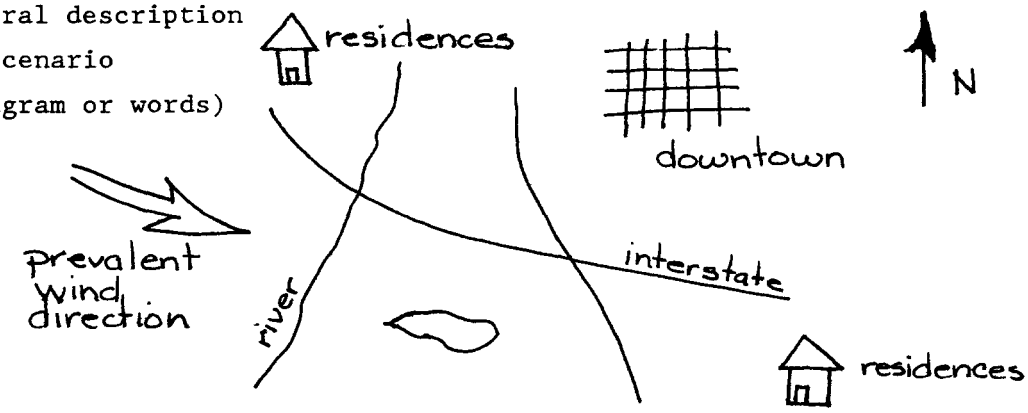
Site Name Example Analyst RPR Date 5-4-87

Page 27

Scenario identifier 1. A

Release from site by: ground-water surface-water air (circle one)

General description of scenario (diagram or words)



Target: sensitive-environment humans (circle one)

center of town 1.5 miles away
nearest residences 100-500 m away

Probability of release: observed very high high medium low (circle one)
no air measurements have been taken; mitigating factors: a) most waste in ponds, b) site vegetated c) highway & railroad embankment will capture some dust

Source/release mechanism[a]

Vapor from ponds, fugitive dust from pond shore, spills, haphazard disposal areas

Exposure point and method[b]

townspeople

Comments and Assumptions references A-1, B, D

[a] e.g., leaching from contaminated soil

[b] e.g., ingestion of drinking water; wells 2 miles--serving rural neighborhood

SITE RANKING SYSTEM

Worksheet for Scoring Waste Placement and Engineered Barriers

Site Name Example Analyst RPR Date 5-4-87

Page 28

Property	Table	Description	Best score	Pessimistic score	Ref
Ground-water route containment					
Waste placement	8.7	waste ponds and some surface deposition	1	2	A-1,C
Leachate reduction	8.8	none	0	0	A-1
Leachate collection	8.9	none	0	0	A-1
		Total [F_{bar}]	1	2	
Surface-water route containment					
Waste placement	8.7	placed in lagoon (scored as in 1982)	1	1	A-1,C
Leachate collection	8.9	none	0	0	A-1
Surface drainage	8.10	no flood control before 1983	0	0	A-1
		Total [F_{bar}]	1	1	
Air route containment					
Waste placement [F_{bar}]	8.7	waste ponds and some surface deposition	1	2	A-1,C

SITE RANKING SYSTEM

Worksheet for Scoring General Parameters of Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 1. G-A-R Page 29

Site parameter	Table	Quantity (best est)	Factor[a]	Best score	Pessimistic score	Ref
Population [N]	8.11	4 sw users		1	1	A-1,C
Distance (m) [$1/x_{gw}^{1/2}$]	8.12	300 m		-1	-1	A-1,D
Engineered barrier [F_{bar}]				1	2	p28
Pore vel (m/d) [$1/V_{gw}$]	8.17	2.86*m/d		0	0	p30
Thickness (m) [1/m]	8.18	1.5 m		0	0	A-II
Pathway dilution	8.19					
[$i_r/(i_r+Q_w+Q_r+Q_a)$] where:				-5	-3**	
i_r= leachate rate (m^3/d)		$1.7m^3$/d				p30
Q_w= well withdrawal (m^3/d)						
Q_r= river discharge[b] (m^3/d)		$2.2x10^5m^3$/d				below
Q_a= added dilution (m^3/d)						
				2-6= -4	-1	
Site subtotal[b]						

Check travel time (x_{gw}/V_{gw}) 300/2.86= 105d < 1000 yr

Comments and Assumptions
* travel time is fast, suggesting river water and sediment samples give site risk
** using rainfall as i_r (see p30)

[a]Bracketed expression shown with parameter

[b]If $x_{riv}^{4800} < \ell_m$, then $Q_r = \overset{2.57x10^5}{\text{discharge}} \cdot \left(\frac{x_{riv}}{\ell_m}\right)^{1/2} = 2.10^5$; otherwise Q_r = discharge;

where $\ell_m = 15 \frac{w_{riv}^2}{d_{riv}} = 6700$ w_{riv}= river width = 14.3 d_{riv}= river depth = 0.46

[c]Score = $F_{pop} + F_{dist} + F_{vel} + F_{thick} + F_{dilution}$

SITE RANKING SYSTEM

Supplemental Worksheet for Estimating Flow Rates in Ground-Water

Site Name Example Analyst RPR Date 5-4-87

Scenario 1. G-A-R Page 30

Strata description and/or name	Thickness [L] (m)	Hydraulic conductivity [K][a] (m/d)	Porosity [ϕ]	Hydraulic head [η] (m)	Pore-water velocity[b] [V] (m/d)	Ref
1A. alluvium-gravel coarse sand	3 (1.5sat)	106	0.3	0.0081	2.86	A-II
2A. Morrison, clay shale, siltstone	36	8.3	0.05	0.0051	0.85	A-II
3A. Sundance sandstone	38	1.6	0.10	0.0081	0.13	A-II
4A. Chugwater	61	0.14	0.27	0.0031	0.0016	A-II

Potential rainfall infiltration (m/d) [$\mu_r r_a$]: 0.25 $(7.3\times10^4) = 1.8\times10^{-4}$

Percolation rate (m/d) [landfill: r_{perc} = minimum $\{\mu_r r_a, K_{cover}, K_{unsat}\}$]:
alternate estimate [lagoon: r_{perc} = average $\{\mu_r r_a, K_{unsat}\}$]:
9×10^6gal oil in alluvial aquifer
oil used from 1928-1983 = 55 yr $r_{perc} = \frac{(9\times10^6 \text{gal})}{55 \text{ yr}} \frac{1}{A_s} = 3\times10^6 \text{m/d}$

Unsaturated velocity (m/d) [$V_{unsat} = r_{perc} / \phi_{unsat}$]: 7.7×10^{-4}m/d

Waste site surface area (m^2) [A_s]:

$$A_s = 140 \text{ acre } \frac{(4047 m^2)}{\text{acre}} = 5.7\times10^5 m^2$$

Leachate flow rate (m^3/d) [$i_r = r_{perc} \cdot A_s$]: $1.7 m^3/d$

[a] $K_{ave} = (\Sigma L_i K_i)/\Sigma L_i$
[b] $V = \eta K/\phi$

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 1. G-A-R Chemical Anthracene Page 31

Site parameter (chemical dependence)	Table	Quantity	Factor	Best score	Pessimistic score	Ref
Site subtotal				-4	-1	p29
Chemical score [F_{chem}]				7	8	p14
Mass adjustment	8.20			-6	-3	
[$1-\exp(-i_r t_\ell S/W_i$] where:						
i_r= leachate rate (m^3/d)		$1.7m^3/d$				p30
t_ℓ= time frame [$2.6x10^4$ d]						
S = solubility (kg or Ci/m^3)		$4.5x10^{-5}kg/m^3$				App C
W_i= quantity (kg or Ci)		$8x10^5kg$				p14
Retardation [R] (or K_d)	8.21	kd=0.017	0.02	-1	0	App C
Unsaturated decay[a]						
$t_{1/2}$= half-life (d)						
V_{unsat}= unsat velocity (m/d)						
d = aquifer depth (m)		0m				A-I
α = dispersivity (m) (20 m if < 0.1d)						
Saturated decay[a]						
$t_{1/2}$= half-life (d)		unknown		0	0	p14
V_{gw} = gw velocity (m/d)						
x_{gw} = gw distance (m)						
α = dispersivity (m) (20m if < $0.1x_{gw}$)						
Individual chemical score[b]				7-11=-4*	4	

Comments and Assumptions

* river Co was $1.8x10^{-6}$mg/l

$$Co \cdot Bw \cdot N \cdot T = 1.8x10^{-6}mg \cdot 21 \cdot \frac{11.5}{mg/kg/d} \cdot \frac{1}{70kg}$$

$$= 2.4x10^{-6} \rightarrow -6;\ -6+3 = -3 \simeq -4 \text{(checks)}$$

[a]Decay score is the following value rounded to nearest integer:

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3\ x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

[b]Score = $F_{site} + F_{chem} + F_{barrier} + F_{adj} + F_{rtrd} - F_{unsat\ decay} - F_{sat\ decay}$

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 1. GAR Chemical Naphthalene Page 33

Site parameter (chemical dependence)	Table	Quantity	Factor	Best score	Pessimistic score	Ref
Site subtotal				-4	-1	p29
Chemical score [F_{chem}]				5	6	p19
Mass adjustment	8.20			-3	-2	
[1-exp(-$i_r t_\ell S/W_i$] where:						
i_r= leachate rate (m^3/d)		1.7 m^3/d				p30
t_ℓ= time frame [2.6x10^4 d]						
S = solubility (kg or Ci/m^3)		3.2x10^{-2} kg/m^3				App C
W_i= quantity (kg or Ci)		2.5x10^6 kg				p19
Retardation [R] (or K_d)	8.21			0	0	
Unsaturated decay[a]				0	0	
$t_{1/2}$= half-life (d)						
V_{unsat}= unsat velocity (m/d)						
d = aquifer depth (m)		0m				A-I
α = dispersivity (m) (20 m if < 0.1d)						
Saturated decay[a]				0	0	
$t_{1/2}$= half-life (d)		unknown				p19
V_{gw} = gw velocity (m/d)						
x_{gw} = gw distance (m)						
α = dispersivity (m) (20m if < 0.1x_{gw})						
Individual chemical score[b]				5-7=-2	3	

Comments and Assumptions

[a]Decay score is the following value rounded to nearest integer:

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3\ x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

[b]Score = $F_{site} + F_{chem} + F_{barrier} + F_{adj} + F_{rtrd} - F_{unsat\ decay} - F_{sat\ decay}$

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 1. G-A-R Chemical Phenanthrene Page 34

Site parameter (chemical dependence)	Table	Quantity	Factor	Best score	Pessimistic score	Ref
Site subtotal				-4	-1	p29
Chemical score [F_{chem}]				5	6	p12
Mass adjustment	8.20			-3	-1*	
[1-exp(-$i_r t_\ell S/W_i$] where:						
i_r= leachate rate (m^3/d)		1.7m^3/d				p30
t_ℓ= time frame [2.6x10^4 d]						
S = solubility (kg or Ci/m^3)		1.10^{-3}kg/m^3				App C
W_i= quantity (kg or Ci)		1.5x10^4kg				p12
Retardation [R] (or K_d)	8.21	K_d=0.017≃0.02		-1	0	App C
Unsaturated decay[a]				0	0	
$t_{1/2}$= half-life (d)						
V_{unsat}= unsat velocity (m/d)						
d = aquifer depth (m)		0m				
α = dispersivity (m) {20 m if < 0.1d}						
Saturated decay[a]				0	0	
$t_{1/2}$= half-life (d)		100 d				p12
V_{gw} = gw velocity (m/d)		2.86 m/d				p30
x_{gw} = gw distance (m)		300 m				D
α = dispersivity (m) {20m if < 0.1x_{gw}}		20m				
Individual chemical score[b]				5-7=-3	4	

Comments and Assumptions: * using i_r from rainfall (103m^3/d

[a]Decay score is the following value rounded to nearest integer:

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3\ x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

[b]Score = F_{site} + F_{chem} + $F_{barrier}$ + F_{adj} + F_{rtrd} - $F_{unsat\ decay}$ - $F_{sat\ decay}$

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 1. G-A-R Chemical PCP Page 35

Site parameter (chemical dependence)	Table	Quantity	Factor	Best score	Pessimistic score	Ref
Site subtotal				-4	1	p29
Chemical score [F_{chem}]				4	5	p16
Mass adjustment	8.20			-1	0	
[1-exp($-i_r t_\ell S/W_i$] where:						
i_r= leachate rate (m^3/d)		$1.7m^3/d$				p30
t_ℓ= time frame [$2.6x10^4$ d]						
S = solubility (kg or Ci/m^3)		$1.4x10^{-2}kg/m^3$				App C
W_i= quantity (kg or Ci)		$1.4x10^4kg$				p16
Retardation [R] (or K_d)	8.21	k_d=0.07>0.02m^3/kg		-1	-1	App C
Unsaturated decay[a]				0	0	
$t_{1/2}$= half-life (d)						
V_{unsat}= unsat velocity (m/d)						
d = aquifer depth (m)		0m				A-1
α = dispersivity (m) (20 m if < 0.1d)						
Saturated decay[a]				0*	0	p16
$t_{1/2}$= half-life (d)		500d				
V_{gw} = gw velocity (m/d)		2.86 m/d				p30
x_{gw} = gw distance (m)		300m				D
α = dispersivity (m) (20m if < $0.1x_{gw}$)		20m				
Individual chemical score[b]				4-6=-2	4	

Comments and Assumptions: $*0.7\alpha/vt_{\frac{1}{2}} = 0.01 < \frac{1}{4}$; $0.3x/vt_{\frac{1}{2}} = 0.06 \simeq 0$

[a]Decay score is the following value rounded to nearest integer:

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3\ x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

[b]Score = $F_{site} + F_{chem} + F_{barrier} + F_{adj} + F_{rtrd} - F_{unsat\ decay} - F_{sat\ decay}$

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 1. G-A-R Chemical Arsenic Page 42

Site parameter (chemical dependence)	Table	Quantity	Factor	Best score	Pessimistic score	Ref
Site subtotal				-4	-1	p29
Chemical score [F_{chem}]				2	2	p24
Mass adjustment	8.20			0	0	
[1-exp($-i_r t_\ell S/W_i$] where:						
i_r= leachate rate (m^3/d)		1.7 m^3/d				p30
t_ℓ= time frame [2.6×10^4 d]						
S = solubility (kg or Ci/m^3)		1 kg/m^3*				
W_i= quantity (kg or Ci)		4.7 kg				p24
Retardation [R] (or K_d)	8.21	k_d=0.006m^3/kg< 0.02		0	0	
Unsaturated decay[a]				0	0	
$t_{1/2}$= half-life (d)		metal				
V_{unsat}= unsat velocity (m/d)						
d = aquifer depth (m)		0m				A-1
α = dispersivity (m) {20 m if < 0.1d}						
Saturated decay[a]				0	0	
$t_{1/2}$= half-life (d)		metal				
V_{gw} = gw velocity (m/d)						
x_{gw} = gw distance (m)						
α = dispersivity (m) {20m if < $0.1x_{gw}$}						
Individual chemical score[b]				-2	1	

Comments and Assumptions: * soluble arsenic compound assumed, see table 8.6

[a]Decay score is the following value rounded to nearest integer:

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3\ x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

[b]Score = $F_{site} + F_{chem} + F_{barrier} + F_{adj} + F_{rtrd} - F_{unsat\ decay} - F_{sat\ decay}$

SITE RANKING SYSTEM

Worksheet for Scoring General Parameters of Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 2. G-A-W Page 43

Site parameter	Table	Quantity (best est)	Factor[a]	Best score	Pessimistic score	Ref
Population [N]	8.11	65*		2	2	p44
Distance (m) [$1/x_{gw}^{1/2}$]	8.12	10-999m		-1	0	p44
Engineered barrier [F_{bar}]				1	2	p28
Pore vel (m/d) [$1/V_{gw}$]	8.17	2.86 m/d		0	0	p30
Thickness (m) [1/m]	8.18	1.5 m		0	0	A-II
Pathway dilution	8.19					
[$i_r/(i_r+Q_w+Q_r+Q_a)$] where:				-1	0	
i_r= leachate rate (m^3/d)		1.7 m^3/d				p30
Q_w= well withdrawal (m^3/d)		49 m^3/d**				
Q_r= river discharge[b] (m^3/d)		-				
Q_a= added dilution (m^3/d)		-				
				3-2=1	4	
Site subtotal[b]						

Check travel time (x_{gw}/V_{gw}) 999/2.86 = 350 d < 1000 yr (ok)

Comments and Assumptions

* 17 wells x 3.8 people/well = 65; 6 m to nearest well, other distances unknown (see p 44)

** 65 people x 0.76 m^3/d person = 49 m^3/d

[a]Bracketed expression shown with parameter

[b]If $x_{riv} < \ell_m$, then Q_r= discharge • $\left(\frac{x_{riv}}{\ell_m}\right)^{1/2}$ = ; otherwise Q_r = discharge;

where $\ell_m = 15 \frac{w_{riv}^2}{d_{riv}}$ = w_{riv}= river width = d_{riv}= river depth =

[c]Score = $F_{pop} + F_{dist} + F_{vel} + F_{thick} + F_{dilution}$

SITE RANKING SYSTEM

Supplemental Worksheet for Scoring Population for Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 2. G-A-W Page 44

Distance (m) [x]	Population [N]	Population score	Distance score [$1/x^{1/2}$]	Sum	Ref
< 10	3.8	1	0	1	A-1
10- 999	65*	2	-1	1	A-1
1,000-100,000			-2		

Population and distance sum (largest sum[a]) 1

Comments and Assumptions * 17 wells x 3.8 people/well = 65

[a]If 3 or more sums are the same, increase the sum by one unit

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 2 G-A-W Chemical PCP Page 46

Site parameter (chemical dependence)	Table	Quantity	Factor	Best score	Pessimistic score	Ref
Site subtotal				1	4	p43
Chemical score [F_{chem}]				4	5	p16
Mass adjustment	8.20	same as 1. G-A-R		-1	0	p35
[1-exp($-i_r t_\ell S/W_i$] where:						
i_r= leachate rate (m^3/d)						
t_ℓ= time frame [2.6×10^4 d]						
S = solubility (kg or Ci/m^3)						
W_i= quantity (kg or Ci)						
Retardation [R] (or K_d)	8.21	k_d=0.07 >0.02 m^3/kg		-1	0	p35
Unsaturated decay[a]				0	0	
$t_{1/2}$= half-life (d)						
V_{unsat}= unsat velocity (m/d)						
d = aquifer depth (m)		0m				A-1
α = dispersivity (m) {20 m if < 0.1d}						
Saturated decay[a]						
$t_{1/2}$= half-life (d)		500d		0	0	p16
V_{gw} = gw velocity (m/d)		2.86m/d				p30
x_{gw} = gw distance (m)		999*m				p44
α = dispersivity (m) {20m if < $0.1x_{gw}$}		20m				
Individual chemical score[b]				5-2=3	9	

Comments and Assumptions

* 6m to nearest well, but even max distance does not effect results

$0.72 / vt_{\frac{1}{2}} = 1 \times 10^{-4}$; $-9.3x/vt_{\frac{1}{2}} = -0.2 \simeq 0$

[a]Decay score is the following value rounded to nearest integer:

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3\ x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

[b]Score = $F_{site} + F_{chem} + F_{barrier} + F_{adj} + F_{rtrd} - F_{unsat\ decay} - F_{sat\ decay}$

SITE RANKING SYSTEM

Worksheet for Scoring General Parameters of Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 3. G-M-W Page 48

Site parameter	Table	Quantity (best est)	Factor[a]	Best score	Pessimistic score	Ref
Population [N]	8.11	380		3	3	p49
Distance (m) [$1/x_{gw}^{1/2}$]	8.12	1372.5m*		-2	-2	p49
Engineered barrier [F_{bar}]				1	2	p28
Pore vel (m/d) [$1/V_{gw}$]	8.17	0.85m/d		0	0	p30
Thickness (m) [1/m]	8.18	36m		-2	-2	p30
Pathway dilution	8.19					
[$i_r/(i_r+Q_w+Q_r+Q_a)$] where:				-4	-1	
i_r= leachate rate (m^3/d)		$1.7m^3/d$**				p30
Q_w= well withdrawal (m^3/d)						
Q_r= river discharge[b] (m^3/d)		$60.8m^3/d$***				
Q_a= added dilution (m^3/d)						
				4-6=-2	0	
Site subtotal[b]						

Check travel time (x_{gw}/V_{gw}) 1372.5/0.85 = 1600d=4yr < 1000 yr (ok)

Comments * distance to nearest well

and ** leachate rate into Morrison possibly much less

Assumptions *** Q_w= 380 people *0.76 m^3/d/person = 60.8m^3/d

[a]Bracketed expression shown with parameter

[b]If $x_{riv} < \ell_m$, then Q_r= discharge • $\left(\frac{x_{riv}}{\ell_m}\right)^{1/2}$ = ; otherwise Q_r = discharge;

where $\ell_m = 15 \frac{w_{riv}^2}{d_{riv}}$ = w_{riv}= river width = d_{riv}= river depth =

[c]Score = $F_{pop} + F_{dist} + F_{vel} + F_{thick} + F_{dilution}$

SITE RANKING SYSTEM

Supplemental Worksheet for Scoring Population for Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 3. G-M-W Page 49

Distance (m) [x]	Population [N]	Population score	Distance score [$1/x^{1/2}$]	Sum	Ref
< 10			0		
10- 999			-1		
1,000-100,000	380*	3	-2	1	A-1

Population and distance sum (largest sum[a]) 1

Comments and Assumptions N = 100 wells x 3.8 people/well = 380

[a]If 3 or more sums are the same, increase the sum by one unit

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Ground-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 3. G-M-W Chemical PCP Page 51

Site parameter (chemical dependence)	Table	Quantity	Factor	Best score	Pessimistic score	Ref
Site subtotal				-2	0	p48
Chemical score [F_{chem}]				4	5	p16
Mass adjustment	8.20			-1	0	p35
[$1-\exp(-i_r t_\ell S/W_i$] where:		same as 1. G-A-R				
i_r= leachate rate (m^3/d)						
t_ℓ= time frame [2.6×10^4 d]						
S = solubility (kg or Ci/m^3)						
W_i= quantity (kg or Ci)						
Retardation [R] (or K_d)	8.21	k_d=0.07>0.02m^3/kg		-1	0	p35
Unsaturated decay[a]				0	0	
$t_{1/2}$= half-life (d)						
V_{unsat}= unsat velocity (m/d)						
d = aquifer depth (m)		0m				A-1
α = dispersivity (m) {20 m if < 0.1d}						
Saturated decay[a]				-1*	0	
$t_{1/2}$= half-life (d)		500d				p16
V_{gw} = gw velocity (m/d)		0.85				p30
x_{gw} = gw distance (m)		1375m				p48
α = dispersivity (m) {20m if < $0.1x_{gw}$}						
Individual chemical score[b]				4-5=-1	5	

Comments and Assumptions: * $0.7\alpha/Vt_{\frac{1}{2}} = 0.03 < \frac{1}{4}$; $-0.03x/Vt_{\frac{1}{2}} = -0.97 \simeq -1$

[a]Decay score is the following value rounded to nearest integer:

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3\,x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

[b]Score = $F_{site} + F_{chem} + F_{barrier} + F_{adj} + F_{rtrd} - F_{unsat\ decay} - F_{sat\ decay}$

SITE RANKING SYSTEM

Worksheet for Scoring General Parameters of Surface-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 1. S-R Page 53

Site parameter	Table	Quantity	Factor	Best score	Pessimistic score	Ref
Engineered barrier				0	1	p28
Population [N]		4		1	1	A-1,C
Runoff [1/q]	8.24			-2	-2	
q = runoff (m^3/d) [$A_s \cdot r_{net}$]		256.5*				
A_s = area (m^2)		$5.7 \times 10^5 m^2$**				A-1,D
r_a = annual rainfall (m/d)		(10.5in/yr)7.3×10^{-4}m/d				E
CN = curve number		69				table 8.24
r_{net}^a = runoff rainfall (m/d)		4.5×10^{-4}				below
Dilution [$q/(q + Q_a + Q_r$]	8.25			-3	-3	
Q_a = added dilution (m^3/d)		0				
Q_r = river discharge[b] (m^3/d)		$2.2 \times 10^5 m^3/d$				p29
Site subtotal[c]				1-5=-4	-3	

Comments and Assumptions

* prior to 1983, site in 25 yr floodplain

** ~140 acres of the 700 acre site contaminated

[a] $r_{net} = \frac{(r_a - 0.2S_w)^2}{r_a + 0.8S_w} = 4.5 \times 10^{-4}$ $S_w = 7 \times 10^{-5}\left(\frac{1000}{CN} - 10\right) = 3.14 \times 10^{-4}$

[b] If $x_{riv} < \ell_m$, then Q_r = discharge $\cdot \left(\frac{x_{riv}}{\ell_m}\right)^{1/2}$ = ; otherwise Q_r = discharge;

where $\ell_m = 15 \frac{w_{riv}^2}{d_{riv}}$ = w_{riv} = river width = d_{riv} = river depth =

[c] Subtotal = $F_{pop} + F_{barrier} + F_{runoff} + F_{dilution}$

SITE RANKING SYSTEM

Worksheet of Waste-Specific Parameters of Surface-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 1. S-R Nonadsorbed[a] Chemical Anthracene Page 54

Site Parameter (chemical dependent)	Table	Quantity	Factor	Best score	Pessimistic score	Ref
Site subtotal				-4	-3	p53
Chemical score [F_{chem}]				7	8	p14
Runoff dissolution [r_{net}/r_a]	8.26			0	0	
Mass adjustment	8.27			-3	-2	
[$1-\exp(-qt_\ell S/W_i)$] where:						
q = runoff (m^3/d)		256 m^3				p53
t_ℓ = time frame (2.6×10^4 d)						
S = solubility (kg or Ci/m^3)		4.5×10^{-5} kg/m^3				p31
W_i = quantity (kg or Ci)		8×10^5 kg				p14
Decay factor[b]				0	0	
$t_{1/2}$ = half-life (d)		unknown				p14
V_{riv} = river velocity (m^3/d)						
x_{riv} = river distance (m)						
α = dispersivity (1 m)						
				7-7=0	3	

Individual chemical score[c]

Comments and Assumptions

[a]Retardation [R] small ($R < 100$, or $K_d < 0.02$ m^3/kg)

[b]Decay score is the following value rounded to nearest integer:

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

[c]Score = $F_{subtotal} + F_{chem} + F_{dissolution} + F_{adj} + F_{decay}$

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Surface-Water Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 1. S-R **Adsorbed**[a] Chemical PCP Page 57

Site parameter (chemical dependent)	Table	Quantity	Factor	Best score	Pessimistic score	Ref
Site subtotal				-4	-3	p53
Chemical score [F_{chem}]				4	4	p16
Sediment yield	8.31					
[$3.5 \times 10^{-3} \cdot CP \cdot LS \cdot R_E$] where:		9.4×10^{-3}		-2*	-1	
CP = control practice		0.45				table 8.29
LS = length-slope factor		0.17				D
R_E = rainfall-erosivity		35				fig 8.7
Decay factor[b]				0**	0	
$t_{1/2}$ = half-life (d)		500d				p16
V_{riv} = river velocity (m^3/d)		3.6×10^7 m/d				A-II
x_{riv} = river distance (m)		4800 m				D
α = dispersivity (1 m)		1 m				
Individual chemical score[c]				4-6=-2	0	

Comments and Assumptions

* scenario assumes normal runoff rather than flooding - would neglect for later case.

** $0.7 / Vt_{\frac{1}{2}} = 4 \times 10^{-10} < 0.25$

[a]Retardation [R] large (R > 100, or $K_d > 0.02\ m^3/kg$)

[b]Decay score is the following value rounded to nearest integer

if $\frac{0.7\alpha}{Vt_{1/2}} < \frac{1}{4}$, decay = $\text{int}\left[\frac{-0.3\ x}{Vt_{1/2}}\right]$; otherwise, decay = $\text{int}\left[\frac{-x}{2.8}\left(\frac{1}{\alpha Vt_{1/2}}\right)^{1/2}\right]$

[c]Score = $F_{subtotal} + F_{chem} + F_{sed\ yield} + F_{decay}$

SITE RANKING SYSTEM

Worksheet for Scoring Population and Distance for Air Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 1.A Page 59

Distance (m) [x]	Population [N]	Population score	Distance score [$1/x^2$]	Sum	Ref
0- 17			0		
17- 55			-2		
56- 175			-4		
176- 550	4	1	-5	-4	D,A-1
551- 1750	729	3	-6	-3	D,A-1
1751- 5500	14,777	4	-7	-3	D,A-1
5501-17500			-8		

Largest sum[a]	-3
Waste placement score	1
Site subtotal[b]	-2

Comments and Assumptions

[a]If 3 or more sums are the same, increase the sum by one unit

[b]Add largest sum and waste placement score

SITE RANKING SYSTEM

Worksheet for Waste-Specific Parameters of Air Pathway

Site Name Example Analyst RPR Date 5-4-87

Scenario 1.A Chemical Napthalene* Page 60

Site parameter	Quantity	Factor	Best score	Pessimistic score	Ref
Site subtotal			-2	-2	p59
Chemical score [F_{chem}]			5	6	p19
Mass adjustment	1.0		0	0	
$[1-\exp(-(e_v+e_w)t_\ell/W_i)]$ where:					
t_ℓ = time frame (2.6×10^4 d)					
W_i = quantity (kg or Ci)	2.5×10^6 kg				p19
$e_v = 0.2\ A_s \kappa\ w_m^{1/2}\ p\ f_{covr}\ f_{gen}$	6.3×10^6 kg/d				
A_s = surface area (m^2)	$5.7 \times 10^5 m^2$**				
$\kappa = \frac{W_i}{\rho_b d_{cont} A_s}$ (conc., kg/kg)	2.0×10^{-3} kg/kg				p6
w_m = gram weight (g/mole)	128 g/mol				App C
p = partial pressure (mm Hg)	217 mmHg				App C
$f_{covr} = \phi^{4/3}/(350\ s)$	none				
f_{gen} = 10 if gas generation	none				
$e_w = 0.2\ \frac{A_s}{PE^2}\ \kappa\ (1-\mu_{covr})$	360 kg/d				
PE = Thornthwaite index	38				fig 8-9
μ_{covr} = vegetative cover (10%)	0.10				A-II
Individual chemical score[a]			5-2=3	4	

Comments and Assumptions

* Napthalene has largest vapor pressure of chemicals with high rank

** area = 140 acre = 5.7×10^5 m^2

[a]Score = $F_{subtotal} + F_{chem} + F_{adj}$

SITE RANKING SYSTEM

Summary Worksheet

Site Name Example Analyst RPR Date 5-4-87

Page 61

Pathway	Scenario	Chemical	Scenario score <eq 8.3>	Pessimistic score <eq 8.4>	Pathway[a] score <eq 8.4>
Ground-water	1. G-A-R	a. Anthracene	-4	4	
		b. Napthalene	-2	3	
		c. Phenanthrene	-3	4	
		d. PCP	-2	4	
		e. Arsenic	-2	1	
	2. G-A-W	a. Napthalene	3	8	
		b. PCP	3	9	4
		c. Arsenic	3	6	
	3. G-M-W	a. Napthalene	0	4	
		b. PCP	-1	5	
		c. Arsenic	0	2	
Surface	1. S-R	a. Anthracene	0	3	1
		b. Napthalene	0	3	
		c. Phenanthrene	1	3	
		d. PCP	-2	0	
		e. Arsenic	-2	1	
	2.	a.			
		b.			
		c.			
Air route	1. A	a. Napthalene	3	4	3
		b.			
		c.			
		d.			

SITE SCORE[b]	4

[a]Pathway score = $F_a + 0.1(n_a) + 0.01(n_b)$ <equation 8.4>

where F_a = highest scenario score

n_a = no. of scenarios with score A

n_b = no. of scenarios with score $F_b = F_a - 1$

[b]Largest pathway score unless 2 same, then increase 1 unit

SITE RANKING SYSTEM

References

Site Name Example Analyst RPR Date 5-4-87

Page 62

Reference ID	Reference
A-1	Phase I Report, Investigative research and remedial action, March 1, 1985
A-II	Phase II Report, Investigative research and remedial action, March 17, 1986
B	Hydrogeology of the example area, September, 1986
C	USEPA Record of Decision, September, 1986
D	US Geological Survey, 7.5 minute series topographic map, 1973
E	Meteorological Data from Water Research Center, February, 1987.
F	Jones, T.D., A.P. Watson, and L.W. Barnthouse, Appendix B Human Health Effects Benchmarks, in HARM II User's Manual, Oak Ridge National Laboratories, 1987.

12. APPENDIX C

Chemical Properties of Hazardous Waste

Appendix C presents UCR data for radionuclides and reproduces chemical data from the "Superfund Public Health Evaluation Manual" (EPA, 1986b) (also available on PC floppy disk). This data should help the assessor in applying SRS. The most recent version of the EPA manual should be referenced for additions to the chemical waste data. Following are explanations of tables, table headings, and data sources.

Table C.1

Table C.1 tabulates UCR data for numerous radionuclides with half-lives greater than 100 days. The calculation of the radionuclide UCR values are described below.

Calculation of radionuclide UCR. Provided that cancer risk per rem [CR] and the dose factor for either ingestion [DF_{oral}] or inhalation [DF_{air}] for a radionuclide are known, calculation of an equivalent UCR is straightforward:

$$UCR = CR \cdot DF_{oral,b} \cdot Z \qquad [C.1]$$

where

CR = cancer risk per rem (cancer risk/rem)

DF_{oral} = dose factor from ingestion for organ b (rem per μCi/day)

Z = w (70 kg) if quantity of waste [W_o] is expressed in Ci;

otherwise,

$$= wn\lambda_e = 1.3\text{x}10^{13}(\lambda_e/m_w) \qquad \text{(converts mg to } \mu\text{Ci times 70 kg)}$$

$$= \frac{(70\text{x}10^3 \text{ g})(6.02\text{x}10^{23} \text{ atom/mol})(\lambda_e \text{ day}^{-1})}{(3.2\text{x}10^{15} \text{ dis/day/Ci})\ (m_w \text{ g/mol})}$$

m_w = gram molecular weight of nuclide (g/mol)

n = number of atoms per mass of isotope

λ_e = effective isotope decay or body elimination rate (day^{-1})

Normally for radionuclides, the quantity [W_o] is expressed in terms of its activity (Ci) rather than its mass (kg). For this case, Z converts UCR

toxicity [T] expressed in units of $(\mu Ci/day)^{-1}$ to $(\mu Ci/kg\ body\ mass/day)^{-1}$ to be consistent with ADI toxicity. Occasionally, however, only the original mass of radioactive material is known; then Z converts activity toxicity $(\mu Ci/day)^{-1}$ to mass toxicity $(mg/kg/day)^{-1}$.

Runkle et al. (1981) tabulate dose factors for ingestion [DF_{oral}] and inhalation [$DF_{air,b}$] assuming uniform lifetime (70 yr) intake (not one initial dose) based on ICRP (1959) for numerous radioisotopes. He also tabulates the latent cancer risk (CR_b] (cancer risk/rem) for several types of cancer reported in BEIR (1972). From these tables we calculated the ingestion or inhalation UCR listed in Table C.2 by selecting the maxium of either the whole body $DF_w \cdot CR_w$ product or the sum of $DF_b \cdot CR_b$ for major body organs b:

$$UCR_r = \text{maximum}\ [\ \Sigma_b(CR_b \cdot DF_b),\ CR_w \cdot DF_w] \qquad [C.2]$$

where

UCR_r = unit cancer risk for radionuclide r

CR_b, CR_w = cancer risk for organ b and whole body, respectively

DF_b, DF_w = dose factor for organ b and whole body, respectively

Although, the technique is somewhat dated, we chose this method because

- the DF for uniform annual intake were readily available, and
- federal regulations are based on this method.

Currently, health physists use effective dose equivalents (EDEs) as described in ICRP Publication 26 (1977), ICRP Publication 30 (1979), and BEIR (1980). The scope of this report did not include time for converting ICRP-Publication-30 DF_b values from one initial dose to annual uniform doses, but we will make these changes in the future. The major change in UCR values will probably occur with plutonium (G. Runkle, 1987, prsnl. comm.). The UCR using EDEs would be calculated as (ICRP, 1977)

$$UCR_r = CR\ \Sigma_b \omega_b DF_b$$

where

CR = total risk per unit uniform whole-body radiation (1.65×10^{-4} rem) (ICRP, 1977)

DF_b = dose equivalent (factor) to individual organ b from yearly intake --integrated values of ICRP Publication 30 (1979)

ω_b = fractional contribution of organ b to the total risk under uniform whole-body irradiation (ICRP, 1977)

Calculated scores for radionuclides. Although dose factors for numerous radionuclides have been tabulated and should be available, one can estimate UCR scores from equation [4.1] for quick scoping calculations to determine if certain radionuclides are of concern as follows. First, assume the radioactive quantity is expressed in Ci. Second, assume that cancer risk per rem of exposure [CR] is $1x10^{-4}$ for whole body. Finally, calculate $DF_{oral,b}$ (rem per μCi/day) by (Runkle et al., 1981) (ICRP, 1959)

$$DF_{oral,b} = a \cdot \frac{\mu_b \epsilon_b}{w_b} \cdot \frac{1}{\lambda_{e,b}^2} \cdot \left[\lambda_{e,b}\, t_\ell + \exp(-\lambda_{e,b}\, t_\ell) - 1 \right] \qquad [C.3]$$

where

$a = 5.12x10^{-2} = \frac{(3.2x10^9 \text{ dis/day}/\mu\text{Ci})\ (1.6x10^{-6} \text{ erg/Mev})}{100 \text{ erg/kg of b tissue/rad}}$

t_ℓ = average human life expectancy ($2.56x10^4$ day)

w_b = mass of organ b (kg)

ϵ_b = absorbed energy [ξ] per disintegration of nuclide in organ b (MeV/dis), times a quality factor [QF] to convert rad to rem

$\lambda_{e,b}$ = effective elimination rate of nuclide in organ b (day^{-1})

μ_b = fraction of nuclide absorbed in organ b

As an approximation, assume in equation [C.3] that

QF = quality factor,
- 1 for X-ray, gamma rays, electron decay products
- 10 for fast neutrons, protons
- 20 for alpha particle decay products (Angelo and Buden, 1985)

w_b = w = average body mass = 70 kg

ϵ_b = $\xi \cdot$ QF (MeV/dis • rem/rad)

ξ = energy released for each disintegration

μ_b = 1

Substituting equation [C.3] into [C.1] using the above assumptions yields

$$\log (UCR) \simeq -5 + \log \xi + \log QF - 2\log \lambda_e + \log [\lambda_e t_\ell + \exp(-\lambda_e t_\ell) - 1] \qquad [C.4]$$

As an example, assume $\lambda_e = 1x10^{-5}$ day^{-1}, and $\xi = 5$ MeV for alpha disintegration and $\xi = 0.01$ MeV for nonalpha disintegration; then

score $\simeq$ 5 for alpha disintegrating radionuclide
$\simeq$ 2 for non-alpha disintegrating radionuclide

Table C.2

Table C.2 (EPA, 1986b) lists physical and chemical properties of hazardous wastes. The data were compiled from 14 sources. These 14 sources were ordered as shown below and values taken from these sources according to this established priority. Documents produced especially for Superfund were at the top, other EPA documents followed, and general reference texts were at the bottom. Although documents lower on the list were usually used only if data were unavailable from sources of higher priority, the most recently available data or measured as opposed to estimated data were always used. The data sources were

A) ECAO, 1985
B) Jaber et al., 1984
C) Mabey et al., 1982
D) Callahan et al., 1979
E) ORD, 1981
F) Dawson et al., 1980
G) Lyman, 1982
H) OWRS, 1980
I) Weast et al., 1979
J) Verschueren, 1984
K) Windoholz et al., 1976
L) Perry and Chilton, 1973
M) OSWER, 1984a
N) OSWER, 1984b

Descriptions of the headings for Table C.2 are as follows:

CAS#. The CAS number is used to access information in national data bases.

Water solubility. Values for water solubility in mg/ℓ are given for neutral pH and a temperature between 20 and 30°C. Chemicals listed in the literature as "infinitely soluble" were assigned a solubility of 10^6 mg/ℓ.

Vapor pressure. Vapor pressure, in mm Hg, are given for temperatures between 20 and 30°C.

Henry's law constant. Henry's law constant was calculated by

$$H\ (atm\text{-}m^3/mol) = \frac{\text{vapor pressure (atm)} \cdot \text{molecular weight (g/mol)}}{\text{water solubility } (g/m^3)}$$

Organic carbon partition coefficient. The organic carbon partition coefficient [K_{oc}] (mℓ/g) measures the tendency for organics to adsorb onto the organic fraction of soil and is expressed as

$$K_{oc} = \frac{\text{mass of solute on solid phase/ mass of organic carbon}}{\text{concentration of solute in solution}}$$

Octanol-water partition coefficient. The octanol-water partition coefficent [K_{ow}] is the equilibrium partition between octanol and water. It indicates the relative affinity of a chemical for non-polar and polar solvents. It is a key variable for estimating other parameters.

Bioconcentration factor. The bioconcentration factor (BCF) measures the tendency for a contaminant in water to accumulate in fish tissue. The contaminant concentration in fish tissue is estimated by multiplying surface-water concentration by BCF.

Table C.3

Table C.3 tabulates half-lives for hazardous wastes in various media. The half-lives are a combination of various degradation processes (biodegradation, hydrolysis, oxidation, photolysis). The data came either from source A (ECAO, 1985) or source M (OSWER, 1984a).

Table C.4

Table C.4 tabulates EPA toxicity data on noncarcinogenic chemical wastes. Those chemicals that also exhibit carcinogenic effects are marked with an "@." An assessor should use the UCR or ADI that gives the largest toxicity score [F_{tox}] when evaluating a chemical for SRS.

Subchronic acceptable intake (AIS). AIS toxicity values are short-term acceptable intake levels.

Chronic acceptable intake (AIC). AIC toxic values [designated acceptable daily intake (ADI) in for text] are the long-term acceptable intake levels for a hazardous chemical. As a side note, for EPA, ADI (also referred to as reference doses [RfD]) designate a subset of AIC values that where developed by the Office of Research and Development in 1985 from compilations other than HEA documents (for example, other agencies or old evaluations).

Table C.5

Carcinogenic potency factors. Carcinogenic potency factors [CPF] are upper 95% confidence limits on the slope of the dose-response curve. The reported values are recorded directly from Health Effects Assessment (HEA) or Carcinogen Assessment Group (CAG) documents.

Weight of evidence. The weight of evidence column in Table C.5 is classified according to Table C.6, EPA categories for potential carcinogens.

Table C.7

Although Tables C.4 through C.5 provide toxicity information on numerious hazardous wastes, over 65,000 industrial chemicals exist. In addition to the toxicity information of Tables C.4 and C.5, Smith and Barnthouse (1987) (Table C.7) have provided toxicity estimates for many other chemicals. Convert the "benchmark" health effect in Table C.7 to an ADI by multiplying by (10^{-3}mg/μg)(1/70kg) (Alternatively, divide 0.7 by the "benchmark" to obtain UCR).

Smith and Barnthouse (1987) estimated the benchmark health effect for the chemicals with incomplete toxicity data using the RASH procedure (Jones, et al., 1987). The RASH procedure estimates the toxicity relative to benzo(a)pyrene using data reported in the registry of toxic effects of chemical substances (RTECS) (Tatken and Lewis, 1983).

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Table C.1 UCR toxicity data for radionuclides

Radionuclide	UCR[a] $(\mu Ci/kg/day)^{-1}$	
	Ingestion	Inhalation
^{227}Ac	$2x10^{1}$	$6x10^{4}$
^{241}Am	$2x10^{1}$	$2x10^{4}$
^{243}Am	$2x10^{1}$	$2x10^{4}$
^{14}C	$1x10^{-1}$	$1x10^{-1}$
^{41}Ca	$4x10^{0}$	$4x10^{0}$
^{144}Ce	$1x10^{1}$	$2x10^{1}$
^{243}Cm	$1x10^{1}$	$2x10^{4}$
^{245}Cm	$2x10^{1}$	$3x10^{4}$
^{247}Cm	$2x10^{1}$	$3x10^{4}$
^{60}Co	$1x10^{0}$	$2x10^{0}$
^{134}Cs	$3x10^{1}$	$3x10^{1}$
^{135}Cs	$2x10^{0}$	$4x10^{0}$
^{137}Cs	$2x10^{1}$	$2x10^{1}$
^{154}Eu	$4x10^{-1}$	$3x10^{1}$
^{155}Eu	$6x10^{-2}$	$5x10^{0}$
^{55}Fe	$1x10^{-1}$	$4x10^{-1}$
^{3}H	$3x10^{-2}$	$3x10^{-2}$
^{129}I	$5x10^{2}$	$4x10^{2}$
^{22}Na	$5x10^{0}$	$3x10^{0}$
^{59}Ni	$4x10^{-1}$	$5x10^{-1}$
^{63}Ni	$2x10^{0}$	$3x10^{0}$

[a]UCR = 70 kg • dose factor • cancer risk

Table C.1 UCR toxicity data for radionuclides (concluded)

Radionuclide	UCR[a] $(\mu Ci/kg/day)^{-1}$	
	Ingestion	Inhalation
^{237}Np	$2x10^{1}$	$4x10^{4}$
^{231}Pa	$5x10^{1}$	$7x10^{5}$
^{210}Pb	$8x10^{2}$	$3x10^{3}$
^{147}Pm	$6x10^{-2}$	$3x10^{0}$
^{210}Po	$2x10^{2}$	$1x10^{3}$
^{239}Pu[b]	$1x10^{2}$	$8x10^{5}$
^{241}Pu[b]	$2x10^{0}$	$6x10^{3}$
^{242}Pu[b]	$1x10^{2}$	$8x10^{5}$
^{226}Ra	$4x10^{4}$	$6x10^{4}$
^{90}Sr	$4x10^{2}$	$5x10^{2}$
^{99}Tc	$2x10^{-1}$	$5x10^{0}$
^{228}Th	$8x10^{0}$	$4x10^{4}$
^{232}Th	$3x10^{1}$	$7x10^{4}$
^{233}U	$2x10^{1}$	$2x10^{3}$
^{234}U	$2x10^{1}$	$2x10^{3}$
^{235}U	$2x10^{1}$	$2x10^{3}$
^{238}U	$2x10^{1}$	$2x10^{3}$
^{65}Zn	$2x10^{0}$	$5x10^{0}$
^{95}Zr	$2x10^{-1}$	$1x10^{1}$

[a]UCR = 70 kg • dose factor • cancer risk

[b]Plutonium increased one order of magnitude

Table C.2 Physical, chemical, and fate data for hazardous wastes (EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	CAS #	Mole Weight (g/mole)	Water Solubility (mg/l)	S*	Vapor Pressure (mm Hg)	S*	Henry's Law Constant (atm-m3/mol)	Koc (ml/g)	S*	log Kow	S*	Fish BCF (l/kg)	S*
Acenaphthene	83-32-9	154	3.42E+00	C	1.55E-03	C	9.20E-05	4600	C	4.00	C	242	H
Acenaphthylene	208-96-8	152	3.93E+00	C	2.90E-02	C	1.48E-03	2500	C	3.70	C		
Acetone	67-64-1	58	1.00E+06	#	2.70E+02	J	2.06E-05	2.2	&	-0.24	J		
Acetonitrile	75-05-8	41	1.00E+06	#	7.40E+01	F	4.00E-06	2.2	&	-0.34	F		
2-Acetylaminofluorene	53-96-3	223	6.50E+00	D			NA	1600	&	3.28	D		
Acrylic Acid	79-10-7	72	1.00E+06	#	4.00E+00	F				0.13	F	0	F
Acrylonitrile	107-13-1	53	7.90E+04	C	1.00E+02	C	8.84E-05	0.85	C	0.25	C	48	G
Aflatoxin B1	1162-65-8	312					NA						
Aldicarb	116-06-3	190											
Aldrin	309-00-2	365	1.80E-01	C	6.00E-06	C	1.60E-05	96000	C	5.30	C	28	H
Allyl Alcohol	107-18-6	58	5.10E+05	B	2.46E+01	B	3.69E-06	3.2	&	-0.22	B		
Aluminum Phosphide	20859-73-8	58											
4-Aminobiphenyl	92-67-1	169	8.42E+02	D	6.00E-05	B	1.59E-08	107	&	2.78	D		
Amitrole	61-82-5	84	2.80E+05	B			NA	4.4	&	-2.08	B		
Ammonia	7664-41-7	17	5.30E+05	F	7.60E+03	F	3.21E-04	3.1	&	0.00	F	0	F
Anthracene	120-12-7	178	4.50E-02	A	1.95E-04	A	1.02E-03	14000	C	4.45	A		
Antimony and Compounds	7440-36-0	122			1.00E+00	N	NA					1	H
Arsenic and Compounds	7440-38-2	75			0.00E+00	E	NA					44	H
Asbestos	1332-21-4	NA	NA		NA		NA	NA		NA		0	D
Auramine	2465-27-2	267	2.10E+00	B			NA	2900	&	4.16	B		
Azaserine	115-02-6	173	1.36E+05	B			NA	6.6	&	-1.08	B		
Aziridine	151-56-4	43	2.66E+06	B	2.55E+02	B	5.43E-06	1.3	&	-1.01			
Barium and Compounds	7440-39-3	137					NA						
Benefin	1861-40-1	335											
Benzene	71-43-2	78	1.75E+03	A	9.52E+01	A	5.59E-03	83	G	2.12	A	5.2	H
Benzidine	92-87-5	184	4.00E+02	C	5.00E-04	C	3.03E-07	10.5	C	1.30	C	87.5	H
Benz(a)anthracene	56-55-3	228	5.70E-03	C	2.20E-08	C	1.16E-06	1380000	G	5.60	C		
Benz(c)acridine	225-51-4	229	1.40E+01	B			NA	1000	&	4.56	B		
Benzo(a)pyrene	50-32-8	252	1.20E-03	A	5.60E-09	A	1.55E-06	5500000	C	6.06	C		
Benzo(b)fluoranthene	205-99-2	252	1.40E-02	C	5.00E-07	C	1.19E-05	550000	C	6.06	A		
Benzo(ghi)perylene	191-24-2	276	7.00E-04	A	1.03E-10	A	5.34E-08	1600000	C	6.51	A		
Benzo(k)fluoranthene	207-08-9	252	4.30E-03	C	5.10E-07	C	3.94E-05	550000	C	6.06	C		
Benzotrichloride	98-07-7	195											
Benzyl Chloride	100-44-7	127	3.30E+03	F	1.00E+00	E	5.06E-05	50	&	2.63	F		
Beryllium and Compounds	7440-41-7	9			0.00E+00	E	NA					19	H
1,1-Biphenyl	92-52-4	154											
Bis(2-chloroethyl)ether	111-44-4	143	1.02E+04	C	7.10E-01	C	1.31E-05	13.9	C	1.50	C	6.9	H
Bis(2-chloroisopropyl)ether	108-60-1	171	1.70E+03	C	8.50E-01	C	1.13E-04	61	C	2.10	C	0	D
Bis(chloromethyl)ether	542-88-1	115	2.20E+04	C	3.00E+01	C	2.06E-04	1.2	C	0.38	C	0.63	H
Bis(2-ethylhexyl)phthalate (DEHP)	117-81-7	391											
Bromomethane	74-83-9	95											
Bromoxynil Octanoate	1689-99-2	403											
1,3-Butadiene	106-99-0	54	7.35E+02	F	1.84E+03	F	1.78E-01	120	&	1.99	F		
n-Butanol	71-36-3	74											
Butylphthalyl Butylglycolate	85-70-1	336											
Cacodylic Acid	75-60-5	138	8.30E+05	F			NA	2.4	&	0.00	F		
Cadmium and Compounds	7440-43-9	112			0.00E+00	E	NA					81	H
Captan	133-06-2	301	5.00E-01	E	6.00E-05	E	4.75E-05	6400	&	2.35	F		
Carbaryl	63-25-2	201	4.00E+01	E	5.00E-03	E				2.36	F		
Carbon Disulfide	75-15-0	76	2.94E+03	E	3.60E+02	E	1.23E-02	54	&	2.00	F	0	F
Carbon Tetrachloride	56-23-5	154	7.57E+02	A	9.00E+01	A	2.41E-02	110	&	2.64	A	19	H
Chlordane	57-74-9	410	5.60E-01	A	1.00E-05	A	9.63E-06	140000	C	3.32	A	14000	H
Chlorobenzene	108-90-7	113	4.66E+02	A	1.17E+01	A	3.72E-03	330	C	2.84	A	10	H
Chlorobenzilate	510-15-6	325	2.19E+01	B	1.20E-06	B	2.34E-08	800	&	4.51	B		
Chlorodibromomethane	124-48-1	208			1.50E+01	D	NA			2.09	D		

Table C.2 Physical, chemical, and fate data for hazardous wastes (continued) (EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	CAS #	Mole Weight (g/mole)	Water Solubility (mg/l)	S*	Vapor Pressure (mm Hg)	S*	Henry's Law Constant (atm-m3/mol)	Koc (ml/g)	S*	Log Kow	S*	Fish BCF (l/kg)	S*
Chloroform	67-66-3	119	8.20E+03	A	1.51E+02	A	2.87E-03	31	&	1.97	A	3.75	H
Chloromethyl Methyl Ether	107-30-2	81					NA			0.00	F		
4-Chloro-o-toluidine Hydrochloride	3165-93-3	142					NA						
Chromium III and Compounds	7440-47-3	52			0.00E+00	E	NA					16	H
Chromium VI and Compounds	7440-47-3	52			0.00E+00	E	NA					16	H
Chrysene	218-01-9	228	1.80E-03	A	6.30E-09	A	1.05E-06	200000	C	5.61	A		
Copper and Compounds	7440-50-8	64			0.00E+00	G	NA					200	D
Creosote	8001-58-9	NA					NA						
Cresol	1319-77-3	108	3.10E+04	E	2.40E-01	J	1.10E-06	500	G	1.97	F	0	F
Crotonaldehyde	123-73-9	70											
Cyanides	57-12-5	NA					NA						
-- Barium Cyanide	542-62-1	189											
-- Calcium Cyanide	502-01-8	92											
-- Copper Cyanide	544-92-3	90											
-- Cyanogen	460-19-5	52	2.50E+05	K									
-- Cyanogen Chloride	506-77-4	61	2.50E+03	F	1.00E+03	J				0.00	F		
-- Hydrogen Cyanide	74-90-8	27	1.00E+06	#	6.20E+02	E				-0.25	F	0	F
-- Nickel Cyanide	557-19-7	182											
-- Potassium Cyanide	151-50-8	65	5.00E+05	K									
-- Potassium Silver Cyanide	506-61-6	199											
-- Silver Cyanide	506-64-9	134											
-- Sodium Cyanide	143-33-9	49	8.20E+05	H									
-- Zinc Cyanide	557-21-1	117											
Cyclophosphamide	50-18-0	261	1.31E+09	B			NA	0.042	&	-3.22	B		
Dalapon	75-99-0	143											
DDD	72-54-8	320	1.00E-01	C	1.89E-06	C	7.96E-06	770000	C	6.20	C		
DDE	72-55-9	318	4.00E-02	C	6.50E-06	C	6.80E-05	4400000	C	7.00	C	51000	G
DDT	50-29-3	355	5.00E-03	A	5.50E-06	A	5.13E-04	243000	G	6.19	J	54000	H
Decabromodiphenyl Ether	1163-19-5	959											
Diallate	2303-16-4	274	1.40E+01	B	6.40E-03	B	1.65E-04	1000	&	0.73	B		
2,4-Diaminotoluene	95-80-7	122	4.77E+04	B	3.80E-05	B	1.28E-10	12	&	0.35	B		
1,2,7,8-Dibenzopyrene	189-55-9	305	1.10E-01	B			NA	1200	&	6.62	B		
Dibenz(a,h)anthracene	53-70-3	278	5.00E-04	C	1.00E-10	C	7.33E-08	3300000	C	6.80	C		
1,2-Dibromo-3-chloropropane	96-12-8	236	1.00E+03	B	1.00E+00	B	3.11E-04	98	&	2.29	B		
Dibutylnitrosamine	924-16-3	152					NA						
Dibutyl Phthalate	84-74-2	278	1.30E+01	C	1.00E-05	C	2.82E-07	170000	C	5.60	C		
1,2-Dichlorobenzene	95-50-1	147	1.00E+02	C	1.00E+00	C	1.93E-03	1700	C	3.60	C	56	H
1,3-Dichlorobenzene	541-73-1	147	1.23E+02	C	2.28E+00	C	3.59E-03	1700	C	3.60	C	56	H
1,4-Dichlorobenzene	106-46-7	147	7.90E+01	C	1.18E+00	C	2.89E-03	1700	C	3.60	C	56	H
3,3'-Dichlorobenzidine	91-94-1	253	4.00E+00	C	1.00E-05	C	8.33E-07	1553	C	3.50	C	312	H
Dichlorodifluoromethane	75-71-8	121	2.80E+02	C	4.87E+03			58	C	2.16	D		
1,1-Dichloroethane	75-34-3	99	5.50E+03	A	1.82E+02	A	4.31E-03	30	C	1.79	A		
1,2-Dichloroethane (EDC)	107-06-2	99	8.52E+03	A	6.40E+01	A	9.78E-04	14	C	1.48	A	1.2	H
1,1-Dichloroethylene	75-35-4	97	2.25E+03	A	6.00E+02	A	3.40E-02	65	C	1.84	A	5.6	H
1,2-Dichloroethylene (trans)	540-59-0	97	6.30E+03	A	3.24E+02	A	6.56E-03	59	C	0.48	A	1.6	H
1,2-Dichloroethylene (cis)	540-59-0	97	3.50E+03	A	2.08E+02	A	7.58E-03	49	&	0.70	A	1.6	H
Dichloromethane	75-09-2	85	2.00E+04	C	3.62E+02	C	2.03E-03	8.8	C	1.30	C	5	H
2,4-Dichlorophenol	120-83-2	163	4.60E+03	C	5.90E-02	C	2.75E-06	380	C	2.90	C	41	H
2,4-Dichlorophenoxyacetic Acid (2,4-D)	94-75-7	221	6.20E+02	F	4.00E-01	F	1.88E-04	20	G	2.81	F		
4-(2,4-Dichlorophenoxy)butyric Acid (2,4-DB)	94-82-6												
Dichlorophenylarsine	696-28-6	223					NA						
1,2-Dichloropropane	78-87-5	113	2.70E+03	C	4.20E+01	C	2.31E-03	51	C	2.00	C		

Table C.2 Physical, chemical, and fate data for hazardous wastes (continued) (EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	CAS #	Mole Weight (g/mole)	Water Solubility (mg/l)	S*	Vapor Pressure (mm Hg)	S*	Henry's Law Constant (atm-m3/mol)	S*	Koc (ml/g)	S*	Log Kow	S*	Fish BCF (l/kg)	S*
1,3-Dichloropropene	542-75-6	111	2.80E+03	C	2.50E+01	C	1.30E-03		48	C	2.00	C	1.9	H
Dieldrin	60-57-1	381	1.95E-01	C	1.78E-07	C	4.58E-07		1700	C	3.50	C	4760	H
Diepoxybutane	1464-53-5	86					NA							
Diethanolnitrosamine	-1116-54-7	134					NA							
Diethyl Arsine	692-42-2	134	4.17E+02	B	3.50E+01	B	1.48E-02		160	&	2.97	B		
1,2-Diethylhydrazine	1615-80-1	88	2.88E+07	B			NA		0.3	&	-1.68	B		
Diethylnitrosamine	55-18-5	102			5.00E+00	F	NA				0.48	F		
Diethyl Phthalate	84-66-2	222	8.96E+02	C	3.50E-03	C	1.14E-06		142	C	2.50	C	117	G
Diethylstilbestrol (DES)	56-53-1	268	9.60E-03	B			NA		28	&	5.46	B		
Dihydrosafrole	94-58-6	164	1.50E+03	B			NA		78	&	2.56	B		
Dimethoate	60-51-5	229	2.50E+04	J	2.50E-02	J					2.71	J		
3,3'-Dimethoxybenzidine	119-90-4	244					NA							
Dimethylamine	124-40-3	45	1.00E+06	F	1.52E+03	F	9.02E-05		2.2	&	-0.38	F	0	F
Dimethyl Sulfate	77-78-1	126	3.24E+05	B	6.80E-01	B	3.48E-07		4.1	&	-1.24	B		
Dimethyl Terephthalate	120-61-6	194												
Dimethylaminoazobenzene	60-11-7	225	1.36E+01	B	3.30E-07	B	7.19E-09		1000	&	3.72	B		
7,12-Dimethylbenz(a)anthracene	57-97-6	256	4.40E-03	B			NA		476000	G	6.94	B		
3,3'-Dimethylbenzidine	119-93-7	212												
Dimethylcarbamoyl Chloride	79-44-7	108	1.44E+07	B	1.95E+00	B	1.92E-08		0.5	&	-1.32	B		
1,1-Dimethylhydrazine	57-14-4	60	1.24E+08	B	1.57E+02	B	1.00E-07		0.2	&	-2.42	B		
1,2-Dimethylhydrazine	540-73-8	60					NA							
Dimethylnitrosamine	62-75-9	74	1.00E+06	#	8.10E+00	C	7.90E-07		0.1	C	-0.68	C	0	D
1,3-Dinitrobenzene	99-65-0	168	4.70E+02	J			NA		150	&	1.62	F		
4,6-Dinitro-o-cresol	534-52-1	198	2.90E+02	C	5.00E-02	C	4.49E-05		240	C	2.70	C	0	E
2,4-Dinitrophenol	51-28-5	184	5.60E+03	C	1.49E-05	C	6.45E-10		16.6	C	1.50	C	0	D
2,3-Dinitrotoluene	602-01-7	182	3.10E+03	B			NA		53	&	2.29	B	3.8	H
2,4-Dinitrotoluene	121-14-2	182	2.40E+02	C	5.10E-03	C	5.09E-06		45	C	2.00	C	3.8	H
2,5-Dinitrotoluene	619-15-8	182	1.32E+03	B			NA		84	&	2.28	B	3.8	H
2,6-Dinitrotoluene	606-20-2	182	1.32E+03	B	1.80E-02	C	3.27E-06		92	C	2.00	C	3.8	H
3,4-Dinitrotoluene	610-39-9	182	1.08E+03	B			NA		94	&	2.29	B	3.8	H
Dinoseb	88-85-7	240	5.00E+01	J										
1,4-Dioxane	123-91-1	88	4.31E+05	B	3.99E+01	B	1.07E-05		3.5	&	0.01	B		
N,N-Diphenylamine	122-39-4	169	5.76E+01	B	3.80E-05	B	1.47E-07		470	&	3.60	B	30	G
1,2-Diphenylhydrazine	122-66-7	184	1.84E+03	C	2.60E-05	C	3.42E-09		418	C	2.90	C	25	H
Dipropylnitrosamine	621-64-7	130	9.90E+03	C	4.00E-01	C	6.92E-06		15	C	1.50	C		
Disulfoton	298-04-4	274												
Endosulfan	115-29-7	407												
Epichlorohydrin	106-89-8	93	6.00E+04	J	1.57E+01	B	3.19E-05		10	&	0.15	B		
Ethanol	64-17-5	46	1.00E+06	#	7.40E+02	G	4.48E-05		2.2	&	-0.32	J		
Ethyl Acetate	141-78-6	88												
Ethyl Methanesulfonate	62-50-0	124	3.69E+05	B	2.06E-01	B	9.12E-08		3.8	&	0.21	B		
Ethylbenzene	100-41-4	106	1.52E+02	A	7.00E+00	A	6.43E-03		1100	C	3.15	A	37.5	H
Ethyl-4,4'-dichlorobenzilate	510-15-6	352												
Ethylene Dibromide (EDB)	106-93-4	188	4.30E+03	J	1.17E+01	B	6.73E-04		44	G	1.76	B		
Ethylene Oxide	75-21-8	44	1.00E+06	B	1.31E+03	B	7.56E-05		2.2	&	-0.22	B		
Ethylenethiourea	96-45-7	102	2.00E+03	F			NA		67	&	-0.66	J	0	F
1-Ethyl-nitrosourea	759-73-9	117	3.31E+08	B			NA		0.1	&				
Ethylphthalyl Ethyl Glycolate	84-72-0	280												
Ferric Dextran	9004-66-4	7500					NA							
Fluoranthene	206-44-0	202	2.06E-01	A	5.00E-06	A	6.46E-06		38000	C	4.90	A	1150	H
Fluorene	86-73-7	116	1.69E+00	C	7.10E-04	C	6.42E-05		7300	C	4.20	C	1300	G
Fluorides	7782-41-4	NA					NA							
Fluridone	59756-60-4	329												
Formaldehyde	50-00-0	30	4.00E+05	K	1.00E+01	E	9.87E-07		3.6	&	0.00	F	0	F

Table C.2 Physical, chemical, and fate data for hazardous wastes (continued) (EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	CAS #	Mole Weight (g/mole)	Water Solubility (mg/l)	S*	Vapor Pressure (mm Hg)	S*	Henry's Law Constant (atm-m3/mol)	Koc (ml/g)	S*	Log Kow	S*	Fish BCF (l/kg)	S*
Formic Acid	64-18-6	46	1.00E+06		4.00E+01	E				-0.54	F	0	F
Furan	110-00-9	68											
Glycidaldehyde	765-34-4	72	1.70E+08	B	1.97E+01	B	1.10E-08	0.1	&	-1.55	B		
Glycol Ethers	NA	NA					NA						
-- Diethylene Glycol, Monoethyl Ether	111-90-0	134											
-- 2-Ethoxyethanol	110-80-5	90	1.00E+06	F						0.00	F		
-- Ethylene Glycol, Monobutyl Ether	111-76-2	118	1.00E+06	F						0.00	F		
-- 2-Methoxyethanol	109-86-4	76	1.00E+06	K									
-- Propylene Glycol, Monoethyl Ether	52125-53-8	104											
-- Propylene Glycol, Monomethyl Ether	107-98-2	90											
Heptachlor	76-44-8	374	1.80E-01	C	3.00E-04	C	8.19E-04	12000	C	4.40	C	15700	H
Heptachlor Epoxide	1024-57-3	389	3.50E-01	C	3.00E-04	C	4.39E-04	220	C	2.70	C	14400	G
Hexachlorobenzene	118-74-1	285	6.00E-03	A	1.09E-05	A	6.81E-04	3900	G	5.23	A	8690	H
Hexachlorobutadiene	87-68-3	261	1.50E-01	A	2.00E+00	A	4.57E+00	29000	C	4.78	A	2.8	H
Hexachlorocyclopentadiene	77-47-4	273	2.10E+00	A	8.00E-02	A	1.37E-02	4800	C	5.04	A	4.3	H
alpha-Hexachlorocyclohexane (HCCH)	319-84-6	291	1.63E+00	C	2.50E-05	C	5.87E-06	3800	C	3.90	C	130	H
beta-HCCH	319-85-7	291	2.40E-01	C	2.80E-07	C	4.47E-07	3800	C	3.90	C	130	H
gamma-HCCH (Lindane)	58-89-9	291	7.80E+00	C	1.60E-04	C	7.85E-06	1080	G	3.90	C	130	H
delta-HCCH	319-86-8	291	3.14E+01	C	1.70E-05	C	2.07E-07	6600	C	4.10	C	130	H
Hexachloroethane	67-72-1	237	5.00E+01	C	4.00E-01	C	2.49E-03	20000	C	4.60	C	87	H
Hexachlorophene	70-30-4	407	4.00E-03	F			NA	91000	&	7.54	F		
Hydrazine	302-01-1	32	3.41E+08	B	1.40E+01	B	1.73E-09	0.1	&	-3.08	B		
Hydrogen Sulfide	7783-06-4	34	4.13E+03	K									
Indeno(1,2,3-cd)pyrene	193-39-5	276	5.30E-04	C	1.00E-10	C	6.86E-08	1600000	C	6.50	C		
Iodomethane	77-88-4	142	1.40E+04	J	4.00E+02	J	5.34E-03	23	&	1.69	J		
Iron and Compounds	15438-31-0	56					NA						
Isobutanol	78-83-1	74											
Isoprene	78-79-5	68			4.00E+02	E	NA						
Isosafrole	120-58-1	168	1.09E+03	B	1.60E-08	B	3.25E-12	93	&	2.66	B		
Isophorone	78-59-1	138											
Isopropalin	33820-53-0	309											
Kepone	143-50-0	491	9.90E-03	B			NA	55000	&	2.00	B	8400	G
Lasiocarpine	303-34-4	412	1.60E+03	B			NA	76	&	0.99	B		
Lead and Compounds (Inorganic)	7439-92-1	207			0.00E+00	E	NA					49	H
Linuron	330-55-2	249											
Malathion	121-75-7	330	1.45E+02	E	4.00E-05	E				2.89	J	0	F
Manganese and Compounds	7439-96-5	55					NA						
Melphalan	148-82-3	305											
Mercury and Compounds (Alkyl)	7439-97-6						NA					3750	H
Mercury and Compounds (Inorganic)	7439-97-6	201			2.00E-03	E	NA					5500	H
Mercury Fulminate	628-86-4	285											
Methanol	67-56-1	32											
Methyl Chloride	74-87-3	50	6.50E+03	C	4.31E+03	B	4.40E-02	35	&	0.95	B		
Methyl Ethyl Ketone	78-93-3	72	2.68E+05	A	7.75E+01	A	2.74E-05	4.5	&	0.26	A	0	F
Methyl Ethyl Ketone Peroxide	1338-23-4	176											
Methyl Isobutyl Ketone	108-10-1	100											
Methyl Methacrylate	80-62-6	100	2.00E+01	F	3.70E+01	E	2.43E-01	840	&	0.79	F		
Methyl Parathion	298-00-0	263	6.00E+01	E	9.70E-06	E	5.59E-08	460	&	1.91	F	45	F
2-Methyl-4-chlorophenoxyacetic Acid	94-74-6	201											
2(2-Methyl)-4-Chlorophenoxy-propionic Acid	93-65-2	215											

Table C.2 Physical, chemical, and fate data for hazardous wastes (continued) (EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	CAS #	Mole Weight (g/mole)	Water Solubility (mg/l)	S*	Vapor Pressure (mm Hg)	S*	Henry's Law Constant (atm-m3/mol)	S*	Koc (ml/g)	S*	Log Kow	S*	Fish BCF (l/kg)	S*
3-Methylcholanthrene	56-49-3	268					NA							
4,4'-Methylene-bis-2-chloroaniline	101-14-4	267					NA							
Methylnitrosourea	684-93-5	103	6.89E+08	B			NA		0.1	&	-3.81	B		
Methylthiouracil	56-04-2	142					NA							
Methylvinylnitrosamine	4549-40-0	86	7.60E+05	B	1.23E+01	B	1.83E-06		2.5	&	-0.23	B		
N-Methyl-N'-nitro-N-nitrosoguanadin	70-25-7	147					NA							
Mitomycin C	50-07-7	334					NA							
Mustard Gas	505-60-2	159	8.00E+02	B	1.70E-01	B	4.45E-05		110	&	1.37	B		
1-Napthylamine	134-32-7	143	2.35E+03	B	6.50E-05	B	5.21E-09		61	&	2.07	B		
2-Napthylamine	91-59-8	143	5.86E+02	B	2.56E-04	B	8.23E-08		130	&	2.07	B		
Nickel and Compounds	7440-02-0	59			0.00E+00	D	NA						47	H
Nitric Oxide	10102-43-9	30												
Nitrobenzene	98-95-3	123	1.90E+03	C	1.50E-01	B			36	C	1.85	D		
Nitrogen Dioxide	10102-44-0	46												
Nitrosomethylurethane	615-53-2	132					NA							
N-Nitrosopiperidine	100-75-4	114	1.90E+06	B	1.40E-01	B	1.11E-08		1.5	&	-0.49	B		
N-Nitrosopyrrolidine	930-55-2	100	7.00E+06	B	1.10E-01	B	2.07E-09		0.8	&	-1.06	B		
5-Nitro-o-toluidine	99-55-8	152					NA							
Osmium Tetroxide	20816-12-0	254												
Pentachlorobenzene	608-93-5	250	1.35E-01	F			NA		13000	&	5.19	F	2125	H
Pentachloronitrobenzene	82-68-8	295	7.11E-02	B	1.13E-04	B	6.18E-04		19000	&	5.45	B		
Pentachlorophenol	87-86-5	266	1.40E+01	C	1.10E-04	C	2.75E-06		53000	C	5	C	770	G
Phenacetin	62-44-2	179					NA							
Phenanthrene	85-01-8	178	1.00E+00	A	6.80E-04	A	1.59E-04		14000	C	4.46	A	2630	G
Phenobarbital	50-06-6	232	1.00E+03	B			NA		98	&	-0.19	B		
Phenol	108-95-2	94	9.30E+04	A	3.41E-01	A	4.54E-07		14.2	C	1.46	A	1.4	H
Phenylalanine Mustard	148-82-3	305					NA							
m-Phenylenediamine	108-45-2	108												
Phenyl Mercuric Acetate	62-38-4	337	1.67E+03	K										
Phosphine	7803-51-2	34												
Polychlorinated Biphenyls (PCBs)	1336-36-3	328	3.10E-02	C	7.70E-05	C	1.07E-03		530000	C	6.04	C	100000	G
Propane Sultone	1120-71-4	122					NA							
Propylenimine	75-55-8	57	9.44E+05	B	1.41E+02	B	1.12E-05		2.3	&	-0.48	B		
Pyrene	129-00-0	202	1.32E-01	A	2.50E-06	A	5.04E-06		38000	C	4.88	A		
Pyridine	110-86-1	79	1.00E+06	F	2.00E+01	F					0.66	F		
Saccharin	81-07-2	183					NA							
Safrole	94-59-7	162	1.50E+03	B	9.10E-04	B	1.29E-07		78	&	2.53	B		
Selenium and Compounds	7782-49-2	79			0.00E+00	E	NA						16	H
-- Selenious Acid	7783-00-8	129												
-- Selenourea	630-10-4	123												
-- Thallium Selenite	12039-52-0	488												
Silver and Compounds	7440-22-4	108			0.00E+00	D	NA						3080	D
Sodium Diethyldithiocarbamate	148-18-5	171												
Streptozocin	18883-66-4	457					NA							
Strychnine	57-24-9	334	1.56E+02	E										
Styrene	100-42-5	104												
1,2,4,5-Tetrachlorobenzene	95-94-3	216	6.00E+00	F			NA		1600	&	4.67	F	1125	H
2,3,7,8-TCDD (Dioxin)	1746-01-6	322	2.00E-04	A	1.70E-06	A	3.60E-03		3300000	C	6.72	A	5000	H
1,1,1,2-Tetrachloroethane	630-20-6	168	2.90E+03	J	5.00E+00	J	3.81E-04		54	&				
1,1,2,2-Tetrachloroethane	79-34-5	168	2.90E+03	A	5.00E+00	A	3.81E-04		118	C	2.39	A	42	H
Tetrachloroethylene	127-18-4	166	1.50E+02	A	1.78E+01	A	2.59E-02		364	C	2.6	A	31	H
2,3,4,6-Tetrachlorophenol	58-90-2	232	1.00E+03	F			NA		98	&	4.1	F	240	H
2,3,5,6-Tetrachloroterephthalate Acid (DCPA)	1861-32-1	332												

Table C.2 Physical, chemical, and fate data for hazardous wastes (continued) (EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	CAS #	Mole Weight (g/mole)	Water Solubility (mg/l)	S*	Vapor Pressure (mm Hg)	S*	Henry's Law Constant (atm-m3/mol)	Koc (ml/g)	S*	Log Kow	S*	Fish BCF (l/kg)	S*
Tetraethyl Lead	78-00-2	323	8.00E-01	J	1.50E-01	J	7.97E-02	4900	&				
Thallium and Compounds	7440-28-0	204			0.00E+00	E							
-- Thallium Acetate	563-68-8	263											
-- Thallium Carbonate	6533-73-9	469											
-- Thallium Chloride	7791-12-0	240	2.90E+03	E	0.00E+00	E							
-- Thallium Nitrate	10102-45-1	266											
-- Thallic Oxide	1314-32-5	457											
-- Thallium Sulfate	7446-18-6	505	2.00E+02	E	0.00E+00	E							
Thioacetamide	62-55-5	75					NA			-0.46	J		
Thiourea	62-56-6	76	1.72E+06	B			NA	1.6	&	-2.05	B		
o-Tolidine	119-93-7	212	7.35E+01	B			NA	410	&	2.88	B		
Toluene	108-88-3	92	5.35E+02	A	2.81E+01	A	6.37E-03	300	C	2.73	A	10.7	H
o-Toluidine Hydrochloride	636-21-5	144	1.50E+04	J	1.00E-01	J	9.39E-07	22	&	1.29	J		
Toxaphene	8001-35-2	414	5.00E-01	C	4.00E-01	C	4.36E-01	964	C	3.3	C	13100	H
Tribromomethane (Bromoform)	75-25-2	253	3.01E+03	C	5.00E+00	C	5.52E-04	116	C	2.4	C		
1,2,4-Trichlorobenzene	120-82-1	181	3.00E+01	C	2.90E-01	C	2.31E-03	9200	C	4.3	C	2800	G
1,1,1-Trichloroethane	71-55-6	133	1.50E+03	A	1.23E+02	A	1.44E-02	152	C	2.5	C	5.6	H
1,1,2-Trichloroethane	79-00-5	133	4.50E+03	A	3.00E+01	A	1.17E-03	56	C	2.47	A	5	H
Trichloroethylene	79-01-6	131	1.10E+03	A	5.79E+01	A	9.10E-03	126	C	2.38	A	10.6	H
Trichlorfon	52-68-6	257	1.54E+05	E	7.80E-06	E	1.71E-11	6.1	&	2.29	A		
Trichloromonofluoromethane	75-69-4	137	1.10E+03	C	6.67E+02	C		159	C	2.53	D		
2,4,5-Trichlorophenol	95-95-4	197	1.19E+03	A	1.00E+00	A	2.18E-04	89	&	3.72	A	110	H
2,4,6-Trichlorophenol	88-06-2	197	8.00E+02	A	1.20E-02	A	3.90E-06	2000	C	3.87	A	150	H
2,4,5-Trichlorophenoxyacetic Acid	93-76-5	255											
1,2,3-Trichloropropane	96-18-4	147											
1,1,2-Trichloro-1,2,2,-trifluoroethane	76-13-1	187	1.00E+01	F	2.70E+02	F				2.00	F		
Tris(2,3-dibromopropyl)phosphate	126-72-7	698	1.20E+02	B			NA	310	&	4.12	B	2.7	G
Trinitrotoluene (TNT)	118-96-7	227											
Trypan Blue	72-57-1	961					NA						
Uracil Mustard	66-75-1	252	6.41E+02	B			NA	120	&	-1.09	B		
Uranium and Compounds	7440-61-1	238					NA						
Urethane	51-79-6	89					NA						
Vanadium and Compounds	7440-62-2	51					NA						
Vinyl Chloride	75-01-4	63	2.67E+03	A	2.66E+03	A	8.19E-02	57	&	1.38	A	1.17	H
Warfarin	81-81-2	308											
o-Xylene	95-47-6	106	1.75E+02	F	1.00E+01	E				2.95	F		
m-Xylene	108-38-3	106	1.30E+02	F	1.00E+01	F				3.26	F		
p-Xylene	106-42-3	106	1.98E+02	F	1.00E+01	F				3.15	F		
Xylene (mixed)	1330-20-7	106	1.98E+02	F	1.00E+01	F	7.04E-03	240	&	3.26	F		
Zinc and Compounds	7440-66-6	65			0.00E+00	D	NA					47	H
-- Zinc Phosphide	1314-84-7	258											
Zineb	12122-67-7	276											

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* Letters denote the source of the data, as listed in Section 3.1.
\# Solubility of 1,000,000 mg/l assigned because of reported "infinite solubility" in the literature.
& Koc estimated by the following equation: log Koc = (-0.55*logS) + 3.64 (Note: S in mg/l).

Table C.3 Half-lives of waste in various media (EPA, 1986b)

Date Prepared: December 18, 1985

Chemical Name	CAS #	Half-life Range (Days) Soil Low	Soil High	Soil S*	Air Low	Air High	Air S*	Surface Water Low	Surface Water High	Surface Water S*	Ground Water Low	Ground Water High	Ground Water S*
Acenaphthene	83-32-9												
Acenaphthylene	208-96-8				5.50	-	M	0.125	-	M			
Acetone	67-64-1												
Acetonitrile	75-05-8				390.00	-	M	7.00	-	M			
2-Acetylaminofluorene	53-96-3												
Acrylic Acid	79-10-7												
Acrylonitrile	107-13-1				3.90	-	M	2.40	7.00	M			
Aflatoxin B1	1162-65-8												
Aldrin	309-00-2												
Allyl Alcohol	107-18-6												
Aluminum Phosphide	20859-73-8												
4-Aminobiphenyl	92-67-1												
Amitrole	61-82-5												
Ammonia	7664-41-7												
Anthracene	120-12-7												
Antimony and Compounds	7440-36-0				4.80	-	M	PERS**	-	M			
Arsenic and Compounds	7440-38-2				5.00	-	M	PERS	-	M			
Asbestos	1332-21-4				4.80	-	M	PERS	-	M			
Auramine	2465-27-2												
Azaserine	115-02-6												
Aziridine	151-56-4												
Barium and Compounds	7440-39-3				4.80	-	M	PERS	-	M			
Benzene	71-43-2				6.00	-	A	1.00	6.00	A			
Benzidine	92-87-5												
Benz(a)anthracene	56-55-3				5.50	-	M	1.00	5.00	M			
Benz(c)acridine	225-51-4												
Benzo(a)pyrene	50-32-8	420.00	480.00	A	1.00	6.00	A	0.40	-	A			
Benzo(b)fluoranthene	205-99-2				5.50	-	M	1.00	2.00	M			
Benzo(ghi)perylene	191-24-2												
Benzo(k)fluoranthene	207-08-9												
Benzyl Chloride	100-44-7												
Beryllium and Compounds	7440-41-7												
Bis(2-chloroethyl)ether	111-44-4												
Bis(2-chloroisopropyl)ether	108-60-1												
Bis(chloromethyl)ether	542-88-1				0.14	2.00	M	0.0007	-	M			
1,3-Butadiene	106-99-0												
Cacodylic Acid	75-60-5												
Cadmium and Compounds	7740-43-9				4.80	-	M	PERS	-	M			
Captan	133-06-2												
Carbaryl	63-25-2												
Carbon Disulfide	75-15-0												
Carbon Tetrachloride	56-23-5				8030.00	-	A	0.30	300.00	A			
Chlordane	57-74-9				40.00	-	M	420.00	500.00	A			
Chlorobenzene	108-90-7				3.50	-	A	0.30	-	A			
Chlorobenzilate	510-15-6												
Chlorodibromomethane	124-48-1												
Chloroform	67-66-3				80.00	-	A	0.30	30.00	A			
Chloromethyl Methyl Ether	107-30-2												
4-Chloro-o-toluidine Hydrochloride	3165-93-3												
Chromium III and Compounds	7440-47-3												
Chromium VI and Compounds	7440-47-3				4.80	-	M	3.00	-	M			
Chrysene	218-01-9				5.50	-	M	4.40	-	M			
Copper and Compounds	7440-50-8												

Table C.3 Half-lives of waste in various media (continued) (EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	CAS #	Half-Life Range (Days) Soil Low	Soil High	Soil S*	Air Low	Air High	Air S*	Surface Water Low	Surface Water High	Surface Water S*	Ground Water Low	Ground Water High	Ground Water S*
Chlorodibromomethane	124-48-1												
Chloroform	67-66-3				80.00	-	A	0.30	30.00	A			
Chloromethyl Methyl Ether	107-30-2												
4-Chloro-o-toluidine Hydrochloride	3165-93-3												
Chromium III and Compounds	7440-47-3												
Chromium VI and Compounds	7440-47-3				4.80	-	M	3.00	-	M			
Chrysene	218-01-9				5.50	-	M	0.20	-	M			
Copper and Compounds	7440-50-8												
Creosote	8001-58-9												
Cresol	1319-77-3												
Crotonaldehyde	123-73-9												
Cyanides	57-12-5				73000.00	-	M	0.33	0.80	M			
-- Barium Cyanide	542-62-1												
-- Calcium Cyanide	502-01-8												
-- Copper Cyanide	544-92-3												
-- Cyanogen	460-19-5												
-- Cyanogen Chloride	506-77-4												
-- Hydrogen Cyanide	74-90-8												
-- Nickel Cyanide	557-19-7												
-- Potassium Cyanide	151-50-8												
-- Potassium Silver Cyanide	506-61-6												
-- Silver Cyanide	506-64-9												
-- Sodium Cyanide	143-33-9												
-- Zinc Cyanide	557-21-1												
Cyclophosphamide	50-18-0												
Dalapon	75-99-0												
DDD	72-54-8												
DDE	72-55-9												
DDT	50-29-3	1000.00	5500.00	A				56.00	110.00	A			
Decabromodiphenyl Ether	1163-19-5												
Diallate	2303-16-4												
2,4-Diaminotoluene	95-80-7												
1,2,7,8-Dibenzopyrene	189-55-9												
Dibenz(a,h)anthracene	53-70-3				5.50	-	M	0.0208	2.08	M			
1,2-Dibromo-3-chloropropane	96-12-8												
Dibutylnitrosamine	924-16-3												
Dibutyl Phthalate	84-74-2												
1,2-Dichlorobenzene	95-50-1				26.00	-	M	1.50	8.50	M			
1,3-Dichlorobenzene	541-73-1												
1,4-Dichlorobenzene	106-46-7				23.00	-	M	1.50	8.50	M			
3,3'-Dichlorobenzidine	91-94-1												
Dichlorodifluoromethane	75-71-8												
1,1-Dichloroethane	75-34-3				45.00	-	A	1.00	5.00	A			
1,2-Dichloroethane (EDC)	107-06-2				36.00	127.00	A	0.17	-	A			
1,1-Dichloroethylene	75-35-4				2.00	-	A	1.00	6.00	A			
1,2-Dichloroethylene (trans)	540-59-0				2.10	-	A	1.00	6.00	A			
1,2-Dichloroethylene (cis)	540-59-0				1.30	-	A	1.00	6.00	A			
Dichloromethane	75-09-2				53.20	-	M	1.20	5.80	M			
2,4-Dichlorophenol	120-83-2				2.30	-	M	6.00	-	M			
2,4-Dichlorophenoxyacetic Acid (2,4-D)	94-75-7												
4-(2,4-Dichlorophenoxy)butyric Acid (2,4-DB)	94-82-6												

Table C.3 Half-lives of waste in various media (continued)
(EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	CAS #	Half-Life Range (Days)											
		Soil			Air			Surface Water			Ground Water		
		Low	High	S*	Low	High	S*	Low	High	S*	Low	High	S*
Dichlorophenylarsine	696-28-6												
1,2-Dichloropropane	78-87-5				80.00	-	M	1.40	7.70	M			
1,3-Dichloropropene	542-75-6							1.00	-	M			
Dieldrin	60-57-1												
Diepoxybutane	1464-53-5												
Diethanolnitrosamine	1116-54-7												
Diethyl Arsine	692-42-2												
1,2-Diethylhydrazine	1615-80-1												
Diethylnitrosamine	55-18-5												
Diethyl Phthalate	84-66-2												
Diethylstilbestrol (DES)	56-53-1												
Dihydrosafrole	94-58-6												
Dimethoate	60-51-5												
3,3'-Dimethoxybenzidine	119-90-4												
Dimethylamine	124-40-3												
Dimethyl Sulfate	77-78-1												
Dimethyl Terephthalate	120-61-6												
Dimethylaminoazobenzene	60-11-7												
7,12-Dimethylbenz(a)anthracene	57-97-6												
3,3'-Dimethylbenzidine	119-93-7												
Dimethylcarbamoyl Chloride	79-44-7												
1,1-Dimethylhydrazine	57-14-4												
1,2-Dimethylhydrazine	540-73-8												
Dimethylnitrosamine	62-75-9												
1,3-Dinitrobenzene	99-65-0							96.00	-	M			
4,6-Dinitro-o-cresol	534-52-1												
2,4-Dinitrophenol	51-28-5												
2,3-Dinitrotoluene	602-01-7												
2,4-Dinitrotoluene	121-14-2				133.00	-	M	0.40	10.00	M			
2,5-Dinitrotoluene	619-15-8												
2,6-Dinitrotoluene	606-20-2												
3,4-Dinitrotoluene	610-39-9												
Dinoseb	88-85-7												
1,4-Dioxane	123-91-1												
N,N-Diphenylamine	122-39-4												
1,2-Diphenylhydrazine	122-66-7												
Dipropylnitrosamine	621-64-7												
Disulfoton	298-04-4												
Endosulfan	115-29-7												
Epichlorohydrin	106-89-8				2.70	-	M	3.50	10.80	M			
Ethanol	64-17-5												
Ethyl Acetate	141-78-6												
Ethyl Methanesulfonate	62-50-0												
Ethylbenzene	100-41-4				1.46	-	A	1.50	7.50	A			
Ethyl-4,4'-dichlorobenzilate	510-15-6												
Ethylene Dibromide (EDB)	106-93-4												
Ethylene Oxide	75-21-8												
Ethylenethiourea	96-45-7												
1-Ethyl-nitrosourea	759-73-9												
Ethylphthalyl Ethyl Glycolate	84-72-0												
Ferric Dextran	9004-66-4												
Fluoranthene	206-44-0				5.50	-	M	1.00	2.00	M			
Fluorene	86-73-7												

Table C.3 Half-lives of waste in various media (continued) (EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	CAS #	Half-Life Range (Days) Soil Low	Soil High	Soil S*	Air Low	Air High	Air S*	Surface Water Low	Surface Water High	Surface Water S*	Ground Water Low	Ground Water High	Ground Water S*
Fluorides	7782-41-4												
Fluridone	59756-60-4												
Formaldehyde	50-00-0				0.80	-	M	0.90	3.50	M			
Formic Acid	64-18-6												
Furan	110-00-9												
Glycidaldehyde	765-34-4												
Glycol Ethers	NA												
-- Diethylene Glycol, Monoethyl Ether	111-90-0												
-- 2-Ethoxyethanol	110-80-5												
-- Ethylene Glycol, Monobutyl Ether	111-76-2												
-- 2-Methoxyethanol	109-86-4												
-- Propylene Glycol, Monoethyl Ether	52125-53-8												
-- Propylene Glycol, Monomethyl Ether	107-98-2												
Heptachlor	76-44-8				40.00	-	M	0.96	-	M			
Heptachlor Epoxide	1024-57-3												
Hexachlorobenzene	118-74-1	1100.00	2200.00	A	80.00	-	M	0.30	300.00	A			
Hexachlorobutadiene	87-68-3				0.20	-	M	29.00	2300.00	A			
Hexachlorocyclopentadiene	77-47-4				0.14	-	M	0.007	-	M			
alpha-Hexachlorocyclohexane (HCCH)	319-84-6												
beta-HCCH	319-85-7												
gamma-HCCH (Lindane)	58-89-9												
delta-HCCH	319-86-8												
Hexachloroethane	67-72-1				7900	-	M	1.10	9.50	M			
Hexachlorophene	70-30-4												
Hydrazine	302-01-1												
Hydrogen Sulfide	7783-06-4												
Indeno(1,2,3-cd)pyrene	193-39-5				5.50	-	M	0.0208	2.08	M			
Iodomethane	77-88-4												
Iron and Compounds	15438-31-0												
Isobutanol	78-83-1												
Isoprene	78-79-5												
Isosafrole	120-58-1												
Isophorone	78-59-1												
Isopropalin	33820-53-0												
Kepone	143-50-0												
Lasiocarpine	303-34-4												
Lead and Compounds (Inorganic)	7439-92-1				4.80	-	M	PERS	-	M			
Linuron	330-55-2												
Malathion	121-75-7												
Manganese and Compounds	7439-96-5												
Melphalan	148-82-3												
Mercury and Compounds (Alkyl)	7439-97-6												
Mercury and Compounds (Inorganic)	7439-97-6				4.80	-	M	PERS	-	M			
Mercury Fulminate	628-86-4												
Methanol	67-56-1												
Methyl Chloride	74-87-3							1.00	-	M			
Methyl Ethyl Ketone	78-93-3				0.58	-	A	10.00	-	A			
Methyl Ethyl Ketone Peroxide	1338-23-4												
Methyl Isobutyl Ketone	108-10-1												

Table C.3 Half-lives of waste in various media (continued)
(EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	CAS #	Half-Life Range (Days) Soil Low	Soil High	Soil S*	Air Low	Air High	Air S*	Surface Water Low	Surface Water High	Surface Water S*	Ground Water Low	Ground Water High	Ground Water S*
Methyl Methacrylate	80-62-6							15.00	-	M			
Methyl Parathion	298-00-0												
2-Methyl-4-chlorophenoxyacetic Acid	94-74-6												
2(2-Methyl)-4-Chlorophenoxy-propionic Acid	93-65-2												
3-Methylcholanthrene	56-49-3												
4,4'-Methylene-bis-2-chloroaniline	101-14-4												
Methylnitrosourea	684-93-5												
Methylthiouracil	56-04-2												
Methylvinylnitrosamine	4549-40-0												
N-Methyl-N'-nitro-N-nitrosoguanadin	70-25-7												
Mitomycin C	50-07-7												
Mustard Gas	505-60-2												
1-Napthylamine	134-32-7												
2-Napthylamine	91-59-8												
Nickel and Compounds	7440-02-0												
Nitric Oxide	10102-43-9												
Nitrobenzene	98-95-3							12.50	-	M			
Nitrogen Dioxide	10102-44-0												
Nitrosomethylurethane	615-53-2												
N-Nitrosopiperidine	100-75-4												
N-Nitrosopyrrolidine	930-55-2												
5-Nitro-o-toluidine	99-55-8												
Osmium Tetroxide	20816-12-0												
Pentachlorobenzene	608-93-5												
Pentachloronitrobenzene	82-68-8												
Pentachlorophenol	87-86-5				21.00	-	M	5.00	-	M			
Phenacetin	62-44-2												
Phenanthrene	85-01-8							0.38	2.00	A			
Phenobarbital	50-06-6												
Phenol	108-95-2				0.62	9.00	A	0.62	9.00	A			
Phenylalanine Mustard	148-82-3												
m-Phenylenediamine	108-45-2												
Phenyl Mercuric Acetate	62-38-4												
Phosphine	7803-51-2												
Polychlorinated Biphenyls (PCBs)	1336-36-3				58.00	-	M	2.00	12.90	M			
Propane Sultone	1120-71-4												
Propyleneimine	75-55-8												
Pyrene	129-00-0				0.08	2.00	A						
Pyridine	110-86-1							2.00	-	M			
Saccharin	81-07-2												
Safrole	94-59-7												
Selenium and Compounds	7782-49-2												
-- Selenious Acid	7783-00-8												
-- Selenourea	630-10-4												
-- Thallium Selenite	12039-52-0												
Silver and Compounds	7440-22-4												
Sodium Diethyldithiocarbamate	148-18-5												
Streptozocin	18883-66-4												
Strychnine	57-24-9												
Styrene	100-42-5												
1,2,4,5-Tetrachlorobenzene	95-94-3												
2,3,7,8-TCDD (Dioxin)	1746-01-6	3650.00	4380.00	A				365.00	730.00	A			

Table C.3 Half-lives of waste in various media (continued) (EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	CAS #	Half-Life Range (Days)											
		Soil			Air			Surface Water			Ground Water		
		Low	High	S*	Low	High	S*	Low	High	S*	Low	High	S*
1,1,1,2-Tetrachloroethane	630-20-6							1.40	-	M			
1,1,2,2-Tetrachloroethane	79-34-5				584.00	-	A	0.04	-	A			
Tetrachloroethylene	127-18-4				47.00	-	A	1.00	30.00	A			
2,3,4,6-Tetrachlorophenol	58-90-2												
2,3,5,6-Tetrachloroterephthalate Acid (DCPA)	1861-32-1												
Tetraethyl Lead	78-00-2												
Thallium and Compounds	7440-28-0												
-- Thallium Acetate	563-68-8												
-- Thallium Carbonate	6533-73-9												
-- Thallium Chloride	7791-12-0												
-- Thallium Nitrate	10102-45-1												
-- Thallic Oxide	1314-32-5												
-- Thallium Sulfate	7446-18-6												
Thioacetamide	62-55-5												
Thiourea	62-56-6												
o-Tolidine	119-93-7												
Toluene	108-88-3				1.30	-	A	0.17	-	A			
o-Toluidine Hydrochloride	636-21-5												
Toxaphene	8001-35-2				40.00	-	M	2.00	14.20	M			
Tribromomethane (Bromoform)	75-25-2												
1,2,4-Trichlorobenzene	120-82-1							1.20	-	M			
1,1,1-Trichloroethane	71-55-6				803.00	1752.00	A	0.14	7.00	A			
1,1,2-Trichloroethane	79-00-5				24.00	-	A	1.90	-	A			
Trichloroethylene	79-01-6				3.70	-	A	1.00	90.00	A			
Trichlorfon	52-68-6												
Trichloromonofluoromethane	75-69-4												
2,4,5-Trichlorophenol	95-95-4	72.00	-	A									
2,4,6-Trichlorophenol	88-06-2	5.00	-	A	1.00	-	A	1.00	19.00	A			
2,4,5-Trichlorophenoxyacetic Acid	93-76-5												
1,2,3-Trichloropropane	96-18-4												
1,1,2-Trichloro-1,2,2,-trifluoroethane	76-13-1												
Tris(2,3-dibromopropyl)phosphate	126-72-7												
Trinitrotoluene (TNT)	118-96-7												
Trypan Blue	72-57-1												
Uracil Mustard	66-75-1												
Uranium and Compounds	7440-61-1												
Urethane	51-79-6												
Vanadium and Compounds	7440-62-2												
Vinyl Chloride	75-01-4				1.20	-	A	1.00	5.00	A			
Warfarin	81-81-2												
o-Xylene	95-47-6												
m-Xylene	108-38-3												
p-Xylene	106-42-3												
Xylene (mixed)	1330-20-7				0.50	-	M	1.50	9.00	M			
Zinc and Compounds	7440-66-6				4.80	20.00	M	PERS	-	M			
-- Zinc Phosphide	1314-84-7												
Zineb	12122-67-7												

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* Letters denote the source of the data, as listed in Section C.1.
** PERS indicates the chemical is persistent for that medium.

Table C.4 ADI toxicity data for noncarcinogens (EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	Oral Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Oral Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Oral Route: Source[2]	Inhalation Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Inhalation Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Inhalation Route: Source[2]
Acenaphthene @						
Acenaphthylene @						
Acetone		1.00E-01	RfD	3.00E+01	3.00E+00	HEA
Acetonitrile						
2-Acetylaminofluorene @						
Acrylic Acid		8.00E-02	RfD[3]			
Acrylonitrile @						
Aflatoxin B1 @						
Aldicarb		1.00E-02	RfD			
Aldrin @		3.00E-05	RfD			
Allyl Alcohol		5.00E-03	RfD			
Aluminum Phosphide		4.00E-04	RfD			
4-Aminobiphenyl @						
Amitrole @						
Ammonia						
Anthracene @						
Antimony and Compounds		4.00E-04	RfD			
Arsenic and Compounds @						
Asbestos @						
Auramine @						
Azaserine @						
Aziridine @						
Barium and Compounds		5.10E-02	HEA	1.4E-3(T)[4]	1.40E-04	HEA
Benefin		3.00E-01	RfD			
Benzene @						
Benzidine @						
Benz(a)anthracene @						
Benz(c)acridine @						
Benzo(a)pyrene @						
Benzo(b)fluoranthene @						
Benzo(ghi)perylene @						
Benzo(k)fluoranthene @						
Benzotrichloride @						
Benzyl Chloride @						
Beryllium and Compounds @		5.00E-04	RfD			
1,1-Biphenyl		5.00E-02	RfD			
Bis(2-chloroethyl)ether @						
Bis(2-chloroisopropyl)ether						
Bis(chloromethyl)ether @						
Bis(2-ethylhexyl)phthalate (DEHP) @		2.00E-02	RfD			
Bromomethane		4.00E-04	RfD			
Bromoxynil Octanoate		3.00E-02	RfD			
1,3-Butadiene						

Table C.4 ADI toxicity data for noncarcinogens (continued) (EPA, 1986b)

Chemical Name	Oral Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Oral Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Oral Route: Source	Inhalation Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Inhalation Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Inhalation Route: Source
n-Butanol		1.00E-01	RfD			
Butylpthalyl Butylglycolate		1.00E+00	RfD			
Cacodylic Acid @		1.00E-02	RfD			
Cadmium and Compounds @		2.90E-04	HEA			
Captan						
Carbaryl		1.00E-01	RfD			
Carbon Disulfide		1.00E-01	RfD			
Carbon Tetrachloride @						
Chlordane @		5.00E-05	RfD			
Chlorobenzene	2.70E-01	2.70E-02	HEA	5.30E-02	5.70E-03	HEA
Chlorobenzilate @						
Chlorodibromomethane						
Chloroform @		1.00E-02	RfD			
Chloromethyl Methyl Ether @						
4-Chloro-o-toluidine Hydrochloride@						
Chromium III and Compounds	1.40E+01	1.00E+00	RfD		5.10E-03	HEA
Chromium VI and Compounds @	2.50E-02	5.00E-03	HEA			
Chrysene @						
Copper and Compounds	3.70E-02	3.70E-02	HEA		1.00E-02	HEA
Creosote @						
Cresol		5.00E-02	RfD		1.00E-01	HEA
Crotonaldehyde		1.00E-02	RfD			
Cyanides (n.o.s.) [5]		2.00E-02	RfD			
-- Barium Cyanide		7.00E-02	RfD			
-- Calcium Cyanide		4.00E-02	RfD			
-- Cyanogen		4.00E-02	RfD			
-- Cyanogen Chloride		5.00E-02	RfD			
-- Copper Cyanide		7.00E-02	RfD			
-- Hydrogen Cyanide		2.00E-02	RfD			
-- Nickel Cyanide		2.00E-02	RfD			
-- Potassium Cyanide		5.00E-02	RfD			
-- Potassium Silver Cyanide		2.00E-01	RfD			
-- Silver Cyanide		1.00E-01	RfD			
-- Sodium Cyanide		4.00E-02	RfD			
-- Zinc Cyanide		5.00E-02	RfD			
Cyclophosphamide @						
Dalapon		8.00E-02	RfD			
DDD @						
DDE @						
DDT @		5.00E-04	RfD			
Decabromodiphenyl Ether		1.00E-02	RfD			
Diallate @						

Table C.4 ADI toxicity data for noncarcinogens (continued) (EPA, 1986b)

Chemical Name	Oral Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Oral Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Oral Route: Source	Inhalation Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Inhalation Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Inhalation Route: Source
2,4-Diaminotoluene @						
1,2,7,8-Dibenzopyrene @						
Dibenz(a,h)anthracene @						
1,2-Dibromo-3-chloropropane @						
Dibutylnitrosamine @						
Dibutyl Phthalate		1.00E-01	RfD			
1,2-Dichlorobenzene						
1,3-Dichlorobenzene						
1,4-Dichlorobenzene						
3,3'-Dichlorobenzidine @						
Dichlorodifluoromethane		2.00E-01	RfD			
1,1-Dichloroethane	1.20E+00	1.20E-01	HEA	1.38E+00	1.38E-01	HEA
1,2-Dichloroethane (EDC) @						
1,1-Dichloroethylene @		9.00E-03	RfD			
1,2-Dichloroethylene (cis)						
1,2-Dichloroethylene (trans)						
Dichloromethane @		6.00E-02	RfD			
2,4-Dichlorophenol		3.00E-03	RfD			
2,4-Dichlorophenoxyacetic Acid (2,4-D)						
4-(2,4-Dichlorophenoxy)butyric Acid (2,4-DB)		8.00E-03	RfD			
Dichlorophenylarsine @						
1,2-Dichloropropane						
1,3-Dichloropropene						
Dieldrin @						
Diepoxybutane @						
Diethanolnitrosamine @						
Diethyl Arsine @						
1,2-Diethylhydrazine @						
Diethylnitrosamine @						
Diethyl Phthalate		1.30E+01	RfD			
Diethylstilbestrol (DES) @						
Dihydrosafrole @						
Dimethoate		2.00E-02	RfD			
3,3'-Dimethoxybenzidine @						
Dimethylamine						
Dimethyl Sulfate @						
Dimethyl Terephthalate		1.00E-01	RfD			
Dimethylaminoazobenzene @						
7,12-Dimethylbenz(a)anthracene @						
3,3'-Dimethylbenzidine @						

Table C.4 ADI toxicity data for noncarcinogens (continued) (EPA, 1986b)

Chemical Name	Oral Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Oral Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Oral Route: Source	Inhalation Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Inhalation Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Inhalation Route: Source
Dimethylcarbamoyl Chloride @						
1,1-Dimethylhydrazine @						
1,2-Dimethylhydrazine @						
Dimethylnitrosamine @						
1,3-Dinitrobenzene						
4,6-Dinitro-o-cresol						
2,4-Dinitrophenol		2.00E-03	RfD			
2,3-Dinitrotoluene @						
2,4-Dinitrotoluene @						
2,5-Dinitrotoluene @						
2,6-Dinitrotoluene @						
3,4-Dinitrotoluene @						
Dinoseb		1.00E-03	RfD			
1,4-Dioxane @						
N,N-Diphenylamine @						
1,2-Diphenylhydrazine @						
Dipropylnitrosamine @						
Disulfoton		4.00E-03	RfD			
Endosulfan		1.50E-05	RfD			
Epichlorohydrin @		2.00E-03	RfD			
Ethanol						
Ethyl Acetate		9.00E-01	RfD			
Ethyl Methanesulfonate @						
Ethylbenzene	9.70E-01	1.00E-01	RfD			
Ethyl-4,4'-dichlorobenzilate @						
Ethylene Dibromide (EDB) @						
Ethylene Oxide @						
Ethylenethiourea @						
1-Ethyl-nitrosourea @						
Ethylphthalyl Ethyl Glycolate		3.00E+00	RfD			
Ferric Dextran @						
Fluoranthene @						
Fluorene @						
Fluorides		6.00E-02	RfD			
Fluridone		8.00E-02	RfD			
Formaldehyde						
Formic Acid		2.00E+00	RfD			
Furan		1.00E-03	RfD			
Glycidaldehyde @						
Glycol Ethers (n.o.s.)						
-- Diethylene Glycol, Monoethyl Ether	5.00E+00	2.00E+00	HEA			

Table C.4 ADI toxicity data for noncarcinogens (continued) (EPA, 1986b)

Chemical Name	Oral Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Oral Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Oral Route: Source	Inhalation Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Inhalation Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Inhalation Route: Source
-- 2-Ethoxyethanol	4.7E-1(T)	3.60E-01	HEA	6.9E-2(T)	5.00E-02	HEA
-- Ethylene Glycol, Monobutyl Ether				1.60E-01	1.60E-02	HEA
-- 2-Methoxyethanol				5.9E-2(T)	2.40E-02	HEA
-- Propylene Glycol, Monoethyl Ether	6.80E+00	6.80E-01	HEA			
-- Propylene Glycol, Monomethyl Ether	6.80E+00	6.80E-01	HEA	4.90E+00	4.90E-01	HEA
Heptachlor @						
Heptachlor Epoxide @		3.00E-05	RfD			
Hexachlorobenzene @						
Hexachlorobutadiene @		2.00E-03	RfD			
Hexachlorocyclopentadiene	7.00E-02	7.00E-03	RfD	2.90E-03	6.60E-05	HEA
alpha-Hexachlorocyclohexane (HCCH)@						
beta-HCCH @						
gamma-HCCH (Lindane) @		3.00E-04	RfD			
delta-HCCH @						
Hexachloroethane @						
Hexachlorophene						
Hydrazine @						
Hydrogen Sulfide		3.00E-03	RfD			
Indeno(1,2,3-cd)pyrene @						
Iodomethane @						
Iron and Compounds					8.60E-03	HEA
Isobutanol		3.00E-01	RfD			
Isoprene						
Isosafrole @						
Isophorone		2.00E-01	RfD			
Isopropalin		3.00E-02	RfD			
Kepone @						
Lasiocarpine @						
Lead and Compounds (Inorganic)		1.40E-03	HEA		4.30E-04	HEA
Linuron						
Malathion		2.00E-02	RfD			
Manganese and Compounds	5.30E-01	2.20E-01	HEA	3.00E-04	3.00E-04	HEA
Melphalan @						
Mercury and Compounds (Alkyl)	2.80E-04	3.00E-04	RfD	1.00E-04	1.00E-04	HEA
Mercury and Compounds (Inorganic)	2.00E-03	2.00E-03	RfD	5.10E-04	5.10E-05	HEA
Mercury Fulminate		3.00E-03	RfD			
Methanol		5.00E-01	RfD			
Methyl Chloride						
Methyl Ethyl Ketone		5.00E-02	RfD	2.20E+00	2.20E-01	HEA

Table C.4 ADI toxicity data for noncarcinogens (continued) (EPA, 1986b)

Chemical Name	Oral Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Oral Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Oral Route: Source	Inhalation Route: Acceptable Intake Subchron (AIS) --mg/kg/day--	Inhalation Route: Acceptable Intake Chronic (AIC) --mg/kg/day--	Inhalation Route: Source
Methyl Ethyl Ketone Perioxide		8.00E-03	RfD			
Methyl Isobutyl Ketone		5.00E-02	RfD			
Methyl Methacrylate						
Methyl Parathion						
2-Methyl-4-Chlorophenoxyacetic Acid		1.00E-03	RfD			
2(2-Methyl-4-Chlorophenoxy) propionic Acid		3.00E-03	RfD			
3-Methylcholanthrene @						
4,4'-Methylene-bis-2-chloroaniline@						
Methylnitrosourea @						
Methylthiouracil @						
Methylvinylnitrosamine @						
N-Methyl-N'-nitro-N-nitrosoguanadine@						
Mitomycin C @						
Mustard Gas @						
1-Napthylamine @						
2-Napthylamine @						
Nickel and Compounds @	2.00E-02	1.00E-02	HEA			
Nitric Oxide		1.00E-01	RfD			
Nitrobenzene		5.00E-04	RfD			
Nitrogen Dioxide		1.00E+00	RfD			
Nitrosomethylurethane @						
N-Nitrosopiperidine @						
N-Nitrosopyrrolidine @						
5-Nitro-o-toluidine @						
Osmium Tetroxide		1.00E-05	RfD			
Pentachlorobenzene		8.00E-04	RfD			
Pentachloronitrobenzene @		8.00E-03	RfD			
Pentachlorophenol	3.0E-2(T)	3.00E-02	RfD			
Phenacetin @						
Phenanthrene @						
Phenobarbital @						
Phenol	1.00E-01	1.00E-01	RfD	1.90E-01	2.00E-02	HEA
Phenylalanine Mustard @						
m-Phenylenediamine		6.00E-03	RfD			
Phenyl Mercuric Acetate		8.00E-05	RfD			
Phosphine		3.00E-04	RfD			
Polychlorinated Biphenyls (PCBs) @						
Propane Sultone @						
Propylenimine @						
Pyrene @						
Pyridine		2.00E-03	RfD			

Table C.4 ADI toxicity data for noncarcinogens (continued) (EPA, 1986b)

Chemical Name	Oral Route Acceptable Intake Subchron (AIS) --mg/kg/day--	Oral Route Acceptable Intake Chronic (AIC) --mg/kg/day--	Oral Route Source	Inhalation Route Acceptable Intake Subchron (AIS) --mg/kg/day--	Inhalation Route Acceptable Intake Chronic (AIC) --mg/kg/day--	Inhalation Route Source
Saccharin @						
Safrole @						
Selenium and Compounds (n.o.s.)	3.20E-03	3.00E-03	HEA		1.00E-03	HEA
-- Selenious Acid		3.00E-03	RfD			
-- Selenourea		5.00E-03	RfD			
-- Thallium Selenite		5.00E-04	RfD			
Silver and Compounds		3.00E-03	RfD			
Sodium Diethyldithiocarbamate		3.00E-02	RfD			
Streptozocin @						
Strychnine		3.00E-04	RfD			
Styrene		2.00E-01	RfD			
1,2,4,5-Tetrachlorobenzene		3.00E-04	RfD			
2,3,7,8-TCDD (Dioxin) @						
1,1,1,2-Tetrachloroethane @						
1,1,2,2-Tetrachloroethane @						
Tetrachloroethylene @		2.00E-02	RfD			
2,3,4,6-Tetrachlorophenol		1.00E-02	RfD			
2,3,5,6-Tetrachloroterephthalate Acid (DCPA)		5.00E-02	RfD			
Tetraethyl Lead @		1.00E-07	RfD			
Thallium and Compounds (n.o.s.)		4.00E-04	RfD			
-- Thallium Acetate		5.00E-04	RfD			
-- Thallium Carbonate		4.00E-04	RfD			
-- Thallium Chloride		5.00E-04	RfD			
-- Thallium Nitrate		5.00E-04	RfD			
-- Thallic Oxide		4.00E-04	RfD			
-- Thallium Sulfate		5.00E-04	RfD			
Thioacetamide @						
Thiourea @						
o-Tolidine @						
Toluene	4.30E-01	3.00E-01	RfD	1.50E+00	1.50E+00	HEA
o-Toluidine Hydrochloride @						
Toxaphene @						
Tribromomethane (Bromoform)						
1,2,4-Trichlorobenzene		2.00E-02	RfD			
1,1,1-Trichloroethane		5.40E-01	HEA	1.10E+01	6.30E+00	HEA
1,1,2-Trichloroethane @						
Trichloroethylene @						
Trichlorofon						
Trichloromonofluoromethane		3.00E-01	RfD			
2,4,5-Trichlorophenol	1.00E+00	1.00E-01	RfD			
2,4,6-Trichlorophenol @						

Table C.4 ADI toxicity data for noncarcinogens (continued) (EPA, 1986b)

Chemical Name	Oral Route Acceptable Intake Subchron (AIS) --mg/kg/day--	Oral Route Acceptable Intake Chronic (AIC) --mg/kg/day--	Source	Inhalation Route Acceptable Intake Subchron (AIS) --mg/kg/day--	Inhalation Route Acceptable Intake Chronic (AIC) --mg/kg/day--	Source
2,4,5-Trichlorophenoxyacetic Acid		3.00E-02	RfD			
1,2,3-Trichloropropane		1.00E-01	RfD			
1,1,2-Trichloro-1,2,2-Trifluoroethane		3.00E+01	RfD			
Tris(2,3-dibromopropyl)phosphate @						
Trinitrotoluene (TNT)		2.00E-04	RfD			
Trypan Blue @						
Uracil Mustard @						
Uranium and Compounds						
Urethane @						
Vanadium and Compounds		2.00E-02	RfD			
Vinyl Chloride @						
Warfarin		3.00E-04	RfD			
o-Xylene	1.00E-01	1.00E-02	HEA	9.6E-1(T)	2.00E-01	HEA
m-Xylene	1.00E-01	1.00E-02	HEA	1.00E+00	2.00E-01	HEA
p-Xylene						
Xylenes (mixed)	1.00E-01	1.00E-02	HEA	6.9E-1(T)	4.00E-01	HEA
Zinc and Compounds	2.10E-01	2.10E-01	HEA	1.00E-01	1.00E-02	HEA
-- Zinc Phosphide		3.00E-04	RfD			
Zineb		5.00E-02	RfD			

@ Potential carcinogenic effects also.

[1] Refer to Exhibit C-5 for toxicity data for indicator selection for the chemicals listed here.

[2] Sources

RfD = Agency-wide reference dose value, developed by an inter-office work group chaired by the Office of Research and Development, U.S. EPA, Washington, D.C., 1986.

HEA = Health Effects Assessment document, prepared by the Environmental Criteria and Assessment Office, U.S. EPA, Cincinnati, Ohio, 1985 (updated in May 1986).

[3] The RfD values listed here are EPA-verified numbers. All RfD values were derived based on oral exposure; however, in the absence of other more specific data, these values may also be useful in assessing risks of inhalation exposure.

[4] T indicates that teratogenic or fetotoxic effects are the basis for the AIS value listed.

[5] N.O.S. = not otherwise specified.

Table C.5 UCR toxicity data for chemical carcinogens (EPA, 1986b)

Date Prepared: October 1, 1986

Chemical Name	Oral Route: Potency Factor (PF) (mg/kg/d)-1	Oral Route: Source[2]	Oral Route: EPA Weight of Evidence	Inhalation Route: Potency Factor (PF) (mg/kg/d)-1	Inhalation Route: Source[2]	Inhalation Route: EPA Weight of Evidence
2-Acetylaminofluorene			B2			B2
Acrylonitrile			B1	2.40E-01	CAG	B1
Aflatoxin B1	2.90E+03	CAG	B2			B2
Aldrin	1.14E+01	CAG	B2			B2
Amitrole			B2			B2
Arsenic and Compounds	1.50E+01	HEA	A	5.00E+01	HEA	A
Asbestos			A			A
Auramine			B2			B2
Azaserine			B2			B2
Aziridine			B2			B2
Benzene	5.20E-02	HEA	A	2.60E-02	HEA	A
Benzidine			A	2.30E+02	CAG	A
Benz(a)anthracene			B2			B2
Benz(c)acridine			C			C
Benzo(a)pyrene	1.15E+01	HEA	B2	6.10E+00	HEA	B2
Benzo(b)fluoranthene			B2			B2
Benzo(k)fluoranthene			D			D
Benzotrichloride			B2			B2
Benzyl Chloride			C			C
Beryllium and Compounds	NA		B1	4.86E+00	CAG	B1
Bis(2-chloroethyl)ether	1.10E+00	CAG	B2			B2
Bis(chloromethyl)ether			A	9.30E+03	CAG	A
Bis(2-ethylhexyl)phthalate (DEHP)	6.84E-04	CAG	B2			B2
Cacodylic Acid			D			D
Cadmium and Compounds	NA			6.10E+00	HEA	B1
Carbon Tetrachloride	1.30E-01	HEA	B2			B2
Chlordane	1.61E+00	HEA	B2			B2
Chloroform	8.10E-02	HEA	B2			B2
4-Chloro-o-toluidine Hydrochloride			B2			B2
Chromium VI and Compounds	NA			4.10E+01	HEA	A
Chrysene			B2			B2
Cyclophosphamide			B1			B1
DDD			B2			B2
DDE			B2			B2
DDT	3.40E-01	HEA	B2			B2
Diallate			C			B2
Diaminotoluene (mixed)			B2			B2
1,2,7,8-Dibenzopyrene			B2			B2
Dibenz(a,h)anthracene			B2			B2
1,2-Dibromo-3-chloropropane			B2			B2
Dibutylnitrosamine	5.40E+00	CAG	B2			B2
3,3'-Dichlorobenzidine	1.70E+00	CAG	B2			B2
1,2-Dichloroethane (EDC)	9.10E-02	HEA	B2	3.50E-02	HEA	B2
1,1-Dichloroethylene	5.80E-01	HEA	C	1.16E+00	HEA	C
Dichloromethane	7.50E-03	HEA	B2	1.43E-02	HEA	B2
Dieldrin	3.00E+01	CAG	B2			B2
Diepoxybutane			B2			B2
Diethanolnitrosamine			B2			B2
Diethyl Arsine			D			D
1,2-Diethylhydrazine			B2			B2
Diethylnitrosamine	4.40E+01	CAG	B2			B2
Diethylstilbestrol (DES)			A			A
Dihydrosafrole			B2			B2
3,3'-Dimethoxybenzidine			B2			B2
Dimethyl Sulfate			B2			B2
Dimethylaminoazobenzene			B2			B2
7,12-Dimethylbenz(a)anthracene			B2			B2
3,3'-Dimethylbenzidene			B2			B2
Dimethylcarbamoyl Chloride			B2			B2
1,1-Dimethylhydrazine			B2			B2
1,2-Dimethylhydrazine			B2			B2
Dimethylnitrosamine	2.60E+01	CAG	B2			B2
Dinitrotoluene (mixed)			B2			B2
2,4-Dinitrotoluene	3.10E-01	CAG	B2			B2
2,6-Dinitrotoluene			C			C
1,4-Dioxane			B2			B2
1,2-Diphenylhydrazine	7.70E-01	CAG	B1			B2
Dipropylnitrosamine			B2			B2
Epichlorohydrin	9.90E-04	CAG	B2			B2
Ethyl-4,4'-dichlorobenzilate			B2			B2
Ethylene Dibromide (EDB)	4.10E+01	CAG	B2			B2

Table C.5 UCR toxicity data for chemical carcinogens (continued) (EPA, 1986b)

Chemical Name	Oral Route: Potency Factor (PF) (mg/kg/d)-1	Oral Route: Source[2]	Oral Route: EPA Weight of Evidence	Inhalation Route: Potency Factor (PF) (mg/kg/d)-1	Inhalation Route: Source[2]	Inhalation Route: EPA Weight of Evidence
Ethylene Oxide			B1/B2	3.50E-01	CAG	B1/B2
Ethylenethiourea			B2			B2
Ethyl Methanesulfonate			B2			B2
1-Ethyl-nitrosourea	3.30E+01	CAG	B2			B2
Formaldehyde			B2			B2
Glycidaldehyde			B2			B2
Heptachlor	3.40E+00	CAG	B2			B2
Heptachlor Epoxide	2.60E+00	CAG	B2			B2
Hexachlorobenzene	1.69E+00	HEA	B2			B2
Hexachlorobutadiene	7.75E-03	HEA	C			C
alpha-Hexachlorocyclohexane (HCCH)	1.10E+01	CAG	B2			B2
beta-HCCH	1.80E+00	CAG	C			C
gamma-HCCH (Lindane)	1.33E+00	HEA	B2/C			B2/C
Hexachloroethane	1.40E-02	CAG	C			C
Hydrazine			B2			B2
Indeno(1,2,3-cd)pyrene			C			C
Iodomethane			C			C
Isosafrole			B2			C
Kepone			B2			B2
Lasiocarpine			B2			B2
Melphalan			B1			B1
Methyl Chloride			C			C
3-Methylcholanthrene			B2			B2
4,4'-Methylene-bis-2-chloroaniline			B2			B2
Methylnitrosourea	3.00E+02	CAG	B2			B2
Methylnitrosourethane			B2			B2
Methylthiouracil			B2			B2
Methylvinylnitrosamine			B2			B2
N-Methyl-N'-nitro-N-nitrosoguanadine			B2			B2
Mitomycin C			B2			B2
1-Napthylamine			C			C
2-Napthylamine			A			A
Nickel and Compounds	NA		A	1.19E+00	HEA	A
N-Nitrosopiperidine			B2			B2
N-Nitrosopyrrolidine	2.10E+00	CAG	B2			B2
5-Nitro-o-toluidine			C			C
Pentachloronitrobenzene			C			C
Pentachlorophenol			D			D
Phenacetin			B2			B2
Polychlorinated Biphenyls (PCBs)	4.34E+00	HEA	B2			B2
Polynuclear Aromatic Hydrocarbons	1.15E+01	HEA		6.11E+00	HEA	
Propane Sultone			B2			B2
1,2-Propylenimine			B2			B2
Saccharin			C			C
Safrole			B2			B2
Streptozocin			B2			B2
2,3,7,8-TCDD (Dioxin)	1.56E+05	HEA	B2			B2
1,1,1,2-Tetrachloroethane			B2			C
1,1,2,2-Tetrachloroethane	2.00E-01	HEA	C			C
Tetrachloroethylene	5.10E-02	HEA	B2	1.70E-03	HEA	B2
Thioacetamide			B2			B2
Thiourea			B2			B2
o-Toluidine hydrochloride			B2			B2
Toxaphene	1.10E+00	CAG	B2			B2
1,1,2-Trichloroethane	5.73E-02	HEA	C			C
Trichloroethylene	1.10E-02	HEA	B2	4.60E-03	HEA	B2
2,4,6-Trichlorophenol	1.98E-02	HEA	B2			B2
Tris(2,3-dibromopropyl)phosphate			B2			B2
Trypan Blue			B2			B2
Uracil Mustard			B2			B2
Urethane			B2			B2
Vinyl Chloride	2.30E+00	HEA	A	2.50E-02	HEA	A

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[1] The list of chemicals presented in this exhibit is based on EPA's Reportable Quantities Analysis and should not be considered an all-inclusive list of suspected carcinogens.

[2] Sources

HEA = Health Effects Assessment, prepared by the Environmental Criteria and Assessment Office, U.S. EPA, Cincinnati, Ohio, 1985 (updated in May 1986).

CAG = Evaluation by Carcinogen Assessment Group, U.S. EPA, Washington, D.C., 1985.

Table C.6 EPA categories for potential carcinogens (EPA, 1986b)

EPA WEIGHT-OF-EVIDENCE
CATEGORIES FOR POTENTIAL CARCINOGENS

EPA Category	Description of Group	Description of Evidence
Group A	Human Carcinogen	Sufficient evidence from epidemiologic studies to support a causal association between exposure and cancer
Group B1	Probable Human Carcinogen	Limited evidence of carcinogenicity in humans from epidemiologic studies
Group B2	Probable Human Carcinogen	Sufficient evidence of carcinogenicity in animals, inadequate evidence of carcinogenicity in humans
Group C	Possible Human Carcinogen	Limited evidence of carcinogenicity in animals
Group D	Not Classified	Inadequate evidence of carcinogenicity in animals
Group E	No Evidence of Carcinogenicity in Humans	No evidence for carcinogenicity in at least two adequate animal tests or in both epidemiologic and animal studies

Table C.7 Estimated carcinogenic potency factors (CPFs) (Smith and Barnthouse, 1987)

Chemical	CAS No.	Health effects Benchmark (µg/d)	Health effects Source[a]	Aquatic life (µg/L)	Irrigated crops (µg/L)	Fish bio-accumulation (L/kg)	Health hazard score	Ecological hazard score
Acenaphthene	83-32-9	0.40E+02	EPA	1,700		390.0	3	2
Acetone	67-64-1	0.40E+02	RASH	10,000		0.16	2	1
Aldicarb [Temik] [Carbanolate]	116-06-3	0.66E-02	RASH	--	--	--	--	--
Aldrin	309-00-2	0.90E-06	EPA	3.0	--	11,000.0	9	4
Aluminum	7429-90-5	3.00E+00	RASH	--	5,000	--	--	2
Antimony	7440-36-0	0.29E+03	EPA	9,000	--	1.0	--	2
Arsenic	7440-38-2	0.04E+00	EPA	360	100	280.0	4	2
Barium	7440-39-3	1.50E-01	ACGIH	14,500		4.0	2	1
Baygon	38777-13-8	0.12E+00	RASH	13	5,000	8.5	2	2
Benzene	71-43-2	0.30E+02	EPA	5,300	--	32.0	2	2
Benzidine	92-87-5	0.34E-02	EPA	2,500	--	41.0	5	2
Benzo(a)anthracene	See Hydrocarbons							
Benzo(a)pyrene	See Hydrocarbons							
Beryllium	7440-41-7	0.17E+00	EPA	130	100	2.0	2	2
BHC and Isomers	See Hexachlorocyclohexane							
Bis(2-chloroethyl) ether [dichloroethylether]	111-44-4	0.84E+00	EPA	54,400	1,640,000	11.0	3	1
Bis(2-ethylhexyl) phthalate	See Phthalate esters							
Bromochloromethane	See Halomethanes							
Bromodichloromethane	See Halomethanes							
2-Butanone	See Methyl ethyl ketone							
Butyl benzyl phthalate	See Phthalate esters							
2-Butyl 1-octanol	See Hydrocarbons							
Cadmium	7440-43-9	0.20E+02	EPA	0.66	10	50.0	2	6
Carbaryl [Sevin]	63-25-2	0.18E+01	RASH	1.7	--	200.0	4	4
Carbon tetrachloride	56-23-5	0.52E+01	EPA	35,200	--	23.0	2	1
Chlordane	57-74-9	0.24E-02	EPA	2.4	--	1,400,000	7	4
Chlorinated benzenes	--	--		250.0	--	--	--	2
Chlorobenzene	108-90-7	0.26E+04	EPA	15,900	--	450	1	1
Dichlorobenzene	--	--		1,120	--		--	2
1,2-Dichlorobenzene [o-dichlorobenzene]	95-50-1	0.46E+03	EPA	1,580	--	560	2	2
1,3-Dichlorobenzene	None	0.46E+03	EPA	2,850	--	740	2	2
1,4-Dichlorobenzene [p-dichlorobenzene]	106-46-7	0.46E+03	EPA	1,120	--	690	2	2
Trichlorobenzene	--	--		1,500	--	--	--	2
1,2,4-Trichlorobenzene	120-82-1	0.74E+02	EPA	1,500	--	1,200	4	2

Table C.7 Estimated carcinogenic potency factors (CPFs) (Smith and Barnthouse, 1987) (continued)

Chemical	CAS No.	Health effects Benchmark (µg/d)	Health effects Source[a]	Aquatic life (µg/L)	Irrigated crops (µg/L)	Fish bio-accumulation (L/kg)	Health hazard score	Ecological hazard score
Chlorinated ethanes	--	--		980	--	--	--	2
Chloroethane	75-00-3	0.10E+02	EPA	980	--	6.5	1	2
Dichloroethane	--	--		118,000	--	--	--	1
1,1-Dichloroethane [ethylidene chloride]	75-34-3	0.15E+02	EPA	118,000	--	14.0	2	1
1,2-Dichloroethane [ethylene chloride]	107-06-2	0.40E+02	EPA	118,000	--	2.0	1	1
Trans-1,2-dichloroethane	--	--	--	118,000	--	2.0	--	1
Trichloroethane								
1,1,1-Trichloroethane [methyl chloroform]	71-55-6	0.90E+02	EPA	31,200	--	8.9	1	1
1,1,2-Trichloroethane	79-00-5	1.20E+01	CAG	18,000	--	9.0	1	1
1,1,2-Trifluoro-1,2-di chloroethane	354-23-4	7.10E-03	RASH	--	--	200	6	--
Tetrachloroethane								
1,1,2,2-Tetra-chloroethane	79-34-5	0.10E+02	EPA	9,320	--	7.9	1	2
Pentachloroethane	76-01-7	0.36E+01	EPA	7,240	--	68.0	2	2
Hexachloroethane	67-72-1	0.36E+01	EPA	980	--	140.0	3	2
Chloroform [trichloro-methane][Freon-20]	67-66-3	0.42E+01	EPA	28,900	--	6.0	1	1
Chloroethane	See Chlorinated ethanes							
2-Chloronaphthalene	91-58-7	4.00E+00	RASH	1,600	--	--	--	2
Chromium	7440-47-3	0.16E-01	EPA	16	100	200.0	6	4
Chromium (III)	16065-83-1	0.16E-01	EPA	980	100	200.0	6	2
Chromium (VI)	18540-29-9	0.16E-01	EPA	16	100	200.0	6	4
1,2-Cis-dichloroethylene	See Dichloroethylenes							
Copper	7440-50-8	0.20E+04	EPA	9.2	200	210.0	1	4
Cyanides	Several	0.40E+03	EPA	22	--	0	0	4
Sodium cyanide	143-33-9	0.96E-01	RASH	--	--	0	2	--
Potassium cyanide	151-50-8	0.32E+00	RASH	--	--	0	2	--
Hydrocyanic acid	74-90-8	0.94E-01	RASH	--	--	0	2	--
Isocyanide (ion)	57-12-5	0.50E+00	RASH	--	--	0	2	--
Cyclohexane	See Hydrocarbons							
Cyclotetramethylene tetranitramine	See HMX							
2,4-D [dichlorophenoxy-acetic acid]	94-75-7	0.22E+00	RASH	1,850	22.1	140	4	4

Table C.7 Estimated carcinogenic potency factors (CPFs) (Smith and Barnthouse, 1987) (continued)

Chemical	CAS No.	Health effects Benchmark (µg/d)	Health effects Source[a]	Aquatic life (µg/L)	Irrigated crops (µg/L)	Fish bio-accumulation (L/kg)	Health hazard score	Ecological hazard score
DDT [dichlorodiphenyl-trichloroethane]	50-29-3	0.56E-02	EPA	1.1	--	34,000	7	4
DDE [1,1-dichloro-2,2-bis(p-chlorophenyl) ethylene]	72-55-9	0.40E+00	RASH	--	--	18,000,000	5	--
DDE [1,1-bis(p-chloro-phenyl) ethane]	3547-04-4	0.26E+00	RASH	--	--	--	--	--
DDD [1,1-dichloro-2,2-bis(p-chlorophenyl) ethane]	72-54-8	0.56E+00	RASH	--	--	170,000	5	--
2,4-DDD [2,4-dichloro-phenyl dichloroethane]	53-19-0	1.4E+01	RASH	--	--	--	--	--
Diazinon	333-41-5	0.2E+00	RASH	0.03	5,000	29	3	6
Dibromochloromethane	See Halomethanes							
Dibromomethane	See Halomethanes							
1,2-Dibromomethane	See Ethylene dibromide							
1,2-Dichlorobenzene	See Chlorinated benzenes							
1,3-Dichlorobenzene	See Chlorinated benzenes							
1,4-Dichlorobenzene	See Chlorinated benzenes							
Dichlorobromomethane	See Halomethanes							
Dichlorodifluoromethane	See Halomethanes							
1,1-Dichloroethane	See Chlorinated ethanes							
1,2-Dichloroethane	See Chlorinated ethanes							
Dichloroethylene	--	--	--	11,600	--	--	--	1
1,1-Dichloroethylene [Vinylidine chloride]	75-35-4	0.26E+01	EPA	11,600	--	7.2	1	1
1,2-Dichloroethylene	540-59-0	0.26E+01	EPA	135,000	--	7.2	1	1
1,2-Cis-dichloro ethylene	156-59-2	0.26E+01	EPA	135,000	2E+08	7.2	1	1
1,2-Trans-dichloro-ethylene	156-60-5	0.26E+01	EPA	135,000	--	7.2	1	1
Dichloroethylether	See Bis(2-chloroethyl)ether							
Dichlorofluoromethane	See Halomethanes							
Dichloromethane	See Halomethanes							
Dichloropropane	--	--	--	23,000	--	--		
1,2-Dichloropropane [propylene dichloride]	78-87-5	0.11E+04	EPA	52,500	1.5E+08	43	1	1
Dieldrin	60-57-1	0.90E-06	EPA	2.5	1,150	14,000	9	2

Table C.7 Estimated carcinogenic potency factors (CPFs) (Smith and Barnthouse, 1987) (continued)

Chemical	CAS No.	Health effects Benchmark (µg/d)	Health effects Source[a]	Aquatic life (µg/L)	Irrigated crops (µg/L)	Fish bio-accumulation (L/kg)	Health hazard score	Ecological hazard score
Diethyl phthalate	See Phthalate esters							
2,4-Dimethylphenol [2,4-xylenol] [m-xylenol]	105-67-9	0.96E+01	RASH	2,120	--	150	3	2
Di-n-butyl phthalate	See Phthalate esters							
Dinitrobenzene	See Nitroaromatics							
Dinitrophenol	See Nitroaromatics							
Dinitrotoluene	See Nitroaromatics							
Dioctyl adipate	123-79-5	7.23E+01	RASH					
Dioxin [TCDD] [2,3,7,8-tetrachloro-dibenzo-p-dioxin]	1746-01-6	0.92E-08	EPA	--	--	9,300	9	--
Endosulfan II	--	--	--	0.22	--	--	--	6
Endrin	72-20-8	0.20E+01	EPA	0.18	--	2,600	4	6
Ethyl benzene [phenylethane]	100-41-4	0.22E+04	EPA	32,000	--	290	1	1
Ethylene chloride	See Chlorinated ethanes							
Ethylene dibromide [1,2-dibromoethane]	106-93-4	0.20E-01	CAG	15,000	--	2.5	2	1
Ethylene glycol [ethylene alcohol]	107-21-1	0.36E+02	RASH	5E+07	--	0.0039	1	0
Fluoranthene	206-44-0	0.40E+03	EPA	3,980	--	--	--	2
Formaldehyde	50-00-0	0.17E+01	RASH	15,000	--	0.28	2	1
Freon-11, Freon-30	See Halomethanes							
Freon-20	See Chloroform							
Freon-113	See Trichlorotrifluoroethane							
Halomethanes	--	--		11,000	--	--	--	1
Bromochloromethane [chlorobromomethane]	74-97-5	0.40E+01	EPA	67,000	--	7.4	1	1
Bromodichloromethane [dichlorobromomethane]	75-27-4	0.40E+01	EPA	11,000	--	17.	2	1
Dibromochloromethane	124-48-1	0.40E+01	EPA	11,000	--	28.	2	1
Dibromomethane [methylene bromide]	74-95-3	0.40E+01	EPA	11,000	50,000	--	--	1
Methylene chloride [dichloromethane] [Freon-30]	75-09-2	0.40E+01	EPA	193,000	--	4.4	1	1

Table C.7 Estimated carcinogenic potency factors (CPFs) (Smith and Barnthouse, 1987) (continued)

Chemical	CAS No.	Health effects Benchmark (µg/d)	Health effects Source[a]	Aquatic life (µg/L)	Irrigated crops (µg/L)	Fish bio-accumulation (L/kg)	Health hazard score	Ecological hazard score
Dichlorofluoromethane	75-43-4	1.16E+02	RASH	11,000	--	8.0	1	1
Dichlorodifluoromethane	75-71-8	2.07E+02	RASH	11,000	--	32	1	1
Trichlorofluoromethane [Freon-11]	75-69-4	0.11E+02	EPA	11,000	--	74	2	1
Heptachlor	76-44-8	0.46E-03	EPA	0.52	--	14,000	7	4
Heptachlor epoxide	1024-57-3	0.34E+00	RASH	0.52	--	14,000	5	4
Hexane	See Hydrocarbons							
Hexachlorocyclohexane [BHC]	608-73-1	0.42E-03	EPA	100	--	1,000	7	2
α-Isomer	319-84-6	0.56E-01	CAG	100	--	710	4	2
-Isomer	319-85-7	0.32E+00	CAG	100	--	720	4	2
γ-Isomer [Lindane]	58-89-9	0.44E+00	CAG	2.0	1,000	1,000	5	4
Hexachloromethane	See Chlorinated ethanes							
Hexadecanoic acid	57-10-3	6.00E-01	RASH	12,000	--	--	--	1
HMX (cyclotetramethylene tetranitramine)	2691-41-0	3.30E+00	RASH	32,000	--	--	--	1
Hydrazine	302-01-2	0.56E-01	RASH	40	--	0.026	2	4
Hydrocarbons								
Benzo(a)anthracene	56-55-3	6.00E-02	RASH	10	--	--	--	4
Benzo(a)pyrene	50-32-8	6.00E-02	EPA	5		30	3	4
Cyclohexane	--	--		32,710	76,440	550	--	1
Methylcyclohexane	--	--		41,000	--	--	--	1
Hexane	--	--		177,500	--	--	--	1
Octane	--	--		100,000	--	--	--	1
Pentane	--	--		100,000	59,340	490	--	1
Pyrene	129-00-1	6.00E+00	RASH	--	--	0.8	1	--
Propylbenzene	--	--		91,400	--	940	4	1
2-Methyl-1,3-butadiene (isoprene)	--	--		42,540	--	--	--	1
2-Butyl-1-octanol	3913-02-8	6.82E+01	RASH					
Isophorone	78-59-1	0.92E+03	EPA	117,000	100	7.1	0	2
Iron	1309-37-1	1.50E+02	RASH	400	5,000	100	2	2
4-Hydroxyazobenzene	1689-82-3	6.50E-01	RASH	--	--	--	--	--
Lead	7439-92-1	0.10E+03	EPA	34	5,000	300	3	4
Lindane	See Hexachlorocyclohexane							
Malathion	121-75-5	0.24E+01	RASH	0.5	--	160	3	6
Manganese	7439-96-5	2.50E-01	CAG	350	200	400	4	2
Mercury	7439-97-6	0.40E+00	EPA	2.4	--	63,000	5	4

Table C.7 Estimated carcinogenic potency factors (CPFs) (Smith and Barnthouse, 1987) (continued)

Chemical	CAS No.	Health effects Benchmark (µg/d)	Health effects Source[a]	Aquatic life (µg/L)	Irrigated crops (µg/L)	Fish bio-accumulation (L/kg)	Health hazard score	Ecological hazard score
Methoxychlor	72-43-5	0.16E+02	RASH	0.50	--	8,300	4	6
2-Methyl-1,3-butadiene	See Hydrocarbons							
Methyl cellosolve [2-methoxyethanol]	109-86-4	0.20E+01	RASH	17,400,000	--	0.050	1	--
Methylcyclohexane	See Hydrocarbons							
Methylene chloride	See Halomethanes							
Methyl ethyl ketone [2-butanone]	78-93-3	0.20E+02	RASH	5,600,000	--	0.60	1	0
Methyl isobutyl ketone	108-10-1	0.19E+02	RASH	460,000	--	6.2	1	4
Naphthalene [Naphthene]	91-20-3	0.28+03	EPA	2,300	--	430	2	2
Nickel	7440-02-0	0.26E+03	EPA	1,100	200	100	2	2
Nitroaromatics								
1,3-Dinitrobenzene	99-65-0	8.30E-01	RASH	7,400	--	7	2	2
1,3,5-Trinitrobenzene	99-35-4	2.20E+00	RASH	1,030	--	6	1	2
2-Amino-4,6-dinitro toluene	35572-78-2	--		4,500	--	3	--	2
2,4-Dinitrotoluene	81121-14-2	2.90E-01	RASH	13,900	--	25	3	1
2,6-Dinitrotoluene	606-20-2	1.60E+00	RASH	14,000	--	22	2	1
2,4,6-Trinitrotoluene	118-96-7	6.50E+00	RASH	2,850	--	16	2	2
2,4,6-Trinitrophenol (picric acid)	88-89-1	1.20E+00	RASH	85,000	--	--	--	1
2,4,6-Trinitroresorcinol (styphnic acid)	82-71-3	--		3,000,000	--	--	--	0
2,4-Dinitrophenol	51-28-5	2.00E-01	RASH	620	--	--	--	2
4-Nitrophenol	100-02-7	7.00E-01	RASH	8,280	--	--	--	2
Nitroglycerin	55-63-0	5.45E+00	RASH	1,670	--	15	2	2
Nitrosamines	--	--		5,850	--	81	--	2
n-Nitrosodimethylamine	62-75-9	0.15E-00	EPA	280,000	--	0.078	2	1
n-Nitrosodiphenylamine	86-30-6	0.19E+01	RASH	5,850	--	81	3	2
Octadecanoic acid	57-11-4	5.71E+00	RASH	--	--	--	--	--
Octane	See Hydrocarbons							
PCBs [polychlorinated biphenyls] [chlorodiphenyls]	Several	0.52E-3	EPA	2.0		10,000,000	7	4
Pentachloroethane	See Chlorinated ethanes							
Pentachlorophenol [PCP]	87-86-5	0.28E+03	EPA	55	37,300	780	2	4
Pentane	See Hydrocarbons							

Table C.7 Estimated carcinogenic potency factors (CPFs) (Smith and Barnthouse, 1987) (continued)

Chemical	CAS No.	Health effects Benchmark (µg/d)	Health effects Source[a]	Aquatic life (µg/L)	Irrigated crops (µg/L)	Fish bio-accumulation (L/kg)	Health hazard score	Ecological hazard score
Perchloroethylene	See Tetrachloroethylene							
PETN (pentaerythritol tetranitrate)	78-17-5	3.20E+03	RASH	--	--	--	--	--
Phenol [carbolic acid]	108-95-2	0.68E+04	EPA	10,000	--	1.7	0	1
Phthalate esters	--	--		940	--	--	--	2
Bis(2-ethylhexyl) phthalate	117-81-7	0.10E+05	EPA	160	--	310	1	2
Butyl benzyl phthalate	85-68-7	0.10E+05	EPA	1,700	--	660	1	2
Diethyl phthalate	84-66-2	0.10E+05	EPA	52,100	--	120	0	1
Di-n-butyl phthalate	84-74-2	0.10E+05	EPA	940	--	89	1	2
Picric acid	See Nitroaromatics							
Potassium nitrate	7757-79-1	1.20E+01	RASH	5,400	--	--	--	2
Propylbenzene	See Hydrocarbons							
Pyrene	See Hydrocarbons							
RDX [cyclonite,] [cyclotrimethylene trinitroamine]	121-82-4	2.10E+00	RASH	5,200	--	5	1	2
Selenium	7782-49-2	0.20E+02	EPA	260	--	8.3	1	2
Sevin	See Carbaryl							
Silver	7440-22-4	0.20E+02	EPA	1.2	--	2.0	1	4
Sodium (I) nitrate (1:1)	7651-99-4	3.80E+02	RASH	--	--	--	--	--
2,4,5-T [2,4,5-trichloro-phenoxyacetic acid]	93-76-5	0.11E+01	RASH	100	25,500	470	4	2
2,4,5-TP [Silvex] [2,4,5-trichlorophenoxy-propionic acid]	93-72-1	0.20E+01	RASH	340	770	1,400	4	2
Temik	See Aldicarb							
Tetrachloroethane	See Chlorinated ethanes							
Tetrachloroethylene [perchloroethylene]	127-18-4	0.40E+01	EPA	5,280	--	44	2	2
Tetrahydrofuran	109-99-9	2.07E+01	RASH	--	--	0.8	1	--
Tetryl	479-45-8	3.00E-02	RASH	2,400,000	--	--	--	0
Tetraethyl lead	78-00-2	1.03E-01	RASH	230	--	--	--	2
Thallium	7440-28-0	0.80E+01	EPA	--	--	10,000	4	--
Toluene [methyl benzene]	108-88-3	0.24E+02	EPA	17,500	--	83	2	1
Trans-1,2-dichlorethane	See Chlorinated ethanes							
Trans-1,2-dichloroethylene	See Dichloroethylene							

Table C.7 Estimated carcinogenic potency factors (CPFs) (Smith and Barnthouse, 1987) (continued)

Chemical	CAS No.	Health effects Benchmark (µg/d)	Health effects Source[a]	Aquatic life (µg/L)	Irrigated crops (µg/L)	Fish bio-accumulation (L/kg)	Health hazard score	Ecological hazard score
1,2-Trans-dichloroethylene	See Dichloroethylene							
1,2,4-Trichlorobenzene	See Chlorinated benzenes							
Trichloroethane	See Chlorinated ethanes							
1,1,1-Trichloroethane	See Chlorinated ethanes							
Trichloroethylene	79-01-6	0.42E+02	EPA	45,000	--	17	2	1
Trichlorofluoromethane	See Halomethanes							
Trichloromethane	See Chloroform							
Trichlorotrifluoroethane [Freon-113]	76-13-1	0.12E+02		--	--	480	3	--
Tricresyl phosphate [TCP]	1330-78-5	0.56E+01	RASH	7,000,000	--	170	3	0
1,1,2-Trifluoro-1,2-dichloroethane	See Chlorinated ethanes							
Trinitrobenzene	See Nitroaromatics							
Trinitrophenol	See Nitroaromatics							
Trinitroresorcinol	See Nitroaromatics							
Trinitrotoluene	See Nitroaromatics							
UDMH [unsymmetrical dimethyl hydrazine] [1,1-dimethylhydrazine]	57-14-7	0.44E+00	RASH	4,700	--	0.36	2	2
Vanadium	1314-62-1	1.50E-02	ACGIH	4,800	100	0.01	2	2
Vinyl chloride	75-01-4	0.10E+04		381,000	--	7.2	0	1
Xylene	1330-20-7	0.16+02	RASH	13,500	--	320	3	1
m-Xylene	108-38-3	0.16E+02	RASH	13,500	--	320	3	1
o-Xylene	95-47-6	0.36E+02	RASH	13,500	--	190	3	1
p-Xylene	106-42-3	0.15+02	RASH	13,500	--	290	3	1
2,4-Xylenol, m-xylenol	See 2,4-Dimethylphenol							
Zinc	7440-66-6	0.10E+05	EPA	180	2,000	1,000	2	4

[a]Source of health effects, benchmarks were Environmental Protection Agency water criteria documents (EPA), EPA Carcinogen Assessment Group publications (CAG), American Council of Governmental Industrial Hygienists (ACGIH), and relative potency estimates (RASH), T. D. Jones, P. J. Walsh, A. P. Watson, L. W. Barnthouse, and D. A. Sanders, "Chemical Scoring by a Rapid Screening Hazard (RASH) Method," J. Risk Analysis (in press).

Table C.7 Estimated carcinogenic potency factors (CPFs) (Smith and Barnthouse, 1987) (continued)

	Health effects (µg/D)	Aquatic life (µg/L)	Fish bioaccumulation (L/kg)	Hazard score	
				Health	Ecological
Diesel fuel	3.47E+01	970	--	--	2
Diesel fuel (marine)	1.71E+02	2,900	--	--	2
Gasoline	1.54E+01	8,000	--	--	2
Heavy fuel oil	1.50E+01	2,400,000	--	--	0
Hydraulic fluid (glycol)	3.53E+01	1,700,000	--	--	0
Hydraulic fluid (organophosphate)	1.36E+01	1,300	2000	4	2
Jet fuel	1.30E+01	28,800	120	3	1
JP-4	1.30E+01	28,800	120	3	1
JP-7	3.33E+02	28,800	120	2	1
Kerosene	1.05E+02	200,000	--	--	1
Light heating oil	6.00E+01	970	--	--	2
Lubricating oil	9.68E+00	2,500	--	--	2
Motor oil (new, used)	6.19E+01	--	--	--	--
Stoddard solvent (mineral spirits)	6.67E+00	--	--	--	--

[a]C. E. Easterly and L. R. Glass, "Toxicity of Petroleum Products as Predicted with a Relative Potency Methodology," Fundamental and Applied Toxicology (in press).

13. APPENDIX D

Data Required

Appendix B lists the data SRS requires to score each of the three generic pathways: ground-water, surface-water, and air. Moreover for each scored parameter, the list divides data requirements into two groups: data that are required or that an analyst will be required to roughly estimate (default values in brackets) and additional useful information that may improve the confidence level or point to unusual circumstances but may not be used directly in the scoring.

Ground-Water Pathway

Chemical Properties

Required Data

- solubility [S] of each hazardous chemical {1 kg/m^3 or Ci/m^3}
- mass [W_o] of each hazardous chemical at site (kg or Ci) (or concentration [C_o] and volume)
- chronic ingestion toxicity [T_{oral}] {1 $(mg/kg/day)^{-1}$ UCR or $1x10^{-5}$ mg/kg/day ADI}

Decay Rates {0 day^{-1}}

- decay rate in near-surface soil [λ_u]
- decay rate in ground-water [λ_{gw}]

Useful Additional Data

Retardation factors

- retardation in soil [$R \simeq 1+\rho_b K_d/\phi$]]
- retardation in ground water

Generation of Leachate

Required Data

- annual precipitation at site [r_a] {0.6 m/yr; $1.6x10^{-3}$m/day}
- percolation velocity in unsaturated zone [V_u] {0.005 m/day} (or hydraulic conductivity [K_u] from waste site to aquifer {10^{-2} m/day})
- hydraulic conductivity of landfill cover [K_{covr}] {10^{-3} m/day}
- surface area of waste site contributing to seepage through site [A_s]

Useful Additional Data

- lysimeter data for water budget on aquifer recharge at waste site

Transport and Dilution

Required Data

- distance from site to target population [x] (usually straight line distance unless channel aquifer) {500 m}
- depth to aquifer if decay important (distance from base of site to aquifer top) [d] {5 m}
- thickness of aquifer [m] {10 m}
- withdrawal discharge from aquifer [Q_w] {250 m^3/day;45 gal/min}
- seepage velocity in aquifer [V_{gw}] {0.1 m/day} (or hydraulic conductivity [K_{gw}] {1 m/day}, hydraulic head [η] {0.03 m/m} or surface slope [θ] {0.03 m/m}, and porosity [ϕ] {0.3})

Useful Additional Data

- lateral offset distance of intake well from downgradient flow vector [y] {0 m}
- aquifer, cover, and unsaturated zone porosity [ϕ] {0.3}
- dispersivity [α] {20 m}

Target Populations

Required Data

- number of persons served by water source (<u>downgradient</u> from waste site) [N]

Useful Additional Data

- population demographics such as sensitive subsets of the population, for example, average age and number of children
- location and populations of threatened, nonhuman biologic systems

Description of Containment

Required Data

- placement of waste

Surface-Water Pathway

Chemical Properties

Required Data

- solubility [S] of hazardous waste in water {1 kg/m^3 or Ci/m^3}
- mass [W_o] of each hazardous chemical (kg or Ci) (or concentration [C_o] and volume)
- chronic ingestion toxicity [T_{oral}] {1 $(mg/kg/day)^{-1}$ UCR or $1x10^{-5}$ mg/kg/day ADI}

Decay Rates {0 day^{-1}}

- decay rate in near-surface soil [λ_u]
- decay rate in surface water [λ_{sw}]

Useful Additional Data

- chemical retardation [$R \simeq 1+\rho_b K_d/\phi$]

Chemical Release Rate

Required Data

- annual precipitation [r_a] {0.6 m/yr; $1.6x10^{-3}$m/day}
- rainfall erosivity factor (USLE) {R_E = 150}
- description of type of surface soil {CN = 80}
- description of surface cover {CP = 0.35}
- contaminated surface area [A_s]
- slope angle of surface area [θ] {0.03 m/m; 3%}
- length of slope [ℓ] {200 m; 600 ft}
- bulk density of top 0.1 m of soil [ρ_b] {1500 kg/m^3}

Transport and Dilution

Required Data

- river discharge rate [Q_r] {10^5 m^3/day}
- average river speed [V_{sw}] if decay important {$2.5x10^4$ m/day}
- distance along watercourse to target [x_{riv}] {2500 m}
- river width (if x_{riv} short) [w_{riv}] {$w_{riv} \leq x_{riv}/40$}
- river depth (if x_{riv} short [d_{riv}] {2 m}

Useful Additional Data

- surface-water dispersivity [α_{sw}] {1 m}
- measured chemical release from waste site
- measurements of storm runoff from contaminated area
- measurements of sediment yield from contaminated area
- average sediment transport velocity [V_{sd}]
- SCS soil type parameter [K]

Target Populations

Required Data

- number of people served by water source [N]

Useful Additional Data

- population demographics
- location and populations of threaten biologic systems

Description of Containment

Required Data

- design-storm probabililty [u] for drainage structure {1/10yr}
- depth of soil cover [s] {1 m}
- placement of waste

<u>Air Pathway</u>

Chemical Properties

Required Data

- quantity [W_o] of each hazardous waste at site (kg or Ci) (or concentration [C_o] and volume)
- vapor pressure [p]
- molecular weight [w_m]
- chronic inhalation toxicity [T_{air}] {1 $(mg/kg/day)^{-1}$UCR}

Useful Additional Data

- decay rate in air [λ_a]

Emission Rate

Required Data

- depth of soil (cap) cover [s] {1 m}
- Thornthwaite's PE index [PE] {60}

Useful Additional Data

- porosity of soil cover [ϕ] {0.3}
- air monitoring data
- mean annual temperature [T_c] {288 K}
- fraction of soil < 10 μm diam {0.10}

Air Transport

Required Data

- distance to target population [x_{air}]

Useful Additional Data

- average annual wind speed [V_w] {4×10^5 m/day; 5 m/s}}
- prevalent wind directions, "wind rose"

Target Populations

Required Data

- number of persons threatened [N]

Useful Additional Data

- population demographics
- location and populations of threatened biologic systems

Description of Containment

Required Data

- placement of waste

14. APPENDIX E

Nomenclature

Mathematical Symbols

A_{drain} - area of river drainage basin (m^2)

A_s - surface area contributing seepage [r_{seep}] into landfill or releasing gas or fugitive dust [e] (usually equivalent to the landfill or lagoon surface area) (m^2)

a - conversion constant

B_a, B_w - average human inhalation {20 m^3/day} and ingestion {$2x10^{-3}$ m^3/day}

B_u - average water use per capita {0.76 m^3/day/person}

b - hydraulic radius (m)

C_a - concentration of chemical waste injected into aquifer (kg/m^3)

C_b - contaminant concentration in air directly downwind of site (kg/m^3)

C_i - concentration of chemical waste available for release (kg/m^3)

C_o - disposed concentration of chemical waste (kg/m^3)

C_p - concentration in ground-water plume (kg/m^3)

C_r - concentration at release from waste site (kg/m^3)

C_v - saturation vapor concentration (kg/m^3)

C_w - concentration at withdrawal point for water supply (kg/m^3)

CN - Soil Conservation Service (SCS) curve number

CP - SCS control practice factor

CR - latent cancer risk (risk/rem)

D_{ij} - dispersion tensor

D_u, D_{gw} - hydrodynamic dispersion in unsaturated and saturated zones, respectively = $\nu D^*/\tau + \alpha V$ (m^2/day)

D_x, D_y - longitudinal and lateral dispersion, respectively (m^2/day)

D^* - molecular diffusion (m^2/day)

D_c^* - diffusion constant in air (m^2/day)

d - vertical distance from base of landfill or lagoon to aquifer (m)

d_{cont} - depth dimension of soil contamination (m)

d_{plume} - unsaturated lateral plume dimension (1-D transport in aquifer) (m)

d_{riv} - mean river depth (m)

DF_{oral}, DF_{air} - ingestion and inhalation radionuclide human dose factors, respectively (rem per μCi/day)

E - exposure; subscripts indicate whether from ground-water [gw], surface-water [sw], or air [air] pathway (kg)

e - total emission rate into air pathway (kg/day)

e_v, e_w - emission rate of waste gas or fugitive dust into atmosphere (kg/day)

ET_m - monthly evapotranspiration

F - score of measured parameter (numerous subscripts)

f_{covr} - factor evaluating soil cover for air pathway

f_{cllct} - subjective factor evaluating leachate collection practices

f_{eng} - engineered-barrier factor

f_{gen} - factor increasing emission (if other gas present to sweep waste)

f_{put} - subjective factor evaluating method of waste placement

f_{rtrd} - subjective factor for evaluating chemical retardation

f_{site} - site reduction factor

f_{strct} - subjective factor evaluating soil cover and hydraulic structures

g - acceleration of gravity (m/s^2)

g_{gw}, g_{sw}, g_a - mass-loading adjustment for ground-water, surface-water, and air pathways

H - Henry's gas law constant

h - depth of soil susceptible to erosion

i_r - flow rate of leachate from site to aquifer (m^3/day)

K - SCS soil erodibility factor

K_{covr} - hydraulic conductivity of cover over landfill (m^2/day)

K_d - partition or distribution coefficient (m^3/kg)

K_{gw} - hydraulic conductivity (Darcy flow) of aquifer (m^2/day)

K_u - vertical hydraulic conductivity of unsaturated zone between waste site and aquifer, $K_u = \Sigma_i L_i/(\Sigma_i L_i/K_i)$, where K_i is geologic stratum hydraulic conductivity, L_i is stratum thickness, and n is number of stratum (m^2/day)

k - proportionality constant

$\hat{k}$ - volatilization mass transfer coefficient

L_c - container life before leaking (day)

L_i - height of ith geologic stratum (m)

ℓ - length of slope (ft)

ℓ_m - length for thorough mixing in surface water (m)

LS - length-slope factor in universal soil loss equation

M - total mass released from waste site (kg)

$\bar{M}_{gw}$ - average mass release rate from site per aquifer thickness (g/day/m)

$\bar{M}_a, \bar{M}_{sw}$ - average mass release rate from site (air and surface water) (g/day)

m - aquifer thickness (m)

m_w - gram molecular weight

N - size of target (receptor) population

n - number of atoms in 1 mg of isotope

n_m - Manning's coefficient ($s/m^{1/3}$)

P - probability of scenario

p - vapor pressure of volatile waste (atm)

PE - Thornthwaite precipitation-effectiveness index

$P(v^*)$ - erosion potential, i.e., mass of erodible particles on surface

Q_a - additional clean water mixed with contaminated water {0 m^3/day}

Q_r - river discharge rate (m^3/day)

Q_w - withdrawal rate from aquifer (m^3/day)

Q_q - additional diluting surface runoff in intermittent stream (m^3/day)

q - surface runoff discharge (m^3/day)

QF - radiation quality factor

R - chemical retardation factor

R_c - universal gas constant

R_E - SCS rainfall factor in universal soil loss equation

$\hat{R}_h, \hat{R}_e, R_\$$ - human health risk, general ecological system risk, economic risk, respectively

r_a - average daily precipitation (m/day)

r_m - monthly precipitation (m/month)

r_{net} - net precipitation runoff (m/day)

r_{perc} - leachate release rate (m/day)

r_{seep} - potential seepage into landfill or lagoon (m/day)

S - chemical solubility (kg/m^3)

$S(X_i)$ - standard deviation of variable X_i

$S(\hat{R})$ - standard deviation of risk prediction $\hat{R}$

s - depth of soil cover over the waste (m)

s_{riv} - slope of surface water (m/m)

T - chronic toxicity of the chemical (either allowable daily intake (ADI) (mg/kg/day) or unit cancer risk (UCR) $(mg/kg/day)^{-1}$)

T_c - mean annual temperature (K)

t_ℓ - average human life expectancy (2.56×10^4 day)

$t_{1/2}$ - half-life of hazardous material (day)

U - probability that at least one storm event will exceed design storm frequency [u] over period t_ℓ

u - design storm probability (reciprocal of design storm frequency)

V_{gw}, V_u - aquifer and percolation average interstitial water speed (m/day)

V_{sd} - river sediment speed (m/day)

V_{sw} - surface water speed (m/day)

V_w - mean annual wind speed (m/day)

v^* - fastest mile of wind (m/s)

v_* - river shear velocity (m/day)

W_o - mass of hazardous waste deposited at site (kg)

W_i - mass of hazardous waste available for release (kg)

w - body mass of average individual (70 kg)

w_b - body mass of organ b (kg)

w_{plume} - unsaturated width of plume (1-dimensional transport in aquifer) (m)

w_{riv} - river width (m)

X_i - variable of $\hat{R}$ $[R(X_i,\ldots,X_k)]$

x_{gw}, x_{riv}, x_{air} - horizontal contaminant pathway distance from waste site to target population via ground-water, surface-water, and air pathway (m)

x_i - spatial coordinate

Y_s - sediment yield from contaminated area (kg/m^2)

Y_d - contaminant yield after decay

y - lateral distance (m)

Z - activity of radionuclide per mg/kg body weight/day

z - vertical distance (m)

α - dispersivity (m)

Γ - constant for ground-water, surface-water, air pathways (gw, sw, and a subscripts)

δ - dilution of chemical waste along pathway

ϵ - effective absorbed energy [ξ] per disintegration of radionuclide in organ k, including a quality factor [QF] to convert rad to rem (MeV/dis • rem/rad)

η - hydraulic gradient

θ - slope of surface contaminated with toxic waste (%)

κ - mass concentration $[W_i/(\rho d_{cont} A_s)]$ (kg/kg)

λ - decay rate of material (numerous subscripts) (day^{-1})

μ_b - fraction of radionuclide absorbed in organ b

μ_{dis} - runoff ratio, r_{net}/r_a

μ_{covr} - portion of covered soil (varies from 0 for none to 1 for covered)

μ_r - fraction of annual precipitation percolating through waste dump

ν - constrictivity of porous media

ξ - energy absorbed per disintegration of radionuclide

ρ_b - bulk density of soil

σ - atmospheric dispersion in x, y, or z direction (subscripts) (m^2/day)

τ - tortuosity in porous media

ϕ - porosity of material

$\dot{\chi}$ - diffusion path distance (conceptual)

ψ - consequence of a release scenario

Ω - volume of waste (mixing cell volume) (m^3)

ω_b - fractional contribution of organ b to the total risk under uniform whole-body irradiation

Acronyms and Initialisms

ADI - Acceptable Daily Intake of noncarcinogens (RfD) (mg/kg/day)

AEA - Atomic Energy Act of 1954

CAG - Carcinogen Assessment Group of EPA

CERCLA - Comprehensive Environmental Response, Compensation, and Liability Act (Superfund) of 1980; law applicable to abandoned waste sites

CPF - Carcinogenic Potency Factor; equivalent to UCR

CWA - Clean Water Act

DOE - U.S. Department of Energy

EDE - Effective dose equivalent

EPA - U.S. Environmental Protection Agency

FDA - Food and Drug Administration

FS - Feasibility Study on Superfund sites

HARM - USAF Hazard Assessment Rating Methodology for hazardous waste sites

HAZWRAP- Hazardous Waste Remedial Action Program of DOE Defense Programs Undersecretary

HEA - EPA Health Effects Assessments documents

HPI - Hazard Potential Index used in RAPS

HRS - Hazard Ranking System developed for EPA to rank sites for NPL

mHRS - modified Hazard Ranking System; HRS modified by PNL to include radionuclides

NOAEL - No Observed Adverse Effects Limit; used to establish ADI

NPL - National Priorities List; list of sites that may receive CERCLA funding; established using HRS

NRC - U.S. Nuclear Regulatory Commission

ORNL - Oak Ridge National Laboratories, Oak Ridge, Tennessee

PCBs - Polychlorinated Biphenyl chemicals

PNL - Battelle Pacific Northwest Laboratories, Richland, Washington

RAPS - Remedial Action Priority System under development by PNL

RCRA - Resource Conservation and Recovery Act of 1976; law applicable to current and future hazardous waste sites and handling practices

RfD - EPA reference dose (ADI) (mg/kg/day)

RI - Remedial investigation report of a waste site (EPA term)

SARA - Superfund Admendments and Reauthorization Act of 1986

SCS - U.S. Soil Conservation Service

SNLA - Sandia National Laboratories, Albuquerque, New Mexico

SRS - Site Ranking System developed by SNLA for ranking DOE hazardous waste sites

UCR - Unit Cancer Risk (mg or μCi/kg body weight/day)$^{-1}$

USAF - U.S. Air Force

Definitions

Risk Assessment--Risk assessments estimate effects of substance or process on individuals or population

Risk Assessment policy--Risk assessment policy establishes philosophy used to select among analysis choices

Risk Management--Risk management is the process of evaluating and selecting alternative courses of action

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